NBSIR 79-1751

Custody Transfer Systems for LNG Ships: Tank Survey Techniques and Sounding Tables

Richard H. F. Jackson*
Richard S. Collier**
Seymour Haber*
Peter V. Tryon*

*Center for Applied Mathematics
**Thermophysical Properties Division
National Engineering Laboratory
National Bureau of Standards
U.S. Department of Commerce
Boulder, Colorado 80303

July 1, 1978

Issued May 1979

Prepared for
The Maritime Administration
Department of Commerce
Washington, D.C.

NBSIR 79-1751

CUSTODY TRANSFER SYSTEMS FOR LNG SHIPS: TANK SURVEY TECHNIQUES AND SOUNDING TABLES

Richard H. F. Jackson*
Richard S. Collier**
Seymour Haber*
Peter V. Tryon*

*Center for Applied Mathematics
**Thermophysical Properties Division
National Engineering Laboratory
National Bureau of Standards
U.S. Department of Commerce
Boulder, Colorado 80303

July 1, 1978

Issued May 1979

Prepared for
The Maritime Administration
Department of Commerce
Washington, D.C.

U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*
Jordan J. Baruch, *Assistant Secretary for Science and Technology*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Static measurements of liquefied natural gas (LNG) for custody transfer purposes require an accurate and precise knowledge of the container volume and the volume-height relationship. The extremely low temperatures of LNG (less than 150° K) preclude *in situ* surveys; however, the increasing value of the cargo requires more precise and accurate measurements than previously used for bulk marine cargoes.

A description and assessment of the application of photogrammetric techniques to the ambient temperature survey of a 35-meter diameter spherical aluminum container are presented. Sample sounding tables (height-volume) are calculated, and an estimate of error is given.

Key words: accuracy; statistical analysis; cryogenic; error estimation; liquefied natural gas; LNG; marine; mathematical modeling; measurement; photogrammetric; precision; ship cargo; strapping; survey.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance, advice, and encouragement of James D. Siegwarth, Patricia J. Giarratano, Dwain E. Diller, and Douglas B. Mann of the NBS Thermophysical Properties Division, Robert J. Hocken, NBS Dimensional Technology Division, and Christoph Witzgall of the NBS Operations Research Division. Additionally, without the patience and cooperation of Don Shaaf and personnel in the General Dynamics Quincy Shipbuilding Division much of this work would not have been possible. Discussions with photogrammetric consultants John Kenefick, Duane Brown, and John Strahle were also most helpful.

LIST OF TABLES AND FIGURES

TABLE OF CONTENTS

1. INTRODUCTION

The Liquefied Natural Gas (LNG) Program of the National Bureau of Standards (NBS) is designed primarily to supply property data for the materials and fluids of interest and to aid in the establishment of measurement methods and instrumentation for custody transfer of this fluid in commerce. This report concerns work, supported in part by the Maritime Administration of the Department of Commerce, in the area of custody transfer: specifically, static measurements of the quantity of fluid contained in a storage tank before and after delivery, either into or out of the tank.

The analysis reported herein was performed on spherical LNG tanks constructed by General Dynamics/Quincy Shipbuilding Division for use in the LNG ship Aquarius. Previous methods for calibrating such tanks and calculating "list and trim" tables relied heavily on measurements taken with tapes, referred to as "strapping" [5]. Ship owners and therefore ship builders have a specific interest in these measurements and the resulting tables of volume vs. height, since they are used by a ship's captain to determine the amount of cargo at any particular time. The resultant estimates of volume added or removed are then mathematically combined with fluid density measurements to determine mass transferred. Gas sampling and analysis provide average BTU content, and the combination of mass transferred and BTU content yields total heating value of the cargo.

One objective of the Maritime Administration is to promote the development of the LNG shipbuilding industry in the United States. The Mar Ad was therefore interested in establishing accurate and precise tank-calibration technology for use with the first LNG ships constructed in U.S. shipyards. Since strapping measurements are typically made at the shipyard during construction, the analysis of tank strapping accuracies reported here was undertaken.

In essence, strapping is a geometric survey of the inside of the ship tank, relating measured points on planes and surfaces to fixed reference points. The balance of the work concerns the mathematical treatment of the measured data to construct an accurate model of the tank geometry. (Error estimates can be made by relating the model to the measured and reference points.) The volume-height relationships are then derived from the mathematical model.

This report contains three sections, a list of references, and two appendices. Following this introductory section, section 2 presents the photogrammetric technique for calibrating large tanks. The analysis of sounding table accuracies that can be expected from the survey technique is presented in section 3. Also included is a discussion of similarities and differences between the analysis performed by the photogrammetric consultants and that performed by NBS. Appendix A contains samples of the sounding tables computed by NBS, and appendix B contains portions of the sounding tables computed by the photogrammetric consultants.

It should be pointed out that NBS had no specific contract authority to gather and analyze data. Only the extensive cooperation of the Maritime Administration, the ship builder, the ship owner, and the photogrammetric contractors made it possible to complete and publish this work.

2. THE SURVEY METHOD

Rectangular and spherical tanks are usually dimensioned by conventional strapping techniques; sufficient lengths and circumferences are measured by taping so that the shape of the tank can be determined and used to calculate the volume as a function of height. Since the spherical tanks on the General Dynamics ships do not lend themselves well to conventional taping, a photogrammetric technique to measure tank volume has been developed (by a commercial firm).

Photogrammetric Surveying

The wide-angle analytic photogrammetric technique used to determine the dimensions of the General Dynamics tanks offers potentially higher accuracy than strapping. The claimed precision for this technique approaches 1 part in 100,000, or approximately ±0.4 mm for a 35 m diameter tank.

The photogrammetric method, described in detail in [1], consists of determining the x-, y-, and z-coordinate values for targets on the inner tank surfaces by photographing the targets from nine different positions within a tank. Targets are required on the tank so that points on the surface can be identifiable from photograph to photograph (see figs. 1 and 2 for tank target distributions). The 408 targets used in these tanks are 7/8" diameter white spots surrounded by a black background and are spray-painted on during construction of the tank. Special photographic plates consisting of thin emulsions of uniform thickness on very flat glass plates are used for the photography.

The two-dimensional positions of the target images on the plates are measured to within 3 μm with a monocomparator. These values are related to the

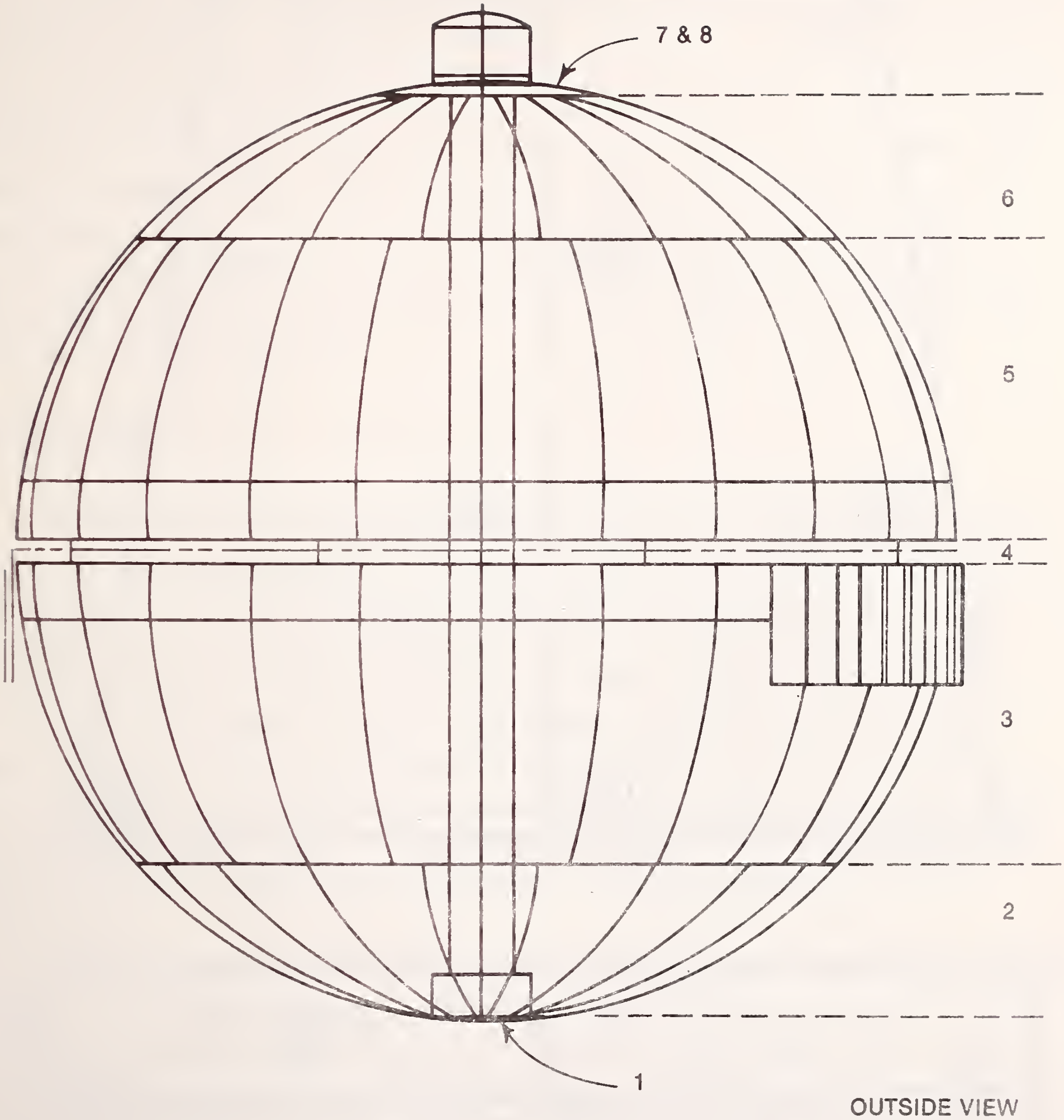


Figure 1. Tank schematic.

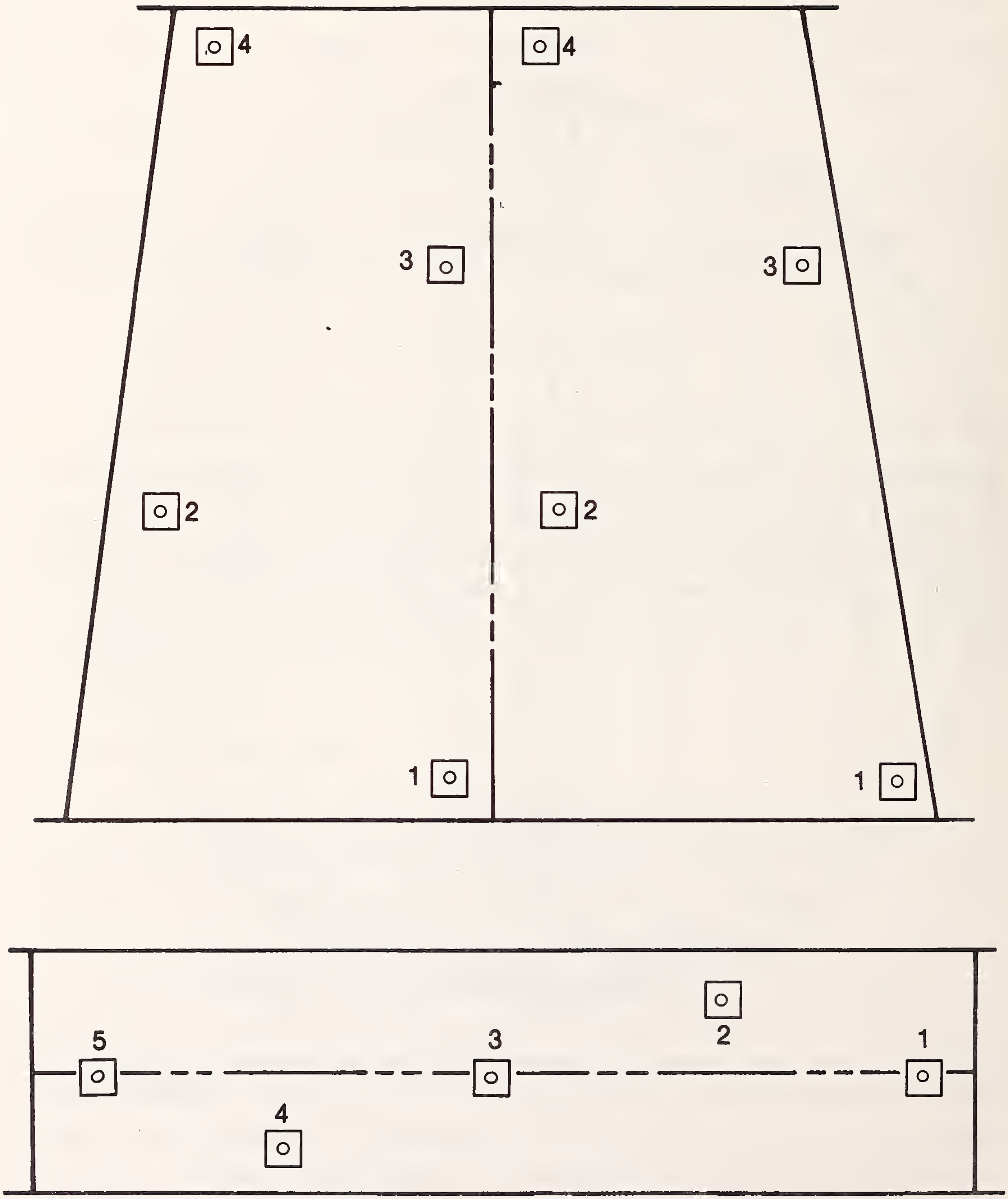


Figure 2. Distribution and numbering scheme for targets on inner plate and equatorial ring.

x-, y-, and z- coordinates through a large set of mathematical equations that are solved by computer. The unknowns calculated are the x-, y-, and z- coordinates, the directions of the principal axis of the camera, the coefficients of the lens distortion correction equation, and the uncertainties for the coordinate values. Details of the technique, however, are proprietary. The resulting coordinates have an arbitrary scale; hence, calibration lengths must be known to correct to coordinates in real space. This information is provided by targets placed at known spacings on calibration tapes visible in the photographs. The targets should be photographed when the tank is isothermal, either after dark or after the tank has been insulated.

The Tank Model

Construction of a mathematical model of the tank is essential to the calculation of tank capacity tables. The model is a mathematical description of the tank surface fitted to the target coordinates; its accuracy depends not only on the accuracy of the target coordinates but also on the density of targets on the tank surface and the regularity of the tank surface between target locations. It is clearly desirable to have as many targets as possible to reduce the uncertainty in interpolating between targets. However, there is a practical limit to the number of targets that can be measured because of the time and cost in reducing the data. With one exception (discussed in the next section), NBS had no control over the number or placement of targets painted on the tank surface.

Model construction usually begins with the calculation of some regular solid, e.g., a perfect sphere, prism, etc., which best fits the target coordinate data developed from the survey. Differences between actual target coordinates and the coordinates of the closest point on the surface of the model solid are then calculated. These "residuals" are then studied for patterns that would indicate systematic distortions (bulges, bends, or twists) in the shape of the tank.

On the basis of patterns discovered during this exploratory residual analysis, a special-purpose technique is developed to integrate numerically the composite tank model, which specifies a regular solid along with a table of deviations or residuals.

The final step in this analysis is the calculation of sounding tables giving tank volumes at regular intervals of liquid height in the tank. Error bounds on these tank table values are developed in this report.

Tank Table Modifications

There are a number of modifications to the sounding tables that must be made before their construction is complete. List, trim, thermal contraction, and stress effects must be accounted for. List and trim corrections, however, are not addressed in this report since NBS did not have access to the data or the procedures used in making these corrections.

It is standard practice to correct tank tables for thermal contraction by applying contraction coefficients as if the tank were mechanically unconstrained. The dimensions of the tank are decreased uniformly according to the thermal contraction of the material. Actually, tank mounting constraints and variations in the thermal expansions of the structural material can introduce strains in the tank that might affect cargo capacity. These thermal stress effects cannot presently be analyzed, because data on constraint effects and anisotropic thermal coefficients are lacking.

Another effect is the cargo load, which stresses both the tank and the ship hull. The tank strains supposedly have been measured during hydrostatic tests, but this information has not been made available. Data on capacity effects from hull strains are also unavailable. An analysis of the effects of these strains on the tank tables is therefore beyond the scope of this work. Furthermore, the photogrammetric contractors do not include such corrections in their report.

3. ANALYSIS OF AQUARIUS TANK NUMBER 4

As part of the Maritime Administration Custody Transfer program mentioned earlier, NBS was asked to evaluate the methodology used to calibrate the LNG tanks constructed by General Dynamics at its Charleston facility. In addition, NBS was asked to comment on the accuracy of the sounding tables subsequently constructed. In this section, we present our analysis and describe how it differs from the analysis performed by the photogrammetric consultants. Included also is a discussion of the accuracy of the sounding tables constructed and an assessment of the limitations, additional to those implicit in the last paragraph, to the applicability of those tables.

Tank Description

Each tank calibrated is spherical, with a diameter of approximately 36.5 meters and a capacity (volume) of 25,000 cubic meters. The tanks are constructed of four bands ("strakes") of aluminum plates in the shape of spherical trapezoids (see fig. 1), with special cap plates at the top and bottom. The only internal structure is a cylindrical tower extending from cap to cap containing piping, wiring, depth gauges, etc.

The first step in constructing a tank is to weld together the equatorial ring by which the tank is supported. The ring is set up on jigs, and the tank plates making up the central strakes (previously welded into pairs) are welded in place above and below the equatorial ring. The top and bottom strakes are then welded in place. The bottom and top circular plates are welded in after the rest of the welding is completed, and the internal staging is removed.

After a tank is completed, it is loaded on a crawler, supported from beneath, and moved to the hydrostatic test stand. After the test, the tank is moved to the insulation building and insulated. Then, it is moved to a barge for transporting to the shipyard at Quincy where it is lifted into place on the ship.

Sources of Error

The procedure for constructing sounding tables was discussed in section 2. Basically, that procedure consists of:

a. photogrammetrically surveying target coordinates on the inside surface of the tank;
b. constructing a mathematical model of the tank geometry;
c. developing a mathematical technique for computing volumes below specified heights in the tank; and
d. determining effects on tank shape (and therefore tank volume) of tank loading, cooling, liquid loading, sagging, sloshing, etc.

Each stage of calculation has associated with it an error bound on the accuracy of the result. These error bounds can be calculated using the appropriate statistical analysis; this can always be done and is straightforward. Difficulties arise only in regard to the "tightness" of those bounds, i.e., their balance between realism and conservatism. These error bounds will be discussed later in this section. First, we present our analysis and the resulting sounding tables.

Exploratory Statistical Analysis

Here we present the results of an exploratory statistical analysis of the target coordinate data for Aquarius Tank Number 4 obtained from the photogrammetric consultants. A best-fitting sphere is obtained by using linear least squares to minimize the sum of the squares of the radial residuals. Analysis of these residuals then provides information on how the tank wall deviates from a true sphere, information of value to the numerical integration procedure described later.

In fitting a sphere, if the usual concept of a distance measure ($d=\sqrt{x^2 + y^2 + z^2}$) is used, the distance between a point and the surface of a sphere is a nonlinear function of the unknown parameters of the sphere. This complexity results in a nonlinear least squares problem for finding the best-fitting sphere. Witzgall [7] has developed a technique that avoids this complexity and reduces the problem to a linear one, allowing the use of linear least squares.

Below, we summarize the approach suggested by Witzgall and show how to remove its bias. The formulation is for an arbitrary n-dimensional space and thus applies equally well to circles in 2-space, spheres in 3-space, and hyperspheres in n-space (R^n).

Calculation of the Best-fitting Sphere

Here we present a summary of the mathematics used in calculating the best-fitting sphere. Although condensed, it remains technical, thereby necessitating a warning: the reader who is uninterested in the mathematical foundations for subsequent results can skip over this section without loss of information.

A sphere consists of all points $x \epsilon R^n$ satisfying

$$x'x - 2a'x - \gamma = 0,$$

where x and a are nx1 vectors, γ is a scalar, and x' is the transpose of x. The vector a represents the coordinates of the center. This equation can be written

$$(x-a)' (x-a) = a'a + \gamma,$$

from which it is seen that the radius of the sphere is

$$r = \sqrt{a'a + \gamma},$$

where we restrict γ to satisfy $\gamma \geq -a'a$.

The Euclidean distance between a point $y \varepsilon R^n$ and the surface of the sphere S(a, r) having center a and radius r is the modulus of the difference of the radius and the distance, ρ, between y and a, i.e.,

$$\Delta_{eucl} (y,S) = |r - \rho|$$

$$\text{where } \rho^2 = (y-a)'(y-a).$$

The technique proposed by Witzgall for avoiding the nonlinearity is to use a different distance measure (or metric) instead of the usual Euclidean measure. He calls this a "square" metric and defines it as follows:

$$\Delta_{square} (y,S) = |r^2 - \rho^2|.$$

Using this metric we have

$$r^2 - \rho^2 = 2y'a + \gamma - y'y$$

or

$$y'y = \gamma + 2a'y + \rho^2 - r^2.$$

This equation is suitable for the applications of linear least squares where

$y'y$ is the dependent variable;

$2y_1, 2y_2, \ldots, 2y_n$ are the independent variables;

$\gamma, a_1, a_2, \ldots, a_n$ are the unknown parameters; and

$\rho^2 - r^2$ is the residual.

Thus, any linear least squares computer program can be used to find the sphere which minimizes

$$\sum_{i=1}^{m} (\rho_i^{\,2} - r^2)^2 ,$$

where m is the number of observations and where ρ is now indexed by i over the set of data points.

Furthermore, we note that

$$\rho_i^{\,2} - r^2 = (\rho_i + r)(\rho_i - r),$$

so that we can transform Δ_{square} to Δ_{eucl} and conversely. In particular,

$$\sum_{i=1}^{m} (\rho_i^{\,2} - r^2)^2 = \sum_{i-1}^{m} (\rho_i + r)^2 (\rho_i - r)^2 ;$$

so that the least squares formulation using square distance is equivalent to weighted least squares in Euclidean distance with weights ρ_i+r. Thus, using "square distance," points outside the sphere receive more weight than points inside, and the sphere will be larger than the "Euclidean distance" sphere. This bias can be reduced by first using unweighted linear least squares and then recomputing using weights $1/(\rho_i+\hat{r})$, where $\hat{r}$ is the estimate of r obtained from the previous unweighted analysis. This could be iterated in an obvious manner; the convergence of this numerical process has not been checked. In the present example, with $r \approx 18$ meters and $\rho_i - r_i \approx .03$ meters, the recomputation reduces the radius by 6×10^{-6} meters, which is negligible. However, if the residuals were large relative to the radius, the correction and its iterative properties could be important.

The Best-fitting Sphere

Using the technique described above, the radius of the best-fitting sphere for Aquarius Tank Number 4 was determined to be:

$$r = 18.2682 \text{ meters},$$

with a standard error of

$$SE \simeq .0071 \text{ meters}.$$

With respect to the coordinate system defined by the consultants, the coordinates of the center are:

$$a_1 = x = .0005 \text{ meters}, \qquad SE = .0013 \text{ meters};$$

$$a_2 = y = -.0009 \text{ meters}, \qquad SE = .0013 \text{ meters};$$

$$a_3 = z = -.0137 \text{ meters}, \qquad SE = .0011 \text{ meters}.$$

The standard errors given above are computed using the usual least squares theory that assumes the radial residuals from a perfect sphere are random. As shown below, this assumption is incorrect. The purpose of the best-fitting sphere, however, is only to serve as a reference surface for further analysis.

Analysis of Residuals

With the calculation of the best-fitting sphere, we are now in a position to perform the exploratory analysis of residuals that provides specific information on tank shape. A thorough residual analysis, such as was performed here, typically includes many types of graphical displays; in the interest of brevity, we present here only a selected few examples. Nevertheless, the discussion includes all important highlights.

The targets are arranged in 21 rows around the sphere: 1 row on each of the top and bottom polar plates; 3 rows on the equatorial ring; and 4 rows on each of the four strakes. On each plate there are 4 targets arranged and numbered as indicated in figure 2.

Figure 3 shows the residuals (in Euclidean distance) plotted versus their height along the vertical axis in the tank. (In that graph and subsequent ones, a dot indicates one value while a number as plot symbol indicates the frequency of the data value.) This clearly shows the general nature of the tank distortion. The bottom polar plate and the bottom edge of the #1 strake are flattened (as if the tank were free-standing on a flat surface) and lie internal to the sphere by as much as 6 cm. The #1 strake must have a "sharp"

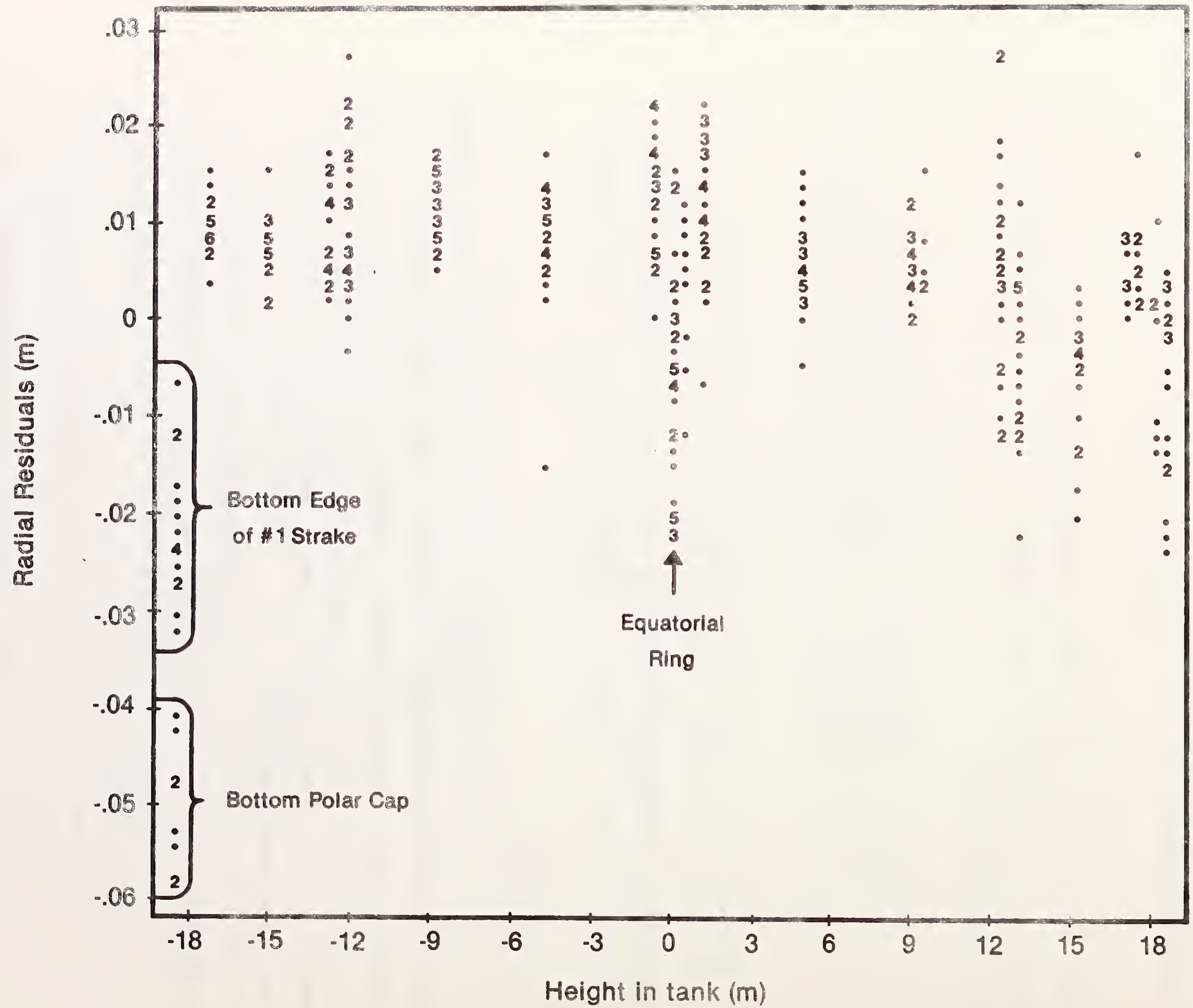


Figure 3. Tank residuals displayed as a function of height.
(Note: plot symbols other than dot indicate frequency of data value.)

bend near the second row of targets, because the residuals for the upper three rows of targets on the #1 strake and all points on the #2 strake average 0.8 cm outside the sphere. Figure 4 is an enlargement showing the residuals from the equatorial ring and the adjacent rows on the strakes. As is clearly shown, the equatorial ring is curved inward.

Figures 5-10 show plots of the amplitude of each of the 21 horizontal rows of residuals versus angle around the tank. Table 1 summarizes the residuals by row. The most interesting fact is that in some regions the residuals are following some major distortion of the tank and are thus not random. In other areas (at joints between strakes), the residuals appear random but have standard deviations similar to those in the nonrandom regions. In particular, the regions of randomness are adjacent to the seams where 42 plates are joined. However, in only one case (bottom polar plate) do the "nonrandom" residuals appear to be such that they could be approximated by a simple surface or polynomial. In fact the first strake, row 1 residuals can be fitted well by a sine curve, though not nearly as well as those for the bottom polar plate.

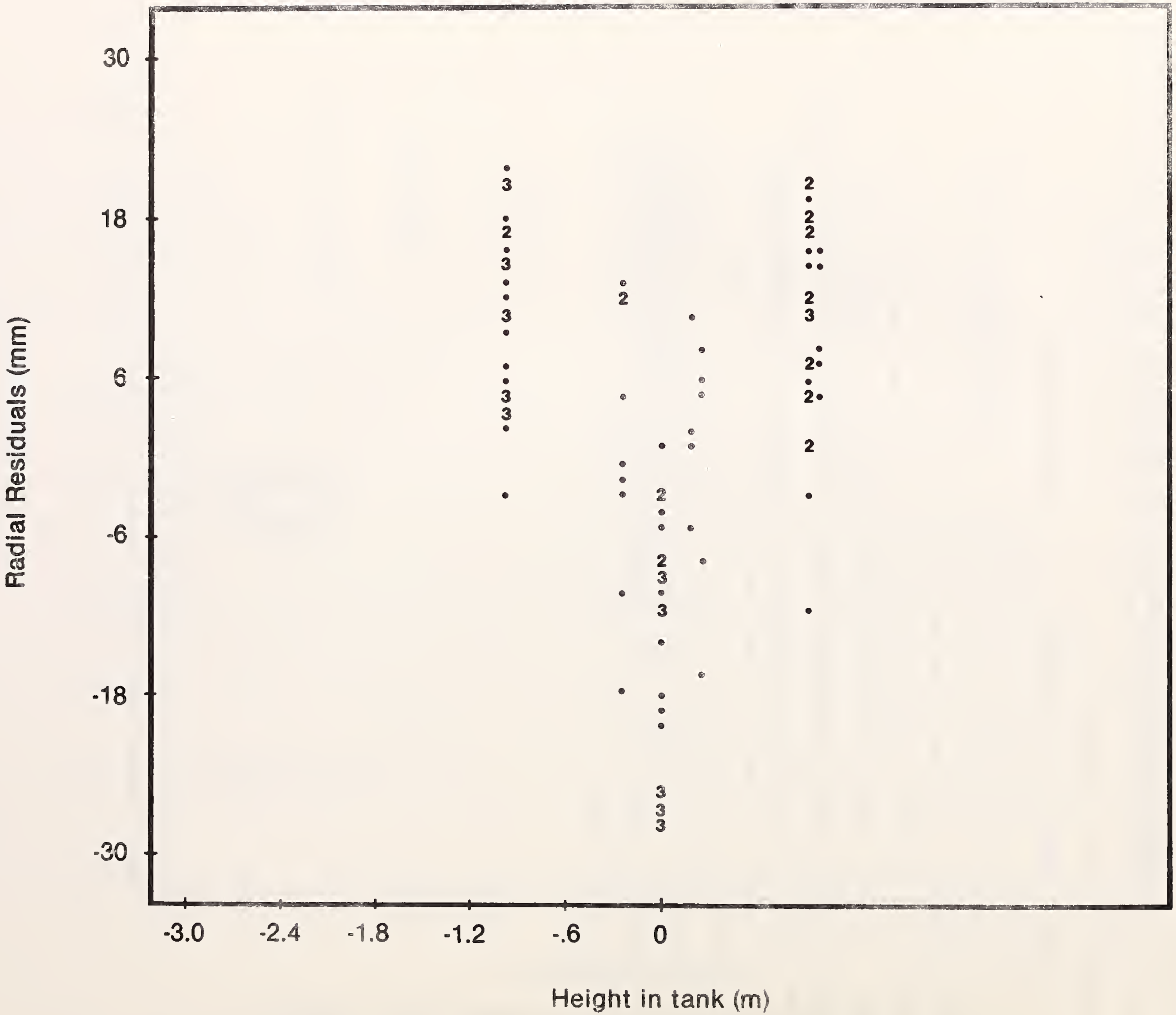


Figure 4. Residuals in equatorial ring region, displayed as function of height.

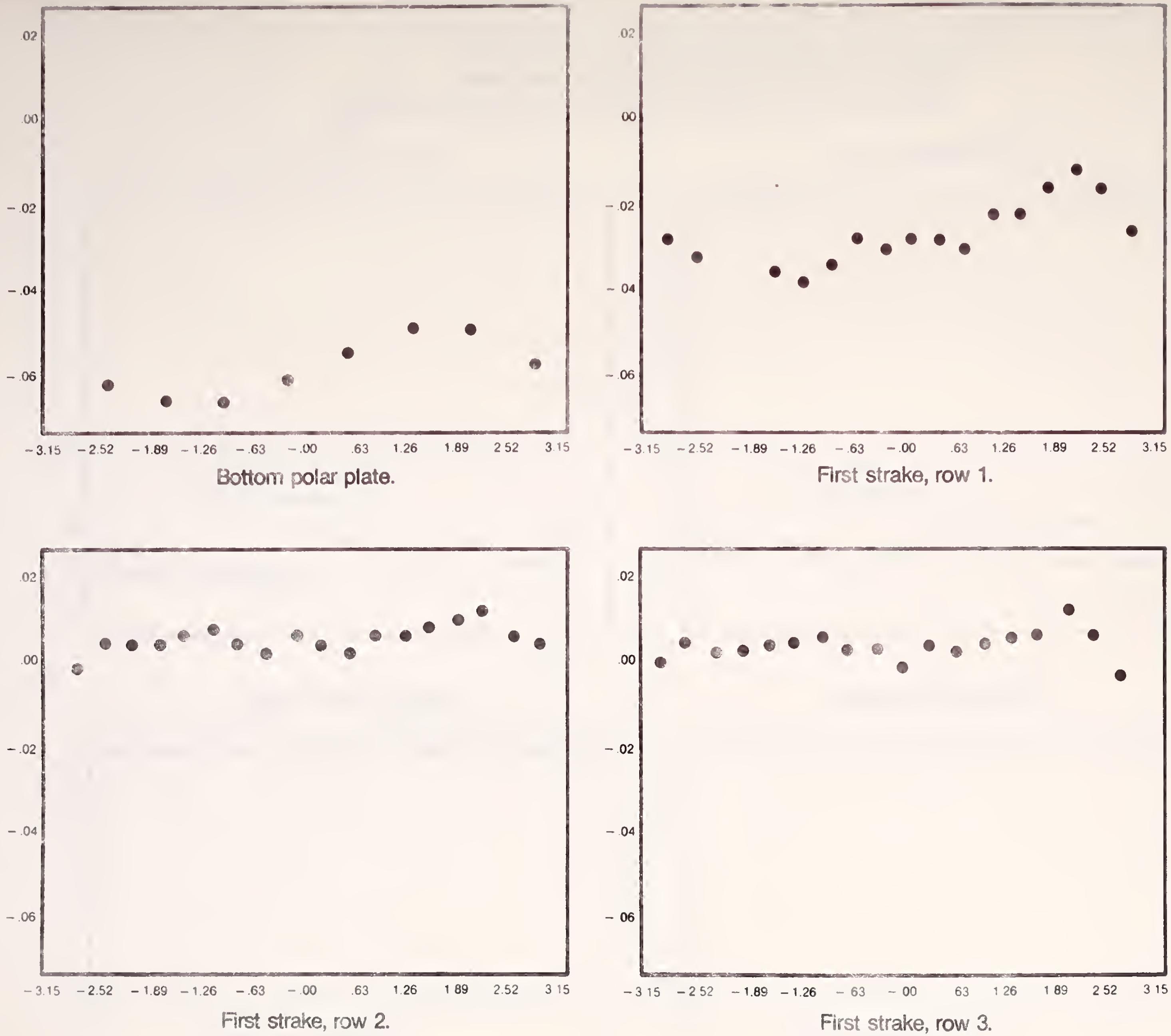


Figure 5. Residual plots of target rows as noted.
(Vertical axis: Residual values in meters.)
(Horizontal axis: Horizontal angle in radians.)

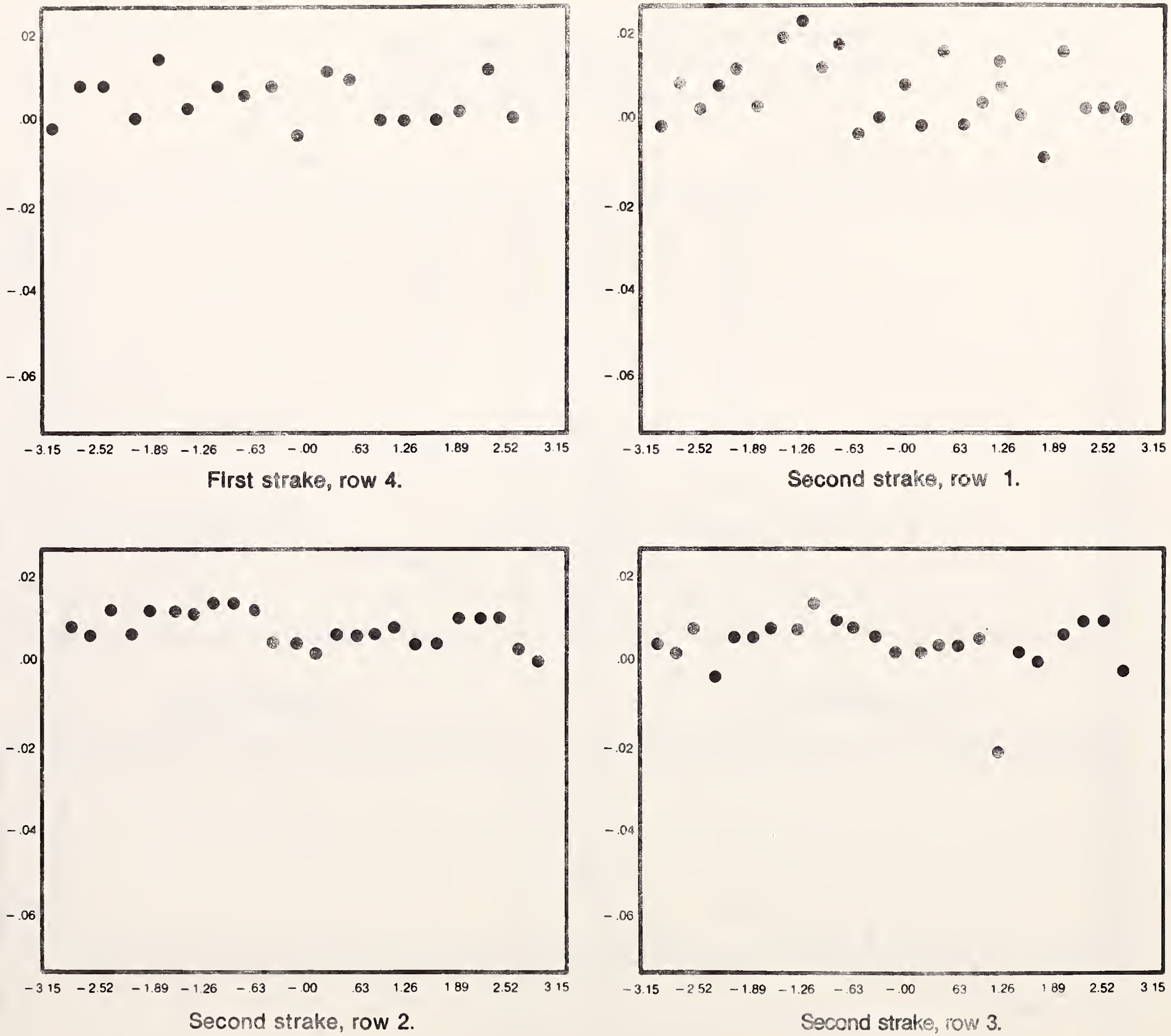


Figure 6. Residual plots of target rows as noted.
(Vertical axis: Residual values in meters.)
(Horizontal axis: Horizontal angle in radians.)

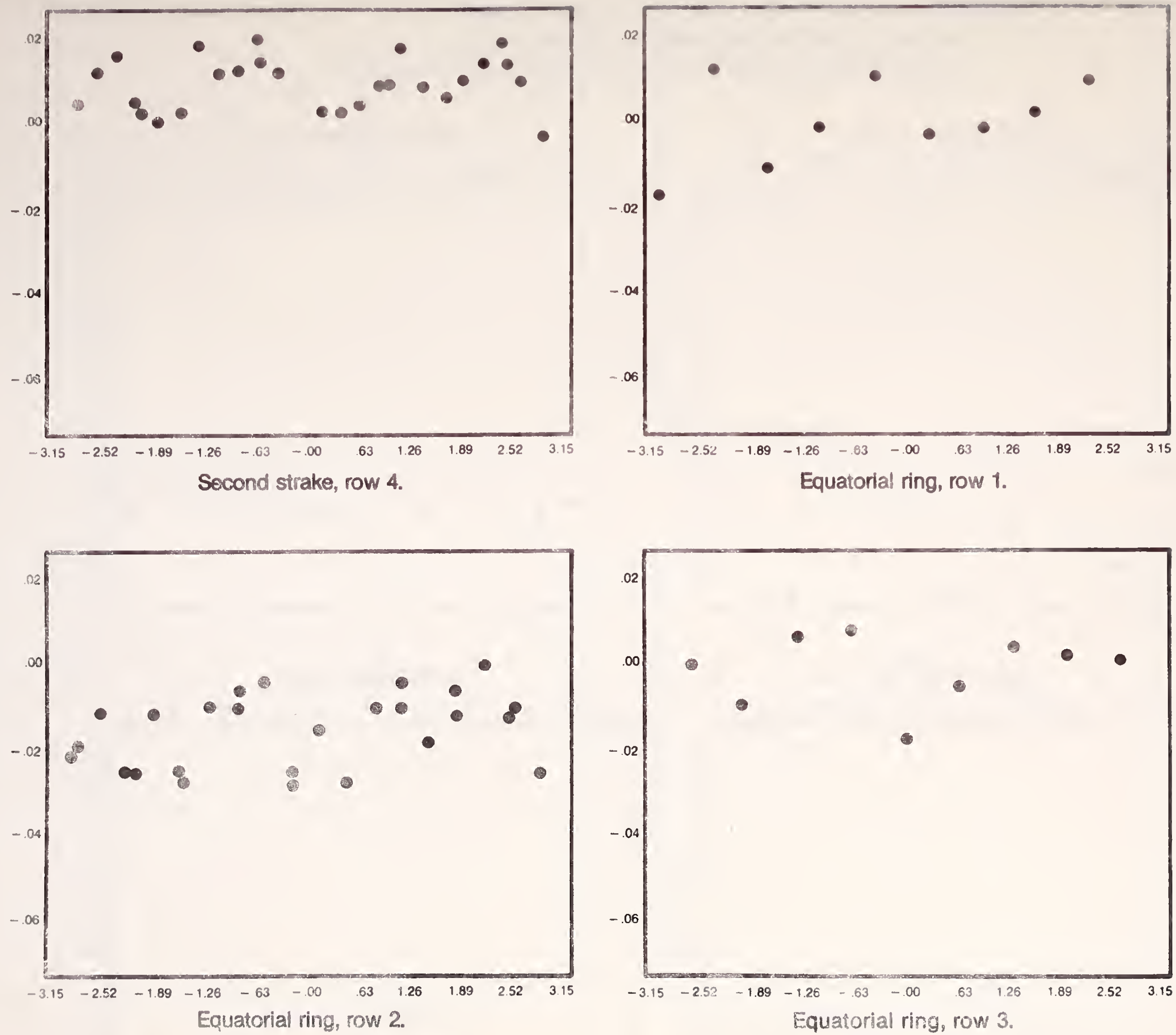
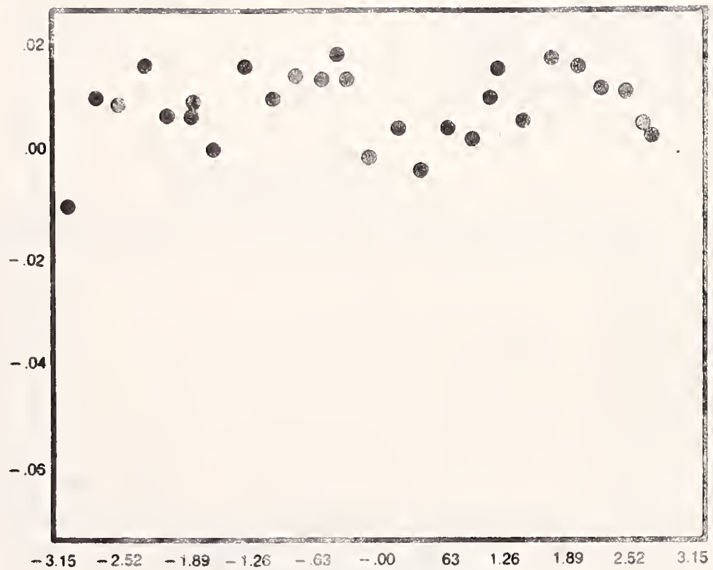
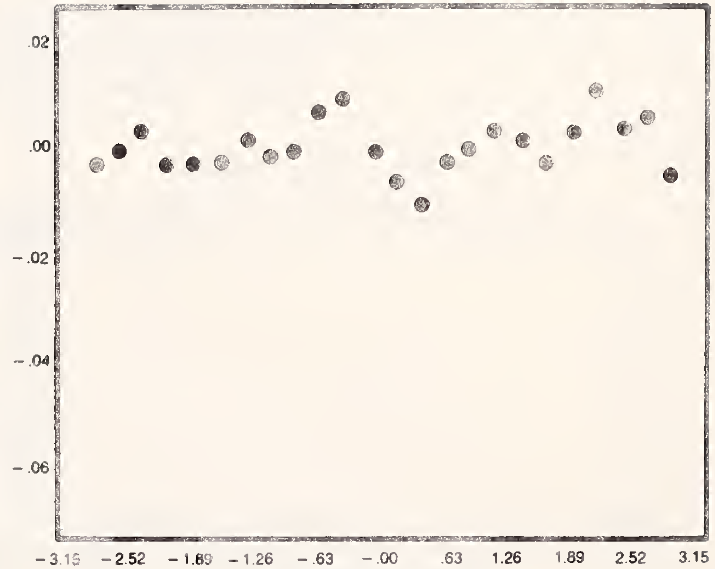


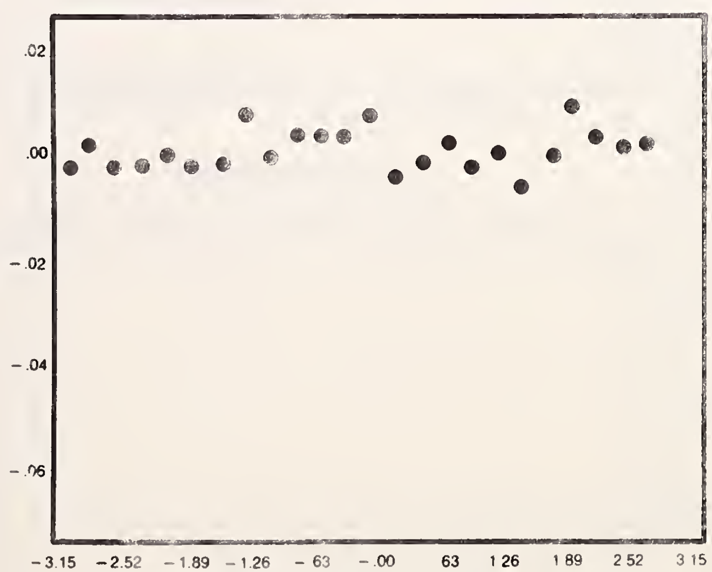
Figure 7. Residual plots of target rows as noted.
(Vertical axis: Residual values in meters.)
(Horizontal axis: Horizontal angle in radians.)



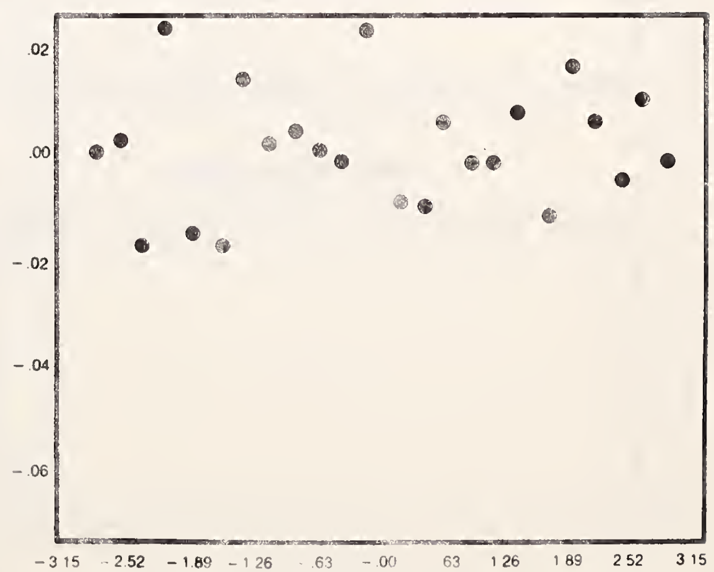
Third strake, row 1.



Third strake, row 2.



Third strake, row 3.



Third strake, row 4.

Figure 8. Residual plots of target rows as noted.
(Vertical axis: Residual values in meters.)
(Horizontal axis: Horizontal angle in radians.)

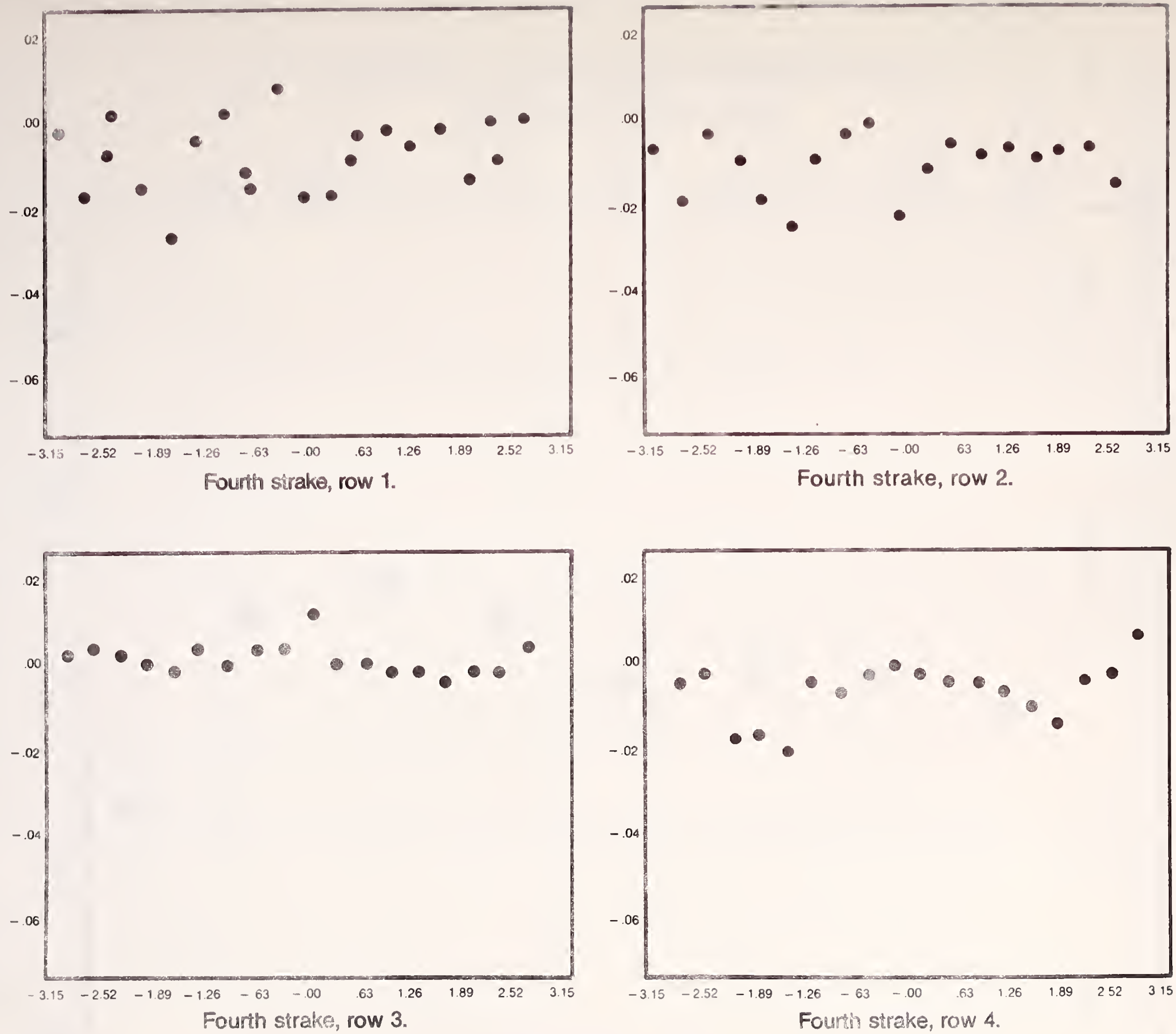


Figure 9. Residual plots of target rows as noted.
(Vertical axis: Residual values in meters.)
(Horizontal axis: Horizontal angle in radians.)

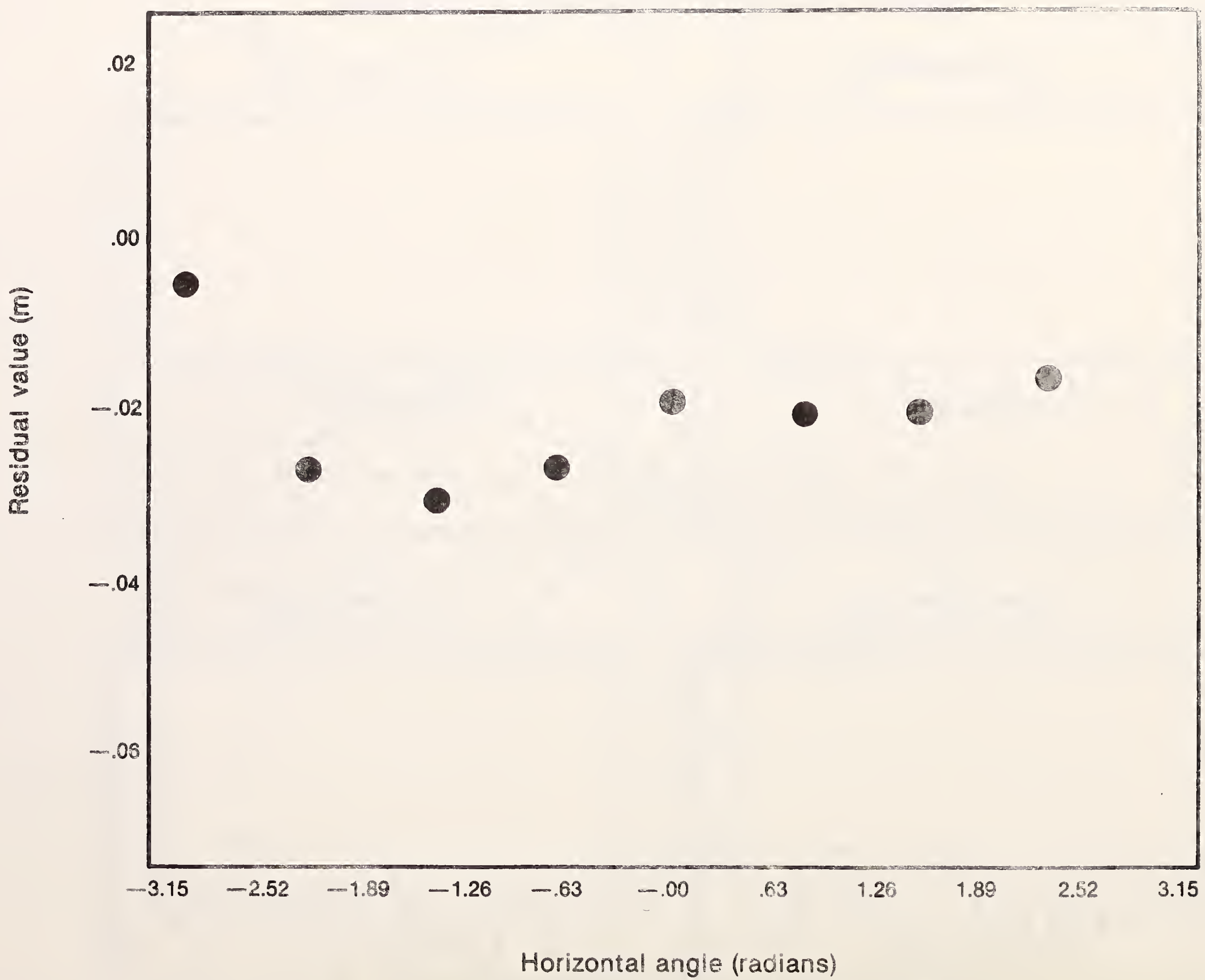


Figure 10. Residual plot of top polar plate.

Table 1. Summary of target residuals by horizontal row.

Row #		Average (cm)	Standard Deviation (cm)	Degrees of Freedom *	Random
1	Bottom plate	-5.75	.70	7	No
2	First Strake	-2.67	.76	15	No
3		.72	.31	17	No
4		.54	.33	17	No
5		.66	.53	17	Yes
6	Second Strake	.81	.84	25	Yes
7		.97	.38	23	No
8		.72	.70	23	No
9		1.11	.66	26	No
10	Equatorial Ring	.14	1.05	8	No
11		-1.45	.90	26	No
12		.06	.82	8	No
13	Third Strake	1.03	.73	27	No
14		.30	.49	23	No
15		.33	.38	23	Yes
16		.28	1.20	23	Yes
17	Fourth Strake	-.62	.89	21	Yes
18		-.94	.70	17	Yes
19		.32	.42	17	No
20		-.43	.69	17	No
21	Top Plate	-1.98	.77	7	No
	Pooled Standard Deviation		.71	387	

Figure 11 shows the set of four residuals for each plate. The zero lines for the 18 plates on the #1 and #4 strakes are indicated in the left margin and for the 24 plates on the #2 and #3 strakes in the right margin. A 1-cm amplitude mark is given in the lower right corner. The plates are adjacent vertically and may also be matched from one set (column) to the next. The plot is intended to show patterns in the "curvature" of the plates. If the curvature of a plate were perfect, the line connecting the four points would be flat. Note, for example, that the first residual from all plates in the #1 strake is large

*"Degrees of freedom" is equal to one less than the number of targets in a row.

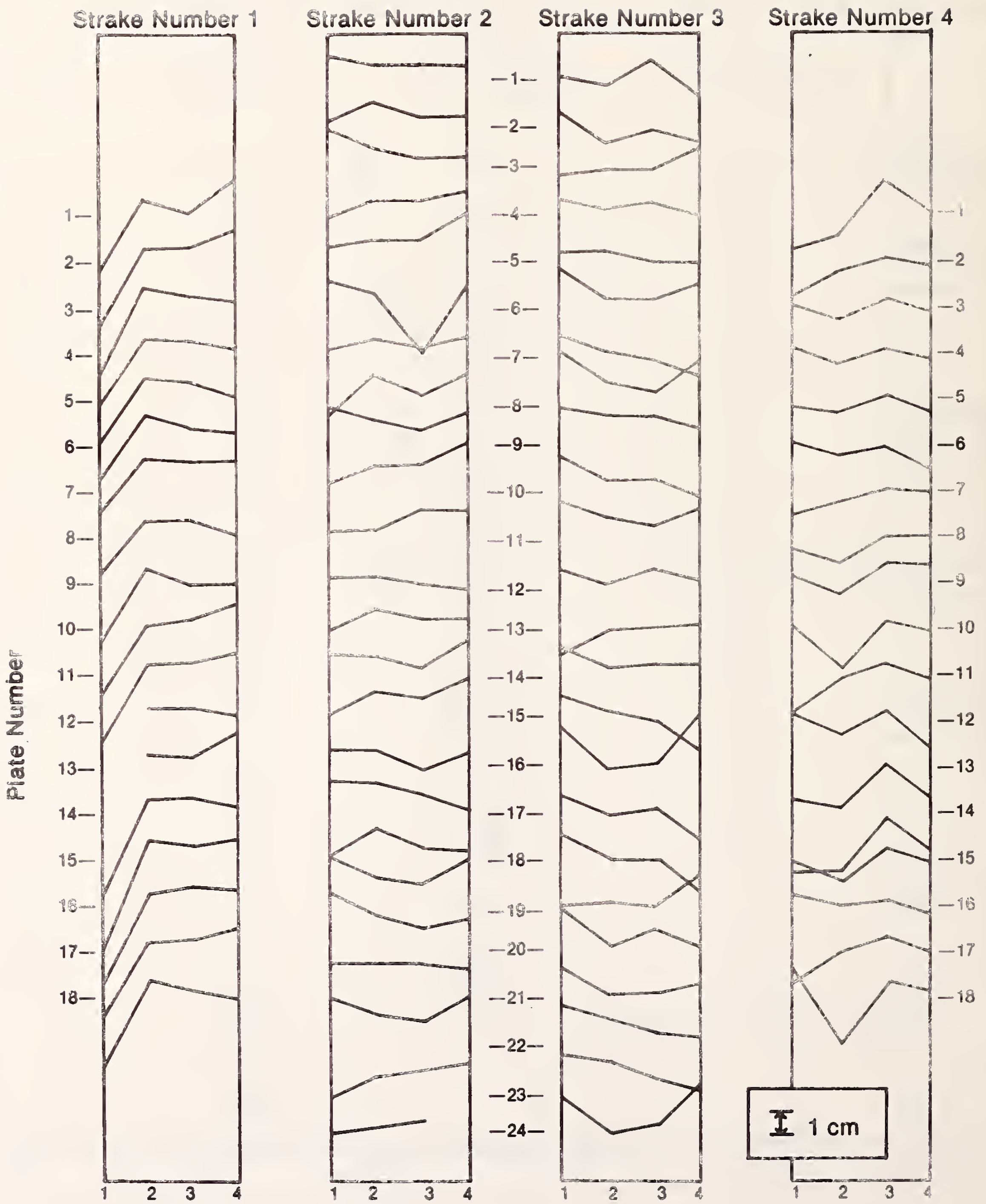


Figure 11. Target residuals grouped by plate and displayed by strake.

and negative, indicating a sharp curvature. Furthermore, the second, third, and fourth residuals for each plate in the #4 strake form a concave pattern, indicating a sharp degree of curvature.

Target Measurement Errors

Errors in the volume tables result in part from random and systematic errors in the target coordinate measurements. We next analyze the experimental evidence available so as to place bounds on the measurement errrors. Later, the effects of the errors on the volume tables are considered.

We are concerned with two types of error: random and systematic (sometimes called bias). Systematic errors, e.g., scaling error, are the types that result in non-zero values for certain average errors: specifically, average error in target location and average error in length of a gauge rod. Random errors, e.g., photographic plate resolution error, cause errors in individual target coordinates that vary about the average error.

Systematic error thus refers to an average error for a given survey. Causes of systematic error may be the same for many surveys; for example, errors in photo equipment, computer programs, or survey techniques. On the other hand, the value of the systematic error in each survey may vary randomly from one survey to the next due, for example, to errors in setting the scale. Since we have only one survey, we cannot study this possibility; the limits to be set on systematic error apply to this survey alone and cannot be extended to other surveys.

The lack of a second independent survey also limits our analysis of random error, but we have two approaches. First, the residual standard deviation from a fitted model provides an upper bound to the measurement error standard deviation. However, it may not be a "sharp" bound because it includes the effects of model error (in this case, actual deviations in the tank surface from the circular cross section assumed by the model). The second approach involves using the internal estimates of the standard error of the estimated coordinates derived from the estimation algorithm. There may, however, be sources of random error that are not included in these internal estimates.

No definitive analysis is possible without two or more independent surveys. Random fluctuations due to model error will be common to all surveys and could perhaps be separated from the measurement random error by variance-component analysis methods.

Random Errors: Analysis of Residuals

An upper bound to the standard deviation of the random errors of the photogrammetric survey in the radial direction can be obtained from table 1. The standard deviation given for each horizontal row of targets is computed from the deviations of individual residuals from the average for that row. It is thus the standard deviation from the best-fitting circle at each height on the sphere. Each standard deviation includes both the target measurement error and the local deviations of the sphere from a circle at each level. These two error components cannot be separated without analyzing repeated independent surveys.

The standard deviations for each row appear to be reasonably consistent from top to bottom of the tank. The pooled value (rms weighted by the number of degrees of freedom*) is 7.1 mm. We will use 7 mm as the upper bound to the standard deviation of the target coordinates in the radial direction.

Random Errors: Internal Estimates of Target Coordinate Error

The standard errors of the x-, y-, and z-coordinate values for each target were provided by the contractor. These standard errors were plotted against the x, y, and z coordinates, and several patterns emerged. First, all plots showed two ranges of values: a sparse distribution of high values and a more dense distribution of low values. These distributions are illustrated in figures 12 and 13. As will be seen later, the upper group probably comes from groups of targets masked by the central tower, and which therefore appear on one fewer photograph than the others. The standard errors of the estimated coordinate values are proportional to $1/\sqrt{m}$, where m is the number of measurements.

The second pattern to emerge results from studying the plots of the standard error of x (s_x) vs. x and the standard error of y (s_y) vs. y. (For brevity, we have included in figure 12 only the first of these plots.) Both plots show U-shaped patterns with the standard errors being highest at coordinate values ±18 meters. This shows that the precision of measurement is poorest in the radial direction (parallel to the plane containing the cameras)

*"Pooling" is a well-known technique; see p. 297 of [2] for an explanation.

and best in the tangential direction (perpendicular to the camera plane). It appears that there is a factor of about 3 relating the radial and tangential errors. This is significant since errors in the radial direction have the most effect on the volume of the tank.

Figure 13 shows the third important pattern observed: standard errors increase with increasing values of z. (The same pattern appears in plots of s_y vs. z and s_z vs. z; but, again for brevity, we include only one as an illustration.) This demonstrates that precision grows poorer with increasing distance from the cameras to the targets.

The standard error of the radius determined for each target can be determined from the standard errors of the three coordinate values using standard propagation of error techniques (see [6]).

The standard error of the radius is:

$$s_r = \left(\frac{x^2 s_x^2 + y^2 s_y^2 + z^2 s_z^2}{x^2 + y^2 + z^2} \right)^{1/2},$$

if the x-, y-, and z-coordinate estimates are independent. If the coordinate estimates are correlated (which is likely since they are derived from the same data), then

$$s_r = \left(\frac{x^2 s_x^2 + y^2 s_y^2 + z^2 s_z^2 + 2xys_x s_y \rho_{xy} + 2xzs_x s_z \rho_{xz} + 2yzs_y s_z \rho_{yz}}{x^2 + y^2 + z^2} \right)^{1/2},$$

where ρ_{xy} is the correlation coefficient of x and y, etc.

There is potential for a significant increase in s_r if the correlation coefficients are large and the signs are such that the contribution is positive. We may place an upper bound on s_r by assuming all the correlation coefficients are ±1 with the sign chosen so that the contribution is positive.

Figures 14, 15, and 16 show the upper bounds for s_r vs. x, y, and z respectively. All the plots show the clustering of higher values, and figure 16 shows the increase in s_r with the z coordinate noted earlier. If independence is assumed, the appearance of the plots remains similar; but the maximum value becomes 1.5 mm instead of 2.0 mm. The effect of correlation among the coordinate estimates on the radial standard deviation is thus not more than +30%. (A reduction in this estimate is possible if the sign of the correlation is favorable.)

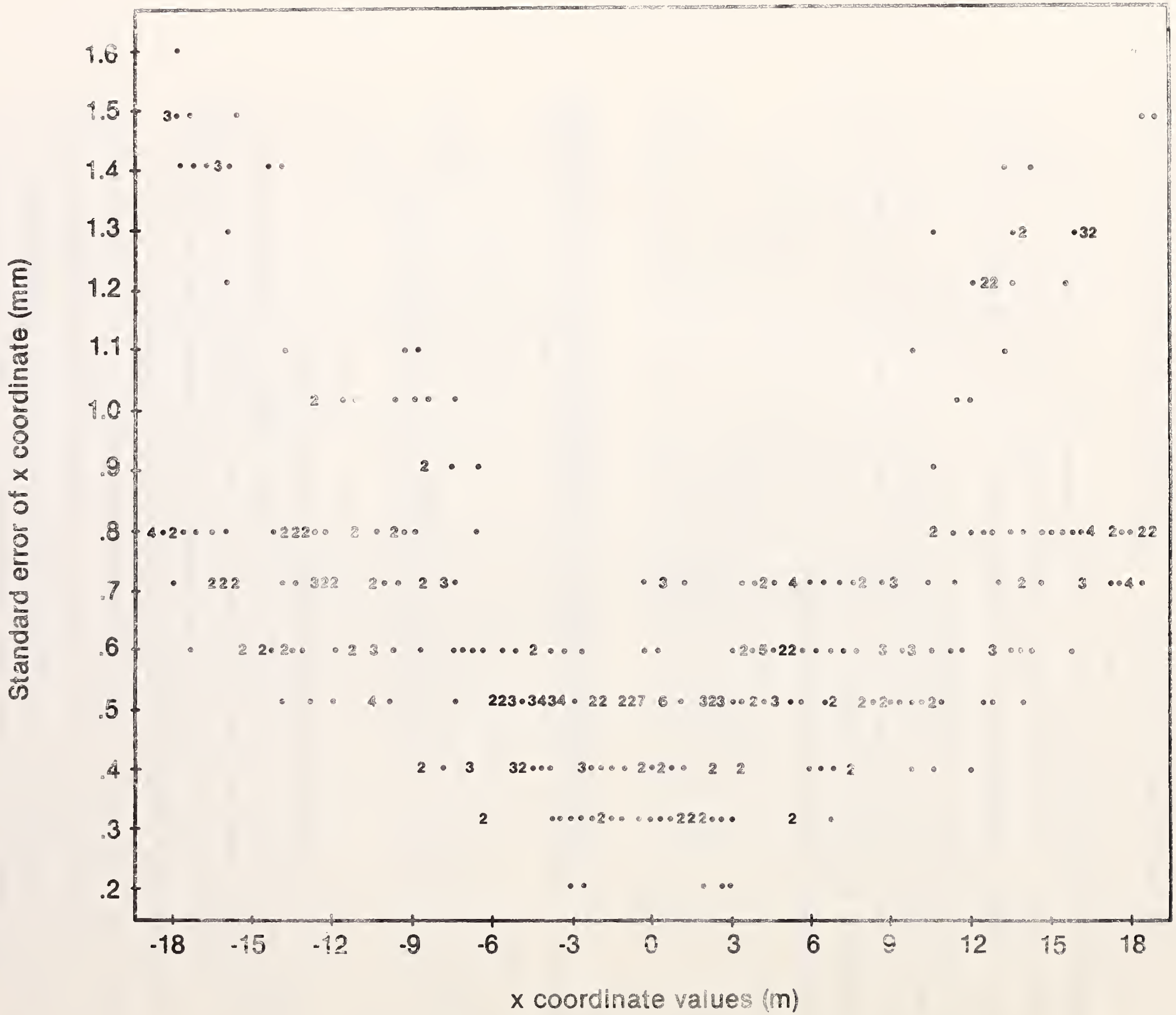


Figure 12. Plot of x coordinate vs. the standard error of x.

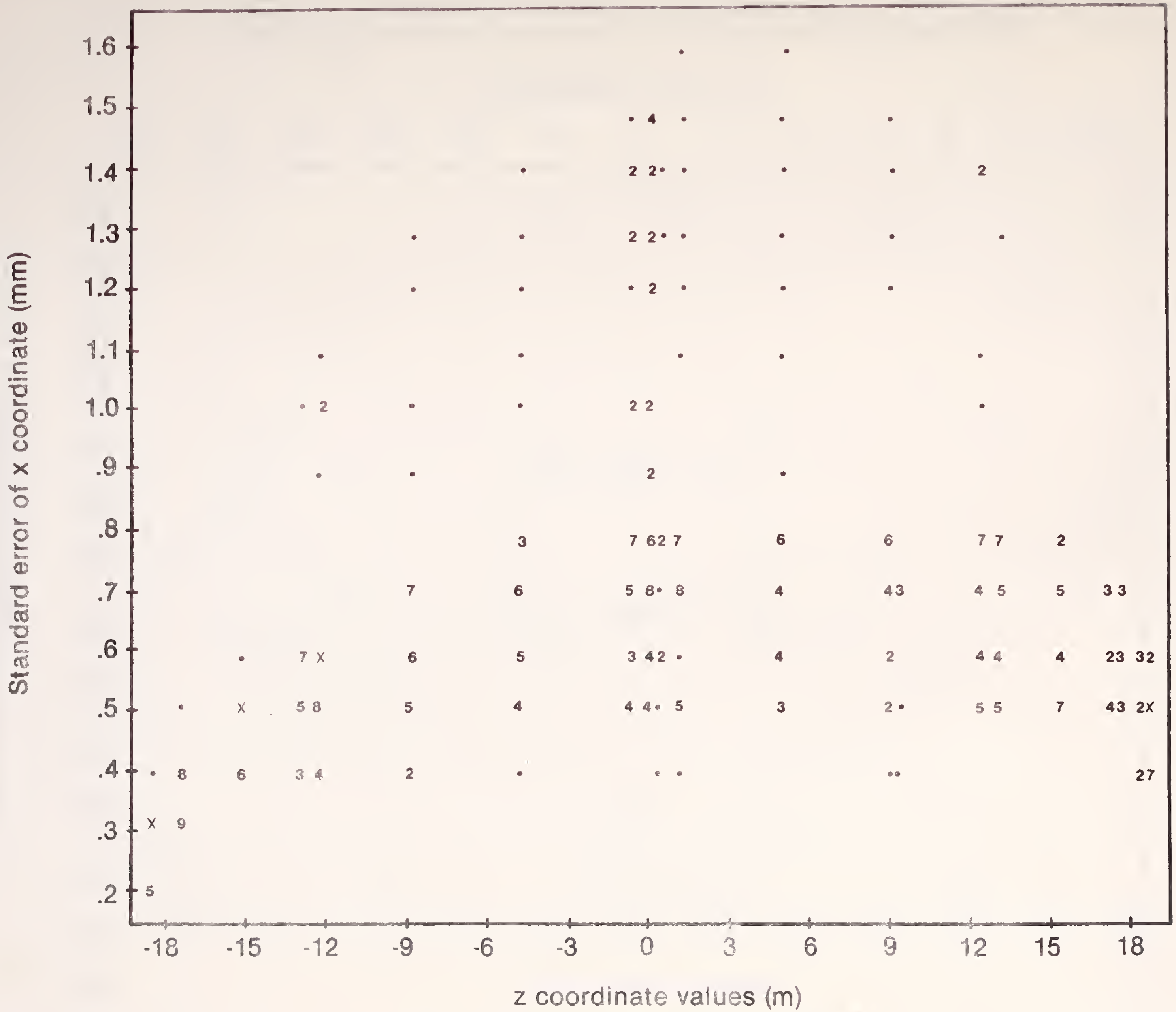


Figure 13. Plot of z coordinate vs. the standard error of x.

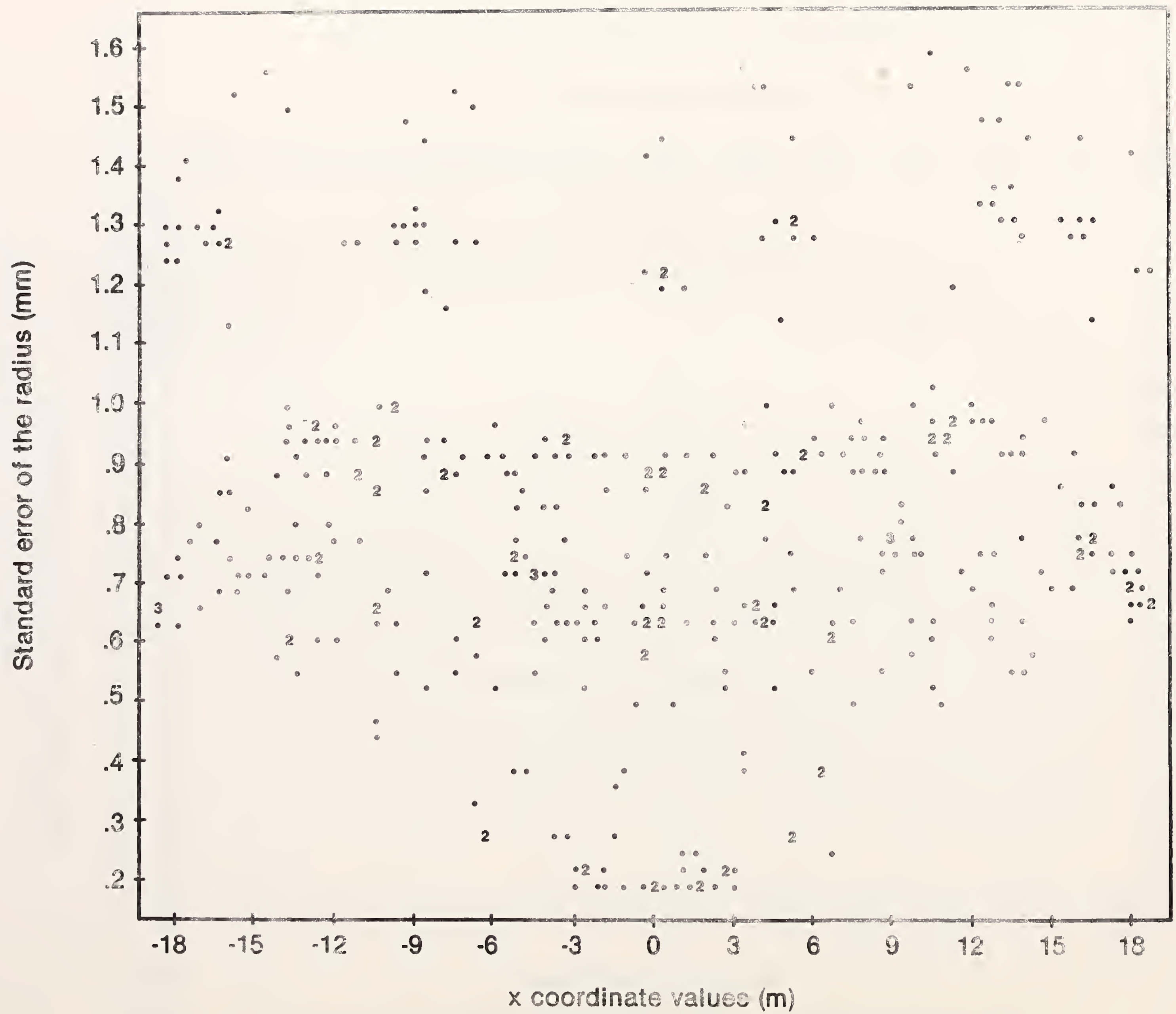


Figure 14. Plot of x coordinate vs. standard error of the radius.

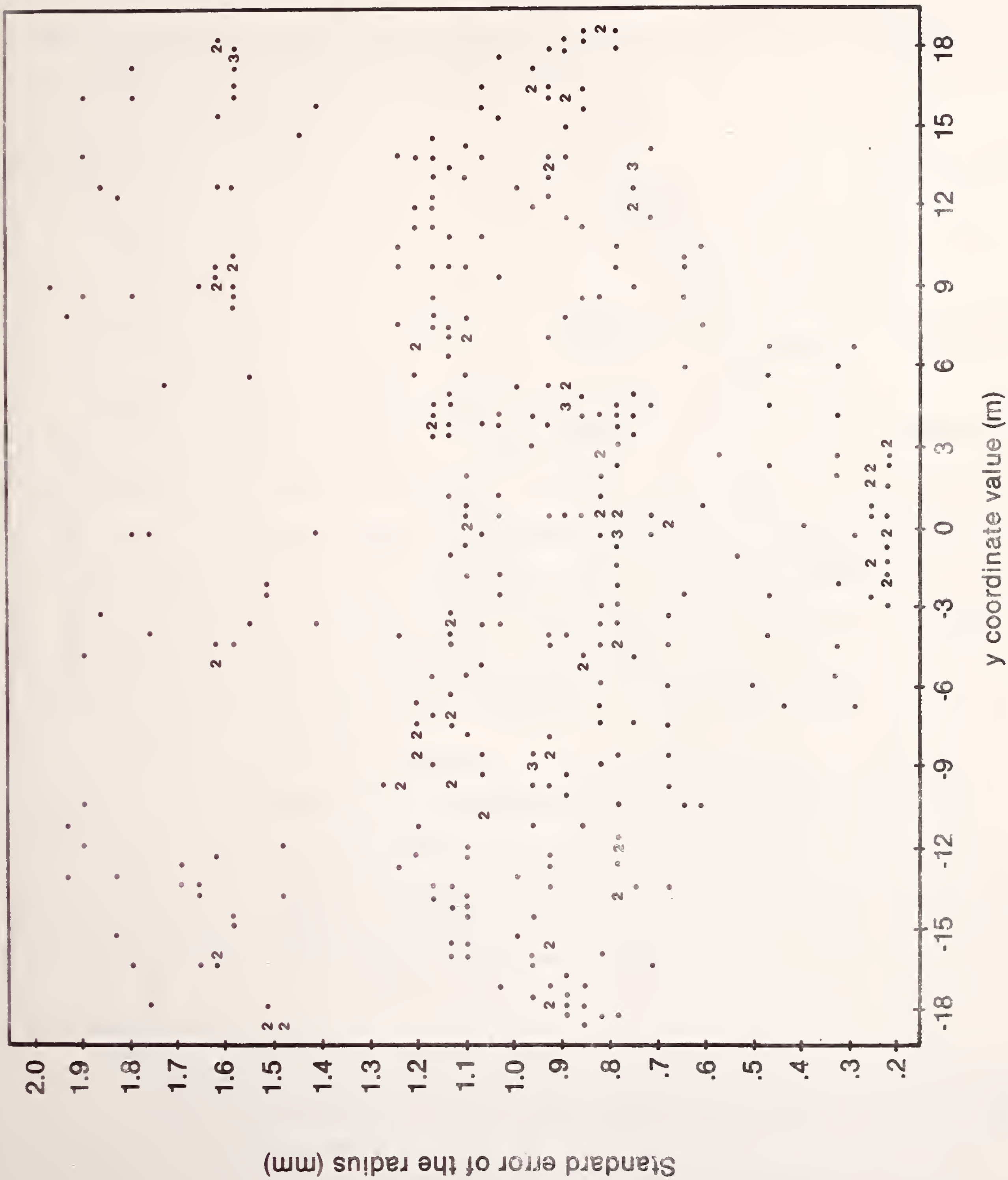


Figure 15. Plot of y coordinate vs. the standard error of the radius.

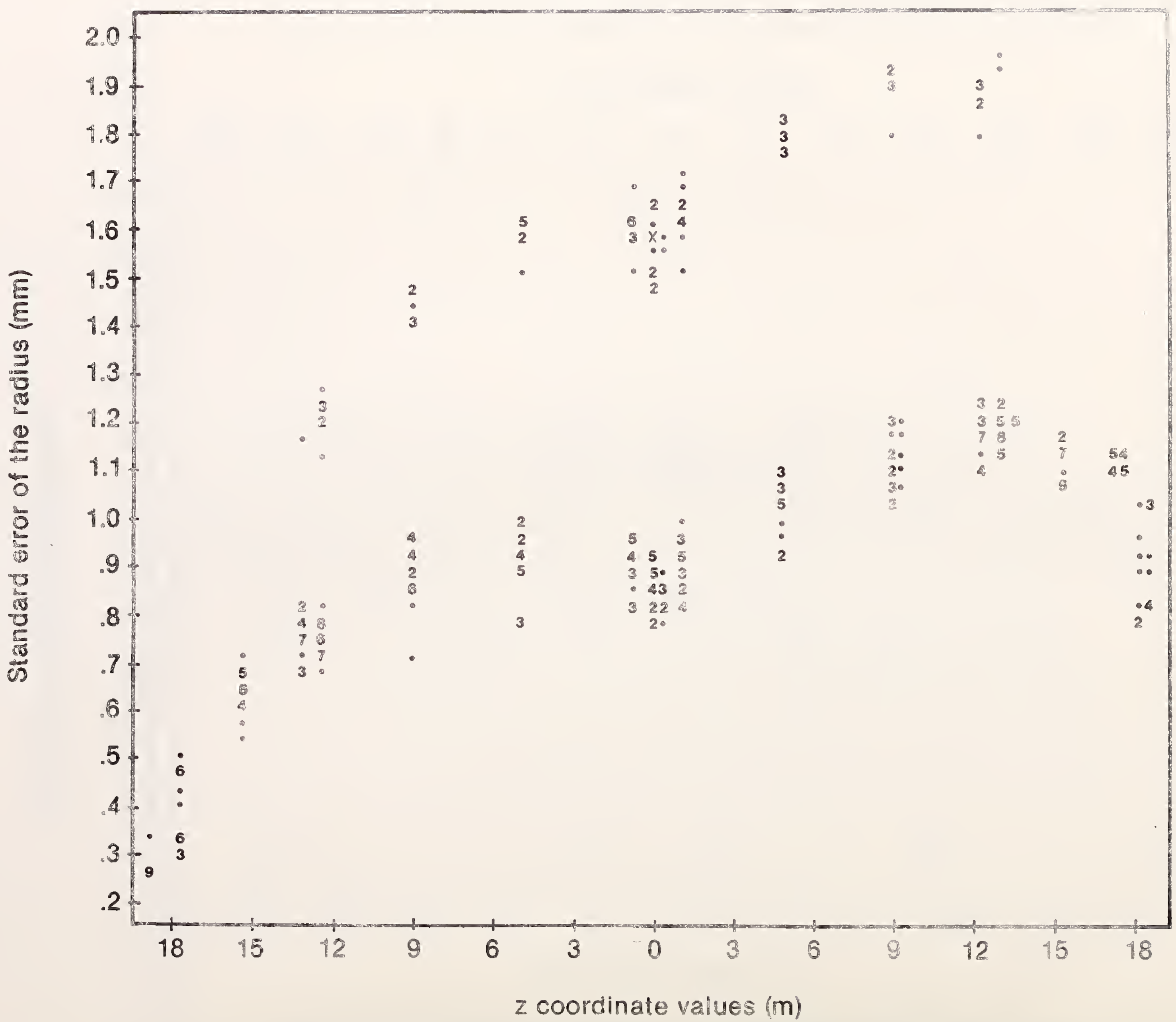


Figure 16. Plot of z coordinate vs. the standard error of the radius.

These results are consistent with the residual standard deviation. The upper bound to the total radial-direction, random-error, standard deviation is 7 mm while the internal estimate is on the order of 1 mm. The peak value is 2 mm. The difference may be due to other sources of random error, random fluctuations in the tank surface, or a combination of the two. Regardless, the question cannot be resolved until a second independent survey is available.

Another informative method of displaying the internal estimates of random error is to plot the target z coordinate on the vertical axis against θ (= $\tan^{-1}(y/x)$, where $-\pi < \theta \leq \pi$), the angle in the horizontal plane. The plot is thus a projection of the target coordinates on a plane surface. Different plotting symbols are then used to display the desired characteristics.

Figures 17 and 18 use the symbols A and B to indicate whether the s_r value for each target is in the lower or upper group respectively (see fig. 16). It can be seen that the B's are arranged in nine narrow vertical groups. Presumably, these targets are masked by the central column from one camera position and thus appear on one less photographic plate, as mentioned earlier.

In an effort to determine more precisely the factor relating the magnitude of errors in the radial and tangential directions, s_x vs. x and s_y vs. y were also plotted separately for narrow ranges of z, and also for the two groups of high- and low-error targets.

The ratio could not be determined from the low-error group because the standard errors provided by the consultants contained only one significant digit. For the high standard-error group, the only z range for which there was an adequate number and distribution of targets was the group that was on, and adjacent to, the equatorial ring. The factor of three holds there. We are not able to determine if the factor changes with height.

Systematic Error

As a check for systematic error in the survey, seven gauge rods with targets at each end were placed in the tank during the survey. The rods were constructed from two-inch square 5093 aluminum tubing in two pieces joined by a flange in the center.

Rods 1-5 were placed around the bottom of the tank while rods 6 and 7 were placed near the top. The x, y, and z coordinates locating the ends of each rod are given in table 2.

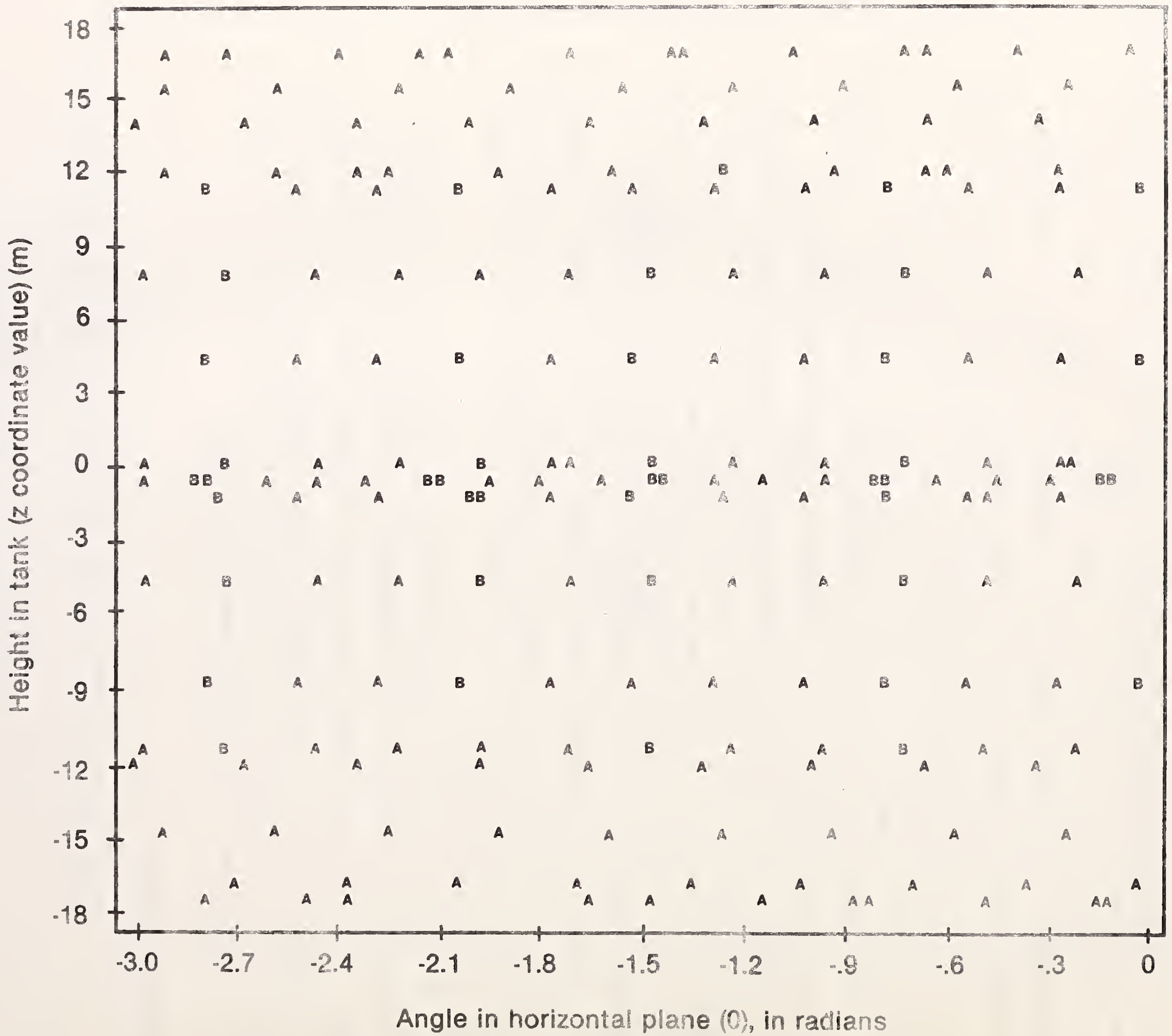


Figure 17. "Wrap around" display of target residuals, from $-\pi$ to 0.

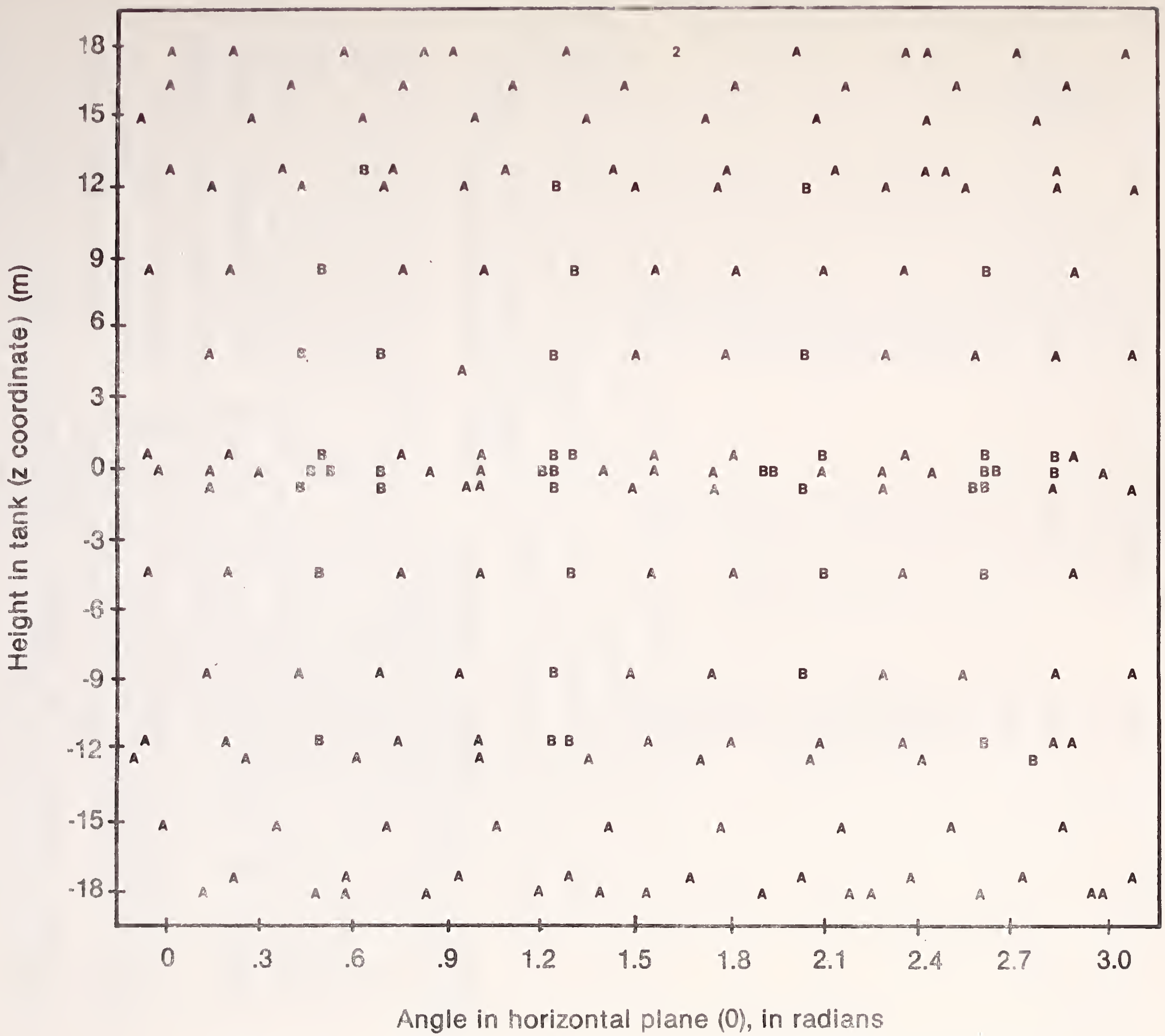


Figure 18. "Wrap-around" display of target residuals, from 0 to π.

Table 2. Rod end-point coordinates (m).

Rod	x	y	z
1	2.1885	-8.9500	-15.7102
	1.3089	-5.1156	-17.4291
2	4.6285	-6.3103	-16.4456
	7.1239	-2.8493	-16.5168
3	7.5256	.7120	-16.5691
	5.8784	4.6593	-16.5997
4	3.0506	7.0377	-16.5191
	-1.1255	7.3089	-16.6504
5	-4.0084	5.7746	-16.8055
	-6.6706	2.4913	-16.7619
6	.9479	-2.4609	17.8288
	-2.6246	- .1752	17.8466
7	2.6472	.0806	17.8384
	- .8601	2.4881	17.8441

All rods were placed with the targets against the tank surface so that length is in the tangential direction. The exact rod orientations can be determined from the above coordinates.

The first six rods were measured by the NBS Dimensional Technology Division. Each rod was broken down, reassembled, and measured three times. The average length for each rod, corrected to 68°F, is given in table 3. The pooled standard deviation from the reassemblies of the rods was 0.024 mm (12 degrees of freedom), and a 95% tolerance interval for 95% of future reassembled lengths is 0.074 mm. It follows that the random error in the rod lengths (due to reassembly, primarily) is a negligible component of the standard deviation of the differences between NBS measurements and the photo survey (s = 0.85 mm). The limit to systematic error in the NBS measurements is ±0.001 mm, which is a negligible fraction of the systematic difference observed.

Table 3. Gauge rod data.

Rod Number	NBS Measurement at 68°F (m.)	Consultants' Measurement Converted to 68°F (m.)	Consultant NBS Difference (mm.)	Average Temp. During Measurement
1	4.2927	4.2937	1.0	34.6
2	4.2664	4.2680	1.6	35.0
3	4.2783	4.2779	- .4	33.5
4	4.1881	4.1876	- .5	34.2
5	4.2278	4.2277	- .1	36.0
6	4.2405	4.2416	1.1	38.0
7	4.2534	4.2545	1.1	37.8

Rod 7 is a special case since it was measured only in Boulder. The Boulder group also measured all 6 other rods. A bias between Boulder and Washington (due in part to the measurement of the halves separately?) of 0.452 mm (S.E. = 0.086 mm) was observed. The length given for rod 7 is the Boulder length minus the estimated bias.

The lengths obtained by the photo survey and their differences from the NBS values are also given in table 3. The photo survey lengths have been adjusted from those supplied by the contractors. The contractors originally corrected the lengths to 68°F assuming a common starting temperature, but NBS temperature measurements showed that the rods were actually at different temperatures (shown in table 3) when measured. The differences between the NBS and photo survey results originally showed a systematic error, which was removed by correcting the lengths for the actual temperature at measurement.

The length differences range from -0.5 mm to +1.6 mm with an average of 0.54 mm (S.E. = 0.32 mm). A 99% confidence interval for bias in the rod lengths is thus 0.54 ±1.19 mm, or the interval (-0.65, 1.73) mm.

This bound, however, applies only to the tangential direction. We assume that the appropriate factor for degrading this to the radial direction is the same factor 3 observed for between-measurement standard error in the radial and tangential directions. This leads to bounds on the bias of (-2.0, 5.2) mm in the radial direction.

While every effort has been made in the above analysis to make the bound on possible bias a conservative one, there are several factors which could cause it to be an underestimate.

1. Most of the rods were at the bottom of the tank where measurement errors (and perhaps bias) are smallest.

2. The rods were very short. Targets close together may have highly correlated measurement errors which cancel in the length computation. In addition, there may be additional errors that accumulate in length measurement when the targets involved span several photographic plates.

3. The factors that resulted in a bias of 0.54 mm on this survey could vary randomly between independent surveys and have a standard deviation much larger than the standard deviation of the errors within a single survey.

<u>The above bound on the bias applies uniquely to this survey and does not apply to the surveys of any other tanks</u>.

These points suggest several concepts to consider in any future efforts to evaluate the precision and accuracy of photo surveys.

1. An additional survey, independent of the first, is essential.

2. Gauge rods should be distributed more uniformly throughout the tank.

3. Some longer rods should be used.

4. Some rods should be placed perpendicularly to the tank surface so that measurement errors in the radial direction can be evaluated directly.

5. The covariances of the coordinate estimates are a necessary part of the analysis and should be supplied by the contractor.

Calculation of Sounding Tables

The sounding tables constructed here are tables of volume versus elevation for the unloaded tank. The use of the term "elevation" requires comment. The term is intended to represent the depth of the LNG in the tank at a particular moment. That is, assuming that the tank is in its standard position (it has the same orientation with respect to the true vertical direction as it had while being measured), and assuming that the liquid surface is a horizontal plane, the elevation should be the distance from that horizontal plane to the (inside) bottom of the tank. However, that last point is apparently not accessible to measurement. It has been assumed that what is, in fact, measured is the distance from the liquid surface plane to the pedestal probe point (P^3), and the elevation is then determined by adding to that measured distance the known vertical distance of the P^3 above the bottom of the tank.

The elevation of the P^3, however, is not obtained through direct measurement. The photogrammetric consultants estimated the location of the tank bottom by using a mathematical model. After determining a "sphere of best fit," they determined a second, concentric sphere that best fit the bottom-most ring of targets on the bottom cap of the tank. They then took the bottom of this second sphere as the bottom of the tank.

In the present analysis, the elevation of the P^3 was also determined from a mathematical model of the bottom region of the tank. However, the model used here is more complicated, and felt to be more reasonable. It is described below in the description of Model 3.

Three different sounding tables were constructed, based on two different mathematical models and one system of volume corrections applied to the second model. The three tables are based on increasingly sophisticated analyses, but the final results differ only slightly.

Tank Model 1

The first model developed was a simple mathematical sphere. The sphere that best fit the target location measurements (at ambient temperature) was found earlier in this section to have center (.005, -.0009, -.0137) and radius

18.2682. We assumed that an isotropic contraction occurs and converted this to the average temperature of LNG, -160°C, by use of the following linear thermal expansion coefficient obtained from the 1967 edition of the Alcoa Aluminum Handbook:

$$L_t(0 \text{ to } -320°F) = L_o(1 + C(11.74t - .00125t^2 - .0000248t^3)10^{-6}),$$

$$L_t(0 \text{ to } 1000°F) = L_o(1 + C(12.19t + .003115t^2)10^{-6}),$$

where

L_o = length at 0°F,
L_t = length at t°F within range indicated,
C = alloy constant (1.020 for 5083 Aluminum).

This resulted in a sphere with the same center but a radius of 18.20485 m.

However, it was felt that for the purposes of building tank models a modification to this "contracted" best-fitting sphere was necessary. The first modification considered was one that resulted in a sphere which would best fit the data if the points on the top and bottom caps of the tank, and those on the equatorial ring, were excluded. This resulted in a sphere with the same center but with a radius of 18.2113.

In this model the height of the P^3 above the bottom of the tank is 0.2352 meters. However, it has been assumed that elevation is determined by the users of the sounding tables by measuring liquid level height above the P^3, and adding to that number the "known" height of the P^3 above the tank bottom. It has furthermore been assumed that this known height will be taken to be 0.1705 m, as given in the report from the photogrammetric consultants. So in the sounding table for Model 1, elevation is defined as: (recorded depth - 0.2352 m + 0.1705 m), which makes the tables reported here directly comparable to those produced by the photogrammetric consultants.

The table for Model 1 is given by the column headed VOLUME 1 in appendix A.

Tank Model 2

In this case, Model 1 is modified by replacing the top and bottom regions of the nominal sphere with segments (caps) of other, flatter spheres. (The nominal sphere is now the sphere of Model 1.) Each such flatter (higher radius) sphere was taken to have its center on the polar axis of the nominal sphere, but not to be concentric with the latter. (If they were concentric and touched somewhere--which they must for the model not to be discontinuous--they would coincide.)

Since Model 2 is still a surface of revolution about the polar axis of the nominal sphere, we can describe it via its (x,z)-plane cross section. Using the coordinates of the center of the best-fitting sphere, the nominal sphere becomes the circle

$$x^2 + (z+.0137)^2 = r_o^2 \qquad (r_o=18.2113\text{m.}),$$

and each of the model caps is given by the equation:

$$x^2 + (z+.0137-a)^2 = (r_o+b)^2.$$

(The fact that the x coordinate of the center of the nominal sphere is actually .0005 rather than 0 is irrelevant to the calculation of the sounding tables and has been ignored.)

Using this model, the parameters for the bottom model cap are

$$a = 2.37\text{m.}, \qquad b = 2.30\text{m.},$$

and for the top model cap

$$a = -2.37\text{m.} \qquad b = 2.30\text{m.}$$

This bottom model cap locates the bottom of the tank at z=-18.1550; the consultants' model described above located it at -18.1603.

Each model cap extends for a vertical distance of 0.537 m and a horizontal distance of 4.389 m before meeting the nominal sphere. Comparing the VOLUME 1 figures with the VOLUME 2 figures in appendix A, we see that the model caps together subtract 2.41 cubic meters from the volume of the tank. The difference between the consultants' model tank bottom and this one, while possibly of interest in connection with the location of the bottom of the tank, is much smaller than the difference between Model 2 and Model 3. It is not significant for the sounding table.

The calculation of the first two sounding tables involved another topic: accounting for the volume displaced by the tower structure inside the tank. This was called "tank internals" by the consultants, and the calculation was based on blueprint specifications rather than on direct measurement. This seems valid; the total volume of the tower structure is about 7.6 cubic meters, so that high accuracy is not needed.

However, in their tank internals figures the consultants also included an estimate of the inward bulge of the equatorial ring relative to their own sphere of best fit. The graph in figure 19 represents the consultants' tank internals figures for tank number 4; the near-vertical part in the middle is the equatorial ring contribution. In the NBS analysis, that part was eliminated and the tank internals were represented by the formula*

$$V_I(a) = \begin{cases} 0.7345a, & 0 \le a \le 2.316, \\ 0.7345 \times 2.316 + 0.1744(a-2.316), & 2.316 \le a . \end{cases}$$

This represents the volume of the tower, as a function of altitude, a (in meters), above the bottom of the tank, to an accuracy of ±0.3 cubic meters.

Tank Model 3

In this case the table is constructed by a numerical integration of the discrepancy between the actual measurements and Model 2. The procedure is as follows.

1. For each horizontal ring of targets, a mean z-coordinate value is established and the mean radial residual is determined. (This is the same as integrating the radial residuals around each ring of targets by the trapezoid rule, which is the best rule for integrating around a circle.) These radial residuals are displayed in table 4.

2. By linear interpolation between adjacent targets on a horizontal ring, a piecewise-linear function of z is constructed, approximating the mean radial residual at all values of z; at the top and bottom of the model tank, the radial residuals are taken to be zero for this purpose.

*The coefficients in this formula were obtained from table V-1 of the consultant's final report.

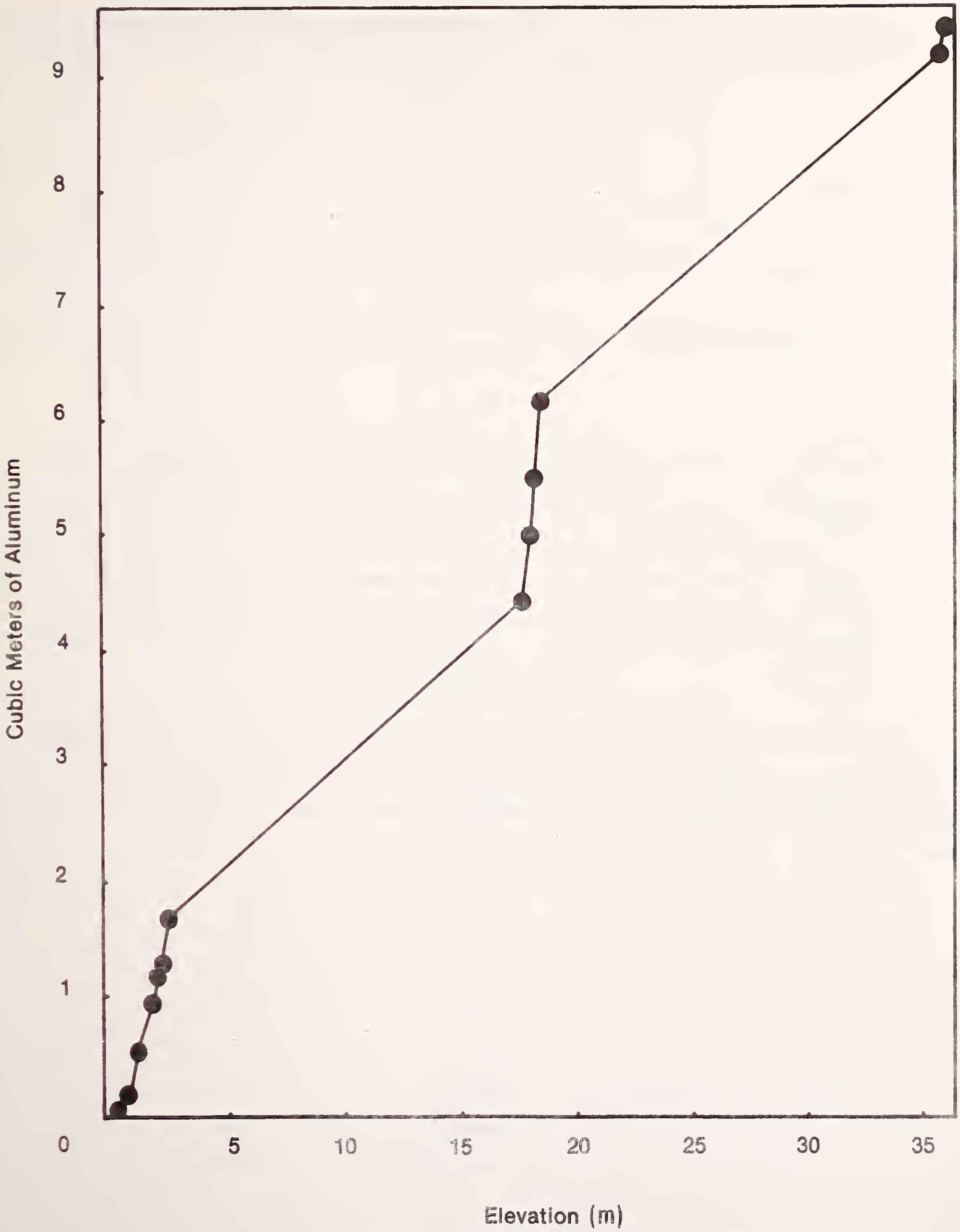


Figure 19. Volumes of tank internals.

3. Calling the piecewise-linear function e(z), the volume corrections are calculated from the formula:

$$V_{CORR}(z) = \begin{cases} 2\pi r_1 \int_{-18.155}^{z} e(t)dt, & z \leq -17.61815; \\ V_{CORR}(-17.61815) + 2\pi r_o \int_{-17.61815}^{z} e(t)dt, & -17.61815 \leq z \leq 17.59075; \\ V_{CORR}(17.59875) + 2\pi r_1 \int_{16.59075}^{z} e(t)dt, & z \leq 17.59075; \end{cases}$$

where r_0 = 18.2113 and r_1 = 20.5113. All units are meters. (The three parts are for the bottom model cap, the nominal sphere, and the top model cap.) The constants are derived as the vertical limits of the top and bottom caps from tank model 2. V_{CORR} is added to the values in VOLUME 2 to give values for VOLUME 3, as listed in the appendix.

It should be noted that the above expression for V_{CORR} is not an exact formula for the change in volume resulting from radial distortion of model 2 in accordance with function e(t). It is an approximation of sufficient accuracy for the present purpose.

Table 4. Mean radial target residuals in meters.

Target Row	Mean z Coordinate, z(i)	e(z)
1	-18.1550	0
2	-18.0329	-.0099
3	-17.9533	+.0106
4	-16.9947	+.0008
5	-14.9747	-.0010
6	-12.5078	+.0002
7	-11.7968	+0017
8	- 8.6966	+.0033
9	- 4.6732	-.0003
10	- .9500	+.0047
11	- .2469	-.0050
12	- .0189	-.0209
13	.2099	-.0058
14	.9187	+.0039
15	4.6301	-.0034
16	8.6699	-.0031
17	11.7571	-.0036
18	12.4686	-.0126
19	14.6601	-.0158
20	16.5733	-.0032
21	17.6457	-.0035
22	17.8109	+.0025
23	17.9894	-.0117
24	18.1276	0

Comparison of NBS' and Consultants' Results

The data from the VOLUME 3 table will be regarded as the "NBS results." These figures are higher than the consultants' by 0.05% to 0.07%, which is probably due to the different methods used for the last numerical integration: where we fitted the data with a piecewise-linear function, the consultants used a polynomial of high degree. The other obvious difference, locating the bottom of the tank, does not account for more than a small fraction of the final differences in the sounding tables.

Sounding Table Error: Target Coordinate Error Contribution

Errors in the sounding tables may arise in four different ways: photo survey systematic error or bias, photo survey random coordinate error, approximation error in the numerical integration procedure, and tank model failure. The first two sources are statistical in nature and can be analyzed directly.

It has been established that an upper bound to the survey bias in the radial direction is 5 mm. We are now concerned with the volume of a spherical segment below a plane at height h above the bottom of the sphere:

$$V_h = \frac{1}{3} \pi h^2 (3r - h).$$

It follows that

$$dV_h = \pi h^2 dr,$$

and that the percentage error in volume is

$$\Delta V_h\% = \frac{100 \, dV_h}{V_h}$$

$$= \frac{300 \, \Delta r}{3r - h} .$$

For $\Delta r = 0.005$ m and $r = 18.2$ meters, we obtain the results shown in table 5.

Table 5. Volume error as a function of meters of height.

h	ΔV_h
2	0.029% (0.064 m^3)
6	0.031%
10	0.034%
14	0.037%
18	0.041%
22	0.046%
26	0.052%
30	0.061%
34	0.073%
36	0.092% (20.7 m^3)

Recall that the bound to possible bias used applies to this tank survey uniquely and need not apply to photo-surveying any other tanks. While the analysis is intentionally conservative, there are several unknown factors that could cause the bias to be underestimated.

Analysis of the coordinate random errors established an upper bound of 7 mm for the standard error of the radius to a target. It is believed that this is predominantly real tank surface fluctuations and that the random errors of measurement are smaller, perhaps as small as a 1-2 mm standard deviation. This implies that the appropriate method for computing volume tables is to integrate through each target as if it were without error rather than to use a fitted surface (Model 3 as opposed to Model 1 or 2). The effects of random error can be approximated as follows.

First, assume that the 408 targets are uniformly distributed over the surface of the sphere and that the effect of one target error on the integration is to displace a neighborhood of the target, equal in area to $1/408^{th}$ of the surface, in or out. The differential effect on the volume is then

$$dV = \frac{4}{408} \pi r^2 dr.$$

It follows that if we let V_i be the volume error associated with the i^{th} target, then

$$sd(V_i) = \frac{4}{408} \pi r^2 sd(r_i).$$

We have sufficient information to let $sd(r_i)$ vary with the z coordinate and with the number of plates involved. However, to obtain an upper bound, we will use the worst-case value, $sd(r_i) = 7$ mm.

Let V_h be the volume below the plane at height h. The error in V_h, ΔV_h, is the sum

$$\Delta V_h = \sum_{i=1}^{K} V_i,$$

where the sum is over the K targets below h. It follows that

$$sd(\Delta V_h) = \frac{\sqrt{K}\, 4 \pi r^2 sd(r)}{408} .$$

If the targets are uniformly distributed on the surface, K can be determined from

$$\frac{K}{408} = \frac{2 \pi rh}{4 \pi r^2}$$

or

$$K = \frac{204 h}{r} .$$

The standard deviation of ΔV_h as a percentage of V_h is thus

$$\frac{100\, sd(\Delta V_h)}{V_h} = \frac{100\, [204(h/r)]^{\frac{1}{2}}\, 4 \pi r^2 sd(r)}{408\, (1/3) \pi h^2 (3r - h)}$$

$$= \frac{42.008\, r^{3/2}\, sd(r)}{h^{3/2} (3r - h)} .$$

If we take the values $sd(r) = 0.007$ m and $r = 18.2$ m, we obtain the results shown in table 6.

Table 6. Percentage standard deviation of the error in the volume of the tank below the plane at height h.

h	$sd(\Delta V_h)$ %	$3sd(\Delta V_h)$%
1	0.42	1.26
2	0.15	0.45
6	0.032	0.096
10	0.016	0.048
14	0.011	0.033
18	0.0082	0.025
22	0.0068	0.020
26	0.0060	0.018
30	0.0056	0.017
34	0.0056	0.017
36	0.0057	0.017

Note that the percentage error for shallow depths is very large because of the large tank-bottom surface involved with a small volume.

In actual use (custody transfer of the contents between the 95% and 5% levels), the top and bottom surfaces are not involved. The following computations apply.

Between the 31.4-meter and 5-meter heights, the surface area is 72.5% of the total, thus

$$sd(\Delta V_s) = \frac{\sqrt{K^*}\, 4\, \pi\, r^2\, sd(r)}{408} ,$$

where ΔV_s is the error in the volume sold and $K^* = 0.725 \times 408 = 295.8$. Then $sd(\Delta V_s)$ is 1.2 m^3. As a percentage of the volume sold, this is 0.0053%. The $\pm 3\sigma$ uncertainty in the volume sold is then ± 3.6 m^2 or ± 0.016%. This result is conservative, being based on an upper bound to the actual random error. However, it is small compared to the possible error due to bias in the radius of the tank.

Sounding Table Error: Model Error Contribution

Earlier in this section, it was pointed out that, since there are no replicate measurements of the target coordinates, it is not possible to provide conclusive statements about target coordinate accuracy. That problem plagues us again in this discussion. We are not in a position to provide definitive, mathematically sound error bounds on model error contribution to sounding table error. We can, however, provide judgments that are sure to be conservative upper bounds. In this section, we offer such judgments.

The accuracy of the final volume corrections (difference between VOLUME 2 and VOLUME 3 values) is the first item of interest. These values are derived from the table of mean radial residuals, which are obtained by integrating (averaging) the individual radial residuals that appear in table 1. It is clear from figures 5 through 10 that the individual residuals varied widely on many rings of targets. How accurately does the mean radial residual represent the integral of the radial residuals for the given "latitude"? The representation is probably not within 10%.

Still more serious is the question of how well the tabulated mean radial residuals--tabulated for just those z-coordinate values that are the mean z values for the several rings of targets--indicate what occurs at intermediate values of z. Not well, we suppose, since the tabulated values of e vary considerably. A graph of the piecewise-linearized e is given in figure 20. Even if the erratic behavior of e at the top, bottom, and equator is removed, the remaining nontabular e values could easily be off by 50% or more.

This last leads to the conclusion that one should not fit a high-degree polynomial to such data. For integration purposes, a piecewise-linear fit is best; it has the effect of localizing the variations of e at the top, bottom, and equator to where they occur. A high-order fit, if used with the unmodified e's, distributes these effects throughout the table. The photogrammetric consultants apparently did remove the equatorial-ring variations before doing their integration. In the piecewise-linear integration, the total effect of these variations is limited to approximately 0.75 cubic meters. The consultants estimate the (negative) volume contribution of the equatorial ring at 1.4 cubic meters. The difference (-0.65 m^3) is less than 0.01% of the volume of the half-full tank and is insignificant. (In a comment on an earlier version of this report, the consultants stated that the sharp fluctuations of the e values in the cap region were also eliminated from the polynomial fit.)

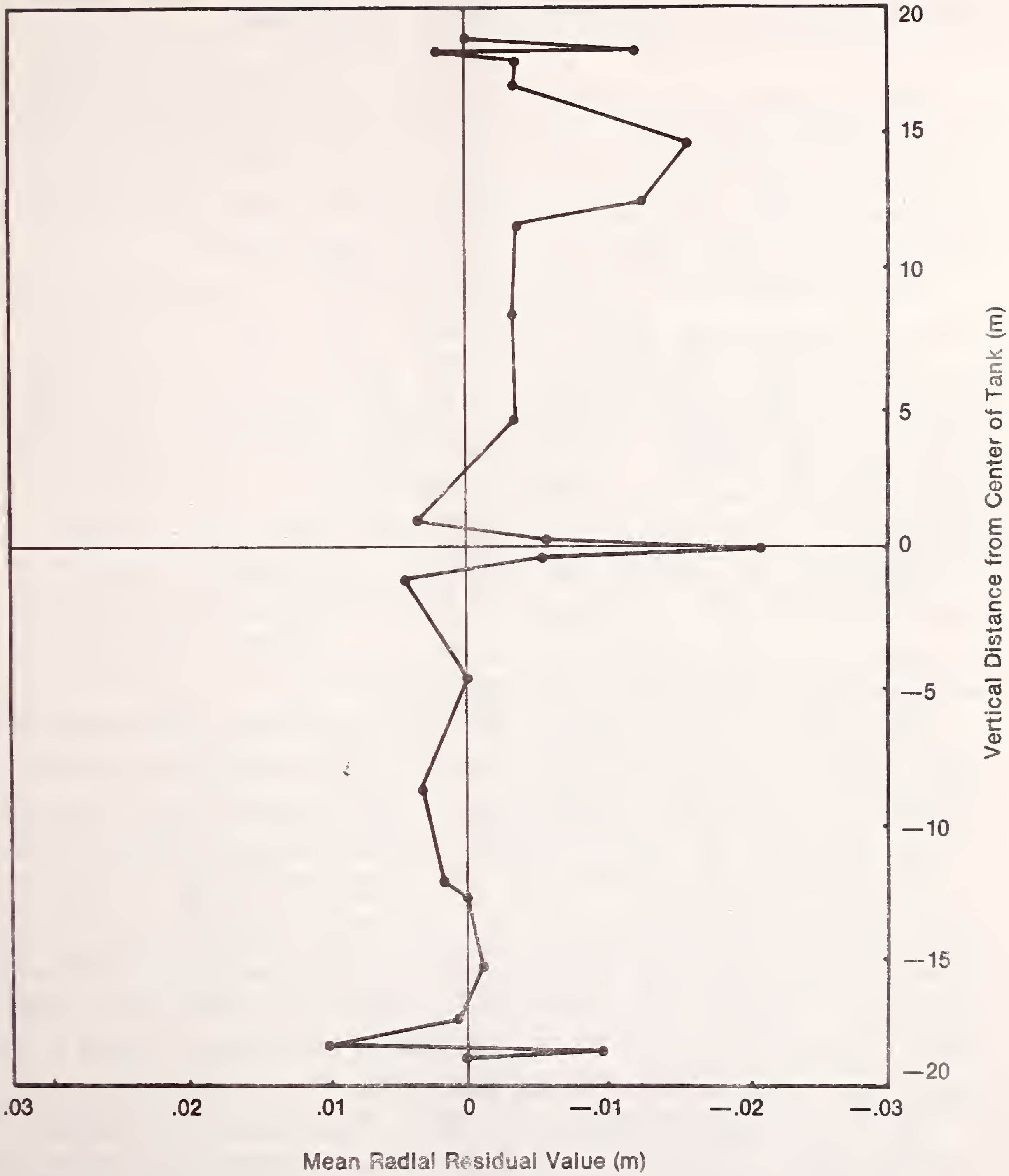


Figure 20. Piecewise linear plot of mean radial residuals.

Sounding Table Error: Plate Curvature Error Contribution

Another question about accuracy which must be addressed is: To what degree is the behavior (i.e., the size and variation of the radial residuals) of the target points typical of the tank as a whole? One way of looking at this is to consider the question of bowing out (or bowing in = flattening) of the individual tank plates relative to the nominal sphere.

In an attempt to gain a clearer picture of this, a sphere was fit to each plate that had four target points, and a "local radius of curvature" was for that plate. The difference, $r-r_{LOC}$, where r is the radius of the sphere of best global fit, indicates the bowing or flattening of the plate. To summarize the results: for the lowest ring of plates (just above the bottom cap of the tank), the difference ranges from +35 cm to +66 cm, averaging +48 cm; for the next ring, $r-r_{LOC}$ ranges from -34 to +15 cm, averaging -2 cm; for the next ring (just above the equatorial ring), the range is from -50 to +17, averaging -7 cm; for the topmost ring of plates, the range is from -10 to +48, averaging +17 cm. A positive value for $r-r_{LOC}$ indicates bowing, a negative value flattening.

From these facts we concluded that the average flattenings of the two middle rows of plates were too small to matter, and probably valueless as averages, considering what the ranges were. For comparison, the flattening of the caps in Model 2 had $r-r_{LOC}$ = -230 cm, and each produced a volume difference of only about 2 cubic meters. As for the top and bottom rings of plates, the larger positive average values of $r-r_{LOC}$ are probably due to the rapid change in curvature where those rings connect to the top and bottom caps of the tank (the "sharp bend" noticed in the exploratory statistical analysis). That volume effect is taken into account in Model 2. So the bowings seem to have no significant effect on the corrected volume calculation.

The final volume corrections, obtained by integrating in the manner described above, ranged from approximately +3 to -7 cubic meters. Figuring that e did not fluctuate between the "tabular" values of z more than twice the amount of fluctuation displayed in those values, and that in any case, these fluctuations are not likely to be in the same direction, we concluded, conservatively, that these final corrections are not off by more than 200%.

Since the correction amounts to no more than 0.03% of the volume, we conclude that the VOLUME 3 values are accurate to ±0.06% or ±2 cubic meters, whichever is the larger for each elevation. Since the consultants' figures are lower than ours, the worst possible case would be that in which our own figures are low by the full amount of our upper estimate. That would make the consultants' figures low by as much as 0.12%.

It should be stressed that these figures are intended as conservative upper bounds on the magnitude of the errors; the actual errors are probably much smaller. (For example, another possibility consistent with our estimate is as follows. The largest inaccuracy in our own table could be only 0.03%, in the direction of overestimation; and the consultants' largest error would then be also about 0.03%, in the opposite direction.)

One further question remains, however: could the target points be atypical? Notice on figure 2 that the points are all near edges (welding seams) of plates, not in the centers. Could it be that the welding seams are "close to" the nominal sphere but the interior of a plate is much farther away (bowed in or bowed out)? This would mean total plate curvature is not that calculated on the basis of the locations of the four target points. We have not been able to discover any reasons why this would be the case. In fact, there is some support for it not being so.

The plates are given their curvature in a hot press and then checked by template and welded into place, with seams that fit well to the design specifications judging from the nearby target points. It would be surprising for this to be the result of a coincidence in which the edges of all the plates possessed the correct curvature while the interiors of the plates had a different one. (It is not unreasonable that the caps came out with a different curvature from the plates because their geometry is different.) The other fairly large deviation from the design--the "sharp bend" referred to above--is presumably the effect, in the completed sphere, of the difference between the caps and the plates, as worked out through the internal stresses of the tank.

More quantitatively, we calculated the effect on the volume of the most extreme flattening, in which the plates would be quite straight in the side-to-side direction and curved only in the z direction (so that a cross section of the tank by a horizontal plane would be a polygon). That would reduce the volume of the tank by about 400 cubic meters. Such bowing would be obvious to the eye. However, visual inspection of the tank, including following the motion of light reflections in its surface, did not reveal any. We conclude, therefore, that there is little or no systematic bowing, and that the volume effect of whatever bowing exists is probably no greater than the errors previously discussed.

REFERENCES

[1] Brown, D. C., Close-range camera calibration, Photogrammetric Engineering, 37, 855-866 (1971).

[2] Brownlee, K. A., Statistical Theory and Methodology in Science and Engineering, John Wiley and Sons, New York (1965).

[3] Collier, R. S., Ellerbruch, D., Cruz, J. E., Stokes, R. W., Luft, P. E., Peterson, R. G., Hiester, A. E., Mass quantity gauging by rf mode analysis, NBS Report NBSIR 73-318, National Bureau of Standards, Boulder, Colo. (1973).

[4] Collier, R. S., Ellerbruch, D., RF total mass gauging in large storage containers: Empty tank modes, NBS Report NBSIR 73-346, National Bureau of Standards, Boulder, Colo. (1973).

[5] Jelffs, P. A., Calibration of containers and gauges, J. Inst. Pet., 53, No. 561, 117-125 (1972).

[6] Ku, H. H., Precision measurement and calibration: Statistical concepts and procedures, NBS Special Publication 300, 1, 331-363 (1969).

[7] Witzgall, C., Best approximating sphere in R^n, unpublished working paper, Center for Applied Mathematics, National Bureau of Standards, Washington, D.C.

ELEVATION PEDESTAL	VOLUME 1	VOLUME 2	VOLUME 3
.1705	2.97856	1.63252	1.53[illegible]
.2	3.72401	2.29199	2.20887
.3	7.22095	5.35397	5.40[illegible]5
.4	11.9294	9.68440	9.84919
.5	17.6439	15.2797	15.549
.6	24.4822	22.1077	22.9627
.7	32.4260	30.3515	3[illegible].4760
.8	41.4659	39.0915	3[illegible].5737
.9	51.5958	49.2214	49.7497
1.0	62.8099	60.4349	60.9976
1.1	75.1032	72.7258	73.3111
1.2	88.4622	86.0877	86.6857
1.3	102.889	100.514	101.120
1.4[illegible]	118.374	116.[illegible]	1[illegible]6.612

ELEVATION	VOLUME 1	VOLUME 2	VOLUME 3
1.5	134.912	132.537	133.156
1.6	152.475	150.121	150.795
1.7	171.119	168.749	169.372
1.8	190.774	188.49	189.031
1.9	211.458	209.183	209.717
2.0	233.162	230.789	231.423
2.1	255.881	253.507	254.142
2.2	279.603	277.239	277.868
2.3	304.364	301.963	302.595
2.4	330.145	327.731	328.361
2.5	356.915	354.502	355.127
2.6	384.668	382.255	382.875
2.7	413.398	410.985	411.599
2.8	443.099	440.685	441.293
2.9	473.764	471.35	471.949
3.0	505.387	502.973	503.563
3.1	537.961	535.547	536.128
3.2	571.481	569.067	569.636
3.3	605.940	603.526	604.084
3.4	641.332	638.918	639.466
3.5	677.65	675.236	675.774
3.6	714.889	712.475	713.003
3.7	753.041	750.628	751.147
3.8	792.102	789.688	790.199
3.9	832.064	829.650	830.153
4.0	872.921	870.507	871.003
4.1	914.666	912.253	912.742
4.2	957.295	954.881	955.364
4.3	1000.80	998.386	998.863
4.4	1045.17	1042.76	1043.23
4.5	1090.41	1088.00	1088.47
4.6	1136.51	1134.09	1134.56
4.7	1183.46	1181.04	1181.5
4.80	1231.25	1228.83	1229.29
4.90	1279.88	1277.46	1277.92
5.00	1329.34	1326.93	1327.38
5.10	1379.63	1377.22	1377.67
5.20	1430.74	1428.32	1428.78
5.30	1482.66	1480.25	1480.70
5.40	1535.39	1532.97	1533.43
5.50	1588.92	1586.5	1586.96
5.60	1643.24	1640.83	1641.29
5.70	1698.36	1695.94	1696.4
5.80	1754.25	1751.84	1752.3
5.90	1810.92	1808.51	1808.98
6.00	1868.36	1865.95	1866.43
6.10	1926.57	1924.15	1924.64
6.20	1985.53	1983.11	1983.62
6.30	2045.24	2042.82	2043.35
6.40	2105.69	2103.28	2103.82
6.50	2166.89	2164.47	2165.03
6.60	2228.81	2226.40	2226.98
6.70	2291.46	2289.05	2289.65
6.80	2354.83	2352.42	2353.04
6.90	2418.91	2416.5	2417.15
7.00	2483.7	2481.29	2481.96
7.10	2549.19	2546.78	2547.47
7.20	2615.38	2612.96	2613.69

ELEVATION	VOLUME 1	VOLUME 2	VOLUME 3
7.30	2682.25	2679.83	2680.13
7.40	2749.8	2747.39	2748.16
7.50	2818.03	2815.62	2816.41
7.60	2886.93	2884.51	2885.33
7.70	2956.49	2954.07	2954.92
7.80	3026.7	3024.29	3025.17
7.90	3097.57	3095.16	3096.06
8.00	3169.08	3166.67	3167.40
8.10	3241.23	3238.81	3239.79
8.20	3314.01	3311.59	3312.59
8.30	3387.41	3385.00	3386.02
8.40	3461.43	3459.02	3460.07
8.50	3536.07	3533.66	3534.74
8.60	3611.31	3608.90	3610.01
8.70	3687.15	3684.74	3685.99
8.80	3763.59	3761.17	3762.36
8.90	3840.61	3838.19	3839.41
9.00	3918.21	3915.80	3917.05
9.10	3996.39	3993.97	3995.26
9.20	4075.13	4072.72	4074.04
9.30	4154.44	4152.03	4153.39
9.40	4234.31	4231.89	4233.29
9.50	4314.72	4312.31	4313.74
9.60	4395.68	4393.26	4394.73
9.70	4477.17	4474.76	4476.26
9.80	4559.19	4556.78	4558.32
9.90	4641.74	4639.33	4640.91
10.00	4724.81	4722.40	4724.01
10.10	4808.39	4805.98	4807.62
10.20	4892.47	4890.06	4891.73
10.30	4977.06	4974.64	4976.35
10.40	5062.13	5059.72	5061.45
10.50	5147.70	5145.28	5147.04
10.60	5233.74	5231.33	5233.11
10.70	5320.26	5317.85	5319.66
10.80	5407.25	5404.83	5406.67
10.90	5494.69	5492.28	5494.14
11.00	5582.60	5580.18	5582.06
11.10	5670.95	5668.53	5670.44
11.20	5759.74	5757.33	5759.25
11.30	5848.97	5846.56	5848.5
11.40	5938.64	5936.22	5938.18
11.50	6028.72	6026.31	6028.29
11.60	6119.22	6116.81	6118.8
11.70	6210.14	6207.72	6209.73
11.80	6301.46	6299.04	6301.07
11.90	6393.17	6390.76	6392.80
12.00	6485.29	6482.87	6484.52
12.10	6577.78	6575.37	6577.43
12.20	6670.66	6668.25	6670.32
12.30	6763.91	6761.50	6763.58
12.40	6857.53	6855.11	6857.2
12.50	6951.51	6949.09	6951.19
12.60	7045.84	7043.43	7045.53
12.70	7140.52	7138.11	7140.22
12.80	7235.54	7233.13	7235.24
12.90	7330.91	7328.49	7330.61
13.00	7426.59	7424.18	7426.30

ELEVATION	VOLUME 1	VOLUME 2	VOLUME 3
13.10	7522.61	7520.19	7522.31
13.20	7619.94	7616.52	7618.64
13.30	7715.58	7713.17	7715.28
13.40	7812.52	7910.11	7812.23
13.50	7909.77	7907.36	7909.47
13.60	8007.3	8004.89	8007.0
13.70	8105.13	8102.71	8104.82
13.80	8203.23	8200.81	8202.92
13.90	8301.6	8299.19	8301.30
14.00	8400.24	8397.83	8399.94
14.10	8499.14	8496.73	8498.85
14.20	8598.30	8595.88	8598.01
14.30	8697.7	8695.29	8697.42
14.40	8797.35	8794.93	8797.08
14.50	8897.23	8894.81	8896.97
14.60	8997.34	8994.92	8997.09
14.70	9097.67	9095.26	9097.44
14.80	9198.22	9195.81	9198.01
14.90	9298.98	9296.57	9298.78
15.00	9399.94	9397.53	9399.76
15.10	9501.1	9498.69	9500.95
15.20	9602.46	9600.04	9602.32
15.30	9703.99	9701.58	9703.88
15.40	9805.71	9803.30	9805.62
15.50	9907.60	9905.19	9907.54
15.60	10009.7	10007.2	10009.6
15.70	10111.9	10109.5	10111.9
15.80	10214.2	10211.8	10214.3
15.90	10316.8	10314.3	10316.8
16.00	10419.4	10417.0	10419.5
16.10	10522.2	10519.8	10522.3
16.20	10625.1	10622.7	10625.3
16.30	10728.2	10725.8	10728.4
16.40	10831.3	10828.9	10831.6
16.50	10934.6	10932.2	10934.9
16.60	11038.0	11035.6	11038.3
16.70	11141.4	11139.0	11141.8
16.80	11245.0	11242.6	11245.4
16.90	11348.6	11346.2	11349.1
17.00	11452.4	11450.0	11452.9
17.10	11556.2	11553.8	11556.7
17.20	11660.0	11657.6	11660.7
17.30	11764.0	11761.5	11764.6
17.40	11867.9	11865.5	11968.6
17.50	11971.9	11969.5	11972.7
17.60	12076.0	12073.6	12076.7
17.70	12180.1	12177.7	12180.8
17.80	12284.2	12281.8	12284.9
17.90	12388.4	12386.0	12389.0
18.00	12492.5	12490.1	12493.1
18.10	12596.7	12594.3	12597.1
18.20	12700.9	12698.5	12701.0
18.30	12805.0	12802.6	12805.1
18.40	12909.2	12906.8	12909.1
18.50	13013.4	13010.9	13013.2
18.60	13117.5	13115.1	13117.3
18.70	13221.6	13219.2	13221.4
18.80	13325.6	13323.2	13325.4

ELEVATION	VOLUME 1	VOLUME 2	VOLUME 3
18.90	13429.6	13427.2	13429.5
19.00	13533.6	13531.2	13533.4
19.10	13637.5	13635.1	13637.4
19.20	13741.4	13739.0	13741.3
19.30	13845.2	13842.8	13845.1
19.40	13948.9	13946.5	13948.9
19.50	14052.5	14050.1	14052.6
19.60	14156.1	14153.7	14156.2
19.70	14259.6	14257.1	14259.7
19.80	14362.9	14360.5	14363.1
19.90	14466.2	14463.8	14466.3
20.00	14569.3	14566.9	14569.5
20.10	14672.4	14670.0	14672.6
20.20	14775.3	14772.9	14775.5
20.30	14878.1	14875.7	14878.3
20.40	14980.7	14978.3	14981.0
20.50	15083.2	15080.8	15083.5
20.60	15185.6	15183.2	15185.9
20.70	15287.8	15285.4	15288.1
20.80	15389.8	15387.4	15390.1
20.90	15491.7	15489.3	15492.0
21.00	15593.4	15591.0	15593.7
21.10	15694.9	15692.5	15695.2
21.20	15796.3	15793.9	15796.6
21.30	15897.4	15895.0	15897.7
21.40	15998.4	15996.0	15998.7
21.50	16099.1	16096.7	16099.4
21.60	16199.7	16197.2	16199.9
21.70	16300.0	16297.6	16300.2
21.80	16400.1	16397.7	16400.3
21.90	16499.9	16497.5	16500.2
22.00	16599.6	16597.2	16599.8
22.10	16699.0	16696.5	16699.1
22.20	16798.1	16795.7	16798.2
22.30	16897.0	16894.6	16897.1
22.40	16995.6	16993.2	16995.7
22.50	17094.0	17091.5	17094.0
22.60	17192.0	17189.6	17192.1
22.70	17289.8	17287.4	17289.9
22.80	17387.4	17384.9	17387.3
22.90	17484.6	17482.2	17484.5
23.00	17581.5	17579.1	17581.4
23.10	17678.1	17675.7	17678.0
23.20	17774.4	17772.0	17774.2
23.30	17870.4	17868.0	17870.2
23.40	17966.1	17963.7	17965.8
23.50	18061.4	18059.0	18061.1
23.60	18156.4	18154.0	18156.1
23.70	18251.1	18248.7	18250.7
23.80	18345.4	18343.0	18345.0
23.90	18439.4	18436.9	18438.9
24.00	18532.9	18530.5	18532.4
24.10	18626.2	18623.8	18625.6
24.20	18719.0	18716.6	18718.4
24.30	18811.5	18809.1	18810.9
24.40	18903.6	18901.2	18902.9
24.50	18995.3	18992.9	18994.6
24.60	19086.6	19084.1	19085.9

ELEVATION	VOLUME 1	VOLUME 2	VOLUME 3
24.70	19177.4	19175.0	19176.7
24.80	19267.9	19265.3	19267.1
24.90	19358.0	19355.6	19357.1
25.00	19447.6	19445.2	19446.7
25.10	19536.8	19534.4	19535.9
25.20	19625.6	19623.2	19624.6
25.30	19713.9	19711.5	19712.9
25.40	19801.8	19799.4	19800.8
25.50	19889.2	19887.8	19888.1
25.60	19976.1	19973.7	19975.0
25.70	20062.6	20060.2	20061.5
25.80	20148.6	20146.2	20147.5
25.90	20234.2	20231.8	20233.0
26.00	20319.2	20316.8	20318.0
26.10	20403.8	20401.4	20402.5
26.20	20487.8	20485.4	20486.5
26.30	20571.4	20568.9	20570.0
26.40	20654.4	20652.0	20653.0
26.50	20736.9	20734.5	20735.5
26.60	20818.9	20816.5	20817.4
26.70	20900.4	20897.9	20898.9
26.80	20981.3	20978.9	20979.7
26.90	21061.6	21059.2	21060.1
27.00	21141.5	21139.1	21139.9
27.10	21220.7	21218.3	21219.1
27.20	21299.5	21297.0	21297.8
27.30	21377.6	21375.2	21375.9
27.40	21455.2	21452.7	21453.4
27.50	21532.1	21529.7	21530.4
27.60	21608.5	21606.1	21606.7
27.70	21684.3	21681.9	21682.5
27.80	21759.5	21757.1	21757.6
27.90	21834.1	21831.7	21832.2
28.00	21908.1	21905.7	21906.1
28.10	21981.5	21979.1	21979.5
28.20	22054.2	22051.8	22052.2
28.30	22126.3	22123.9	22124.2
28.40	22197.8	22195.4	22195.7
28.50	22268.6	22266.2	22266.4
28.60	22338.8	22336.4	22336.6
28.70	22408.3	22405.9	22406.1
28.80	22477.1	22474.7	22474.9
28.90	22545.3	22542.9	22543.0
29.00	22612.8	22610.4	22610.5
29.10	22679.7	22677.2	22677.3
29.20	22745.9	22743.4	22743.4
29.30	22811.2	22808.8	22808.9
29.40	22876.0	22873.6	22873.5
29.50	22940.0	22937.6	22937.5
29.60	23003.3	23000.9	23000.7
29.70	23065.9	23063.5	23063.3
29.80	23127.8	23125.4	23125.1
29.90	23189.0	23186.5	23186.2
30.00	23249.4	23246.9	23246.6
30.10	23309.0	23306.6	23306.2
30.20	23367.7	23365.5	23365.0
30.30	23426.1	23423.7	23423.1
30.40	23483.5	23481.1	23480.4

ELEVATION	VOLUME 1	VOLUME 2	VOLUME 3
30.50	23540.1	23537.7	23536.2
30.60	23595.9	23593.5	23592.6
30.70	23651.4	23649.6	23647.5
30.80	23705.3	23702.8	23701.6
30.90	23759.7	23756.3	23755.6
31.00	23811.4	23809.6	23807.5
31.10	23863.3	23861.9	23859.2
31.20	23914.3	23911.9	23910.1
31.30	23964.6	23962.1	23960.2
31.40	24014.0	24011.6	24009.4
31.50	24062.5	24061.1	24057.8
31.60	24110.3	24107.9	24105.4
31.70	24157.2	24154.8	24152.1
31.80	24203.2	24200.8	24198.0
31.90	24248.4	24246.0	24243.0
32.00	24292.7	24290.3	24287.2
32.10	24336.1	24333.7	24330.5
32.20	24378.7	24376.3	24372.9
32.30	24420.4	24418.0	24414.4
32.40	24461.2	24458.8	24455.0
32.50	24501.1	24498.7	24494.7
32.60	24540.1	24537.7	24533.6
32.70	24578.2	24575.8	24571.5
32.80	24615.4	24612.9	24608.5
32.90	24651.6	24649.2	24644.5
33.00	24686.9	24684.5	24679.7
33.10	24721.3	24718.9	24713.9
33.20	24754.8	24752.4	24747.2
33.30	24787.3	24784.9	24779.6
33.40	24818.9	24816.5	24811.0
33.50	24849.5	24847.1	24841.5
33.60	24879.1	24876.7	24871.0
33.70	24907.8	24905.4	24899.5
33.80	24935.5	24933.0	24927.1
33.90	24962.2	24959.7	24953.7
34.00	24987.9	24985.5	24979.3
34.10	25012.6	25010.2	25004.0
34.20	25036.3	25033.9	25027.6
34.30	25059.0	25056.6	25050.2
34.40	25080.7	25078.3	25071.8
34.50	25101.4	25099.0	25092.5
34.60	25121.0	25118.6	25112.0
34.70	25139.6	25137.2	25130.6
34.80	25157.2	25154.8	25148.1
34.90	25173.7	25171.3	25164.6
35.00	25189.2	25186.8	25180.1
35.10	25203.6	25201.2	25194.4
35.20	25216.9	25214.5	25207.7
35.30	25229.2	25226.8	25220.0
35.40	25240.4	25238.0	25231.1
35.50	25250.5	25248.1	25241.2
35.60	25259.5	25257.1	25250.2
35.70	25267.5	25265.1	25258.1
35.80	25274.3	25271.9	25264.8
35.90	25280.0	25277.4	25270.4
36.00	25284.6	25281.7	25274.7
36.10	25288.1	25284.8	25277.7
36.20	25290.4	25286.5	25279.3

APPENDIX B: PORTIONS OF PHOTOGRAMMETRIC CONSULTANTS' SOUNDING TABLES

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.
BOTTOM		
.0000	.000	-----
PEDESTAL		
.1705	2.213	-----
.18	2.438	.225
.19	2.662	.224
.20	2.897	.235
.21	3.144	.247
.22	3.403	.259
.23	3.673	.270
.24	3.955	.282
.25	4.248	.293
.26	4.553	.305
.27	4.870	.317
.28	5.198	.328
.29	5.538	.340
.30	5.890	.352
.31	6.253	.363
.32	6.628	.375
.33	7.014	.386
.34	7.412	.398
.35	7.821	.409
.36	8.242	.421
.37	8.674	.432
.38	9.118	.444
.39	9.574	.456
.40	10.041	.467
.41	10.519	.478
.42	11.009	.490
.43	11.511	.502
.44	12.024	.513
.45	12.549	.525
.46	13.085	.536
.47	13.632	.547
.48	14.191	.559
.49	14.762	.571
.50	15.344	.582
.51	15.929	.585
.52	16.524	.595
.53	17.130	.606
.54	17.748	.618
.55	18.378	.630
.56	19.019	.641
.57	19.671	.652
.58	20.335	.664
.59	21.010	.675
.60	21.697	.687
.61	22.395	.698
.62	23.104	.709
.63	23.825	.721
.64	24.557	.732
.65	25.301	.744
.66	26.055	.754
.67	26.822	.767
.68	27.599	.777
.69	28.388	.789
.70	29.188	.800
.71	30.000	.812
.72	30.823	.823
.73	31.657	.834
.74	32.502	.845
.75	33.359	.857
.76	34.227	.868
.77	35.107	.880
.78	35.998	.891
.79	36.900	.902
.80	37.813	.913
.81	38.741	.928
.82	39.683	.942
.83	40.637	.954
.84	41.602	.965
.85	42.578	.976
.86	43.566	.988
.87	44.564	.998
.88	45.574	1.010
.89	46.596	1.022
.90	47.628	1.032
.91	48.672	1.044
.92	49.726	1.054
.93	50.792	1.066
.94	51.869	1.077
.95	52.958	1.089
.96	54.057	1.099
.97	55.168	1.111
.98	56.290	1.122
.99	57.423	1.133

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
2.00	228.718	2.221	2.50	352.397	2.722
2.01	230.950	2.232	2.51	355.129	2.732
2.02	233.186	2.236	2.52	357.871	2.742
2.03	235.431	2.245	2.53	360.622	2.751
2.04	237.686	2.255	2.54	363.383	2.761
2.05	239.951	2.265	2.55	366.154	2.771
2.06	242.227	2.276	2.56	368.935	2.781
2.07	244.512	2.285	2.57	371.725	2.790
2.08	246.807	2.295	2.58	374.526	2.801
2.09	249.113	2.306	2.59	377.336	2.810
2.10	251.428	2.315	2.60	380.155	2.819
2.11	253.754	2.326	2.61	382.985	2.830
2.12	256.090	2.336	2.62	385.824	2.839
2.13	258.435	2.345	2.63	388.673	2.849
2.14	260.791	2.356	2.64	391.532	2.859
2.15	263.157	2.366	2.65	394.400	2.868
2.16	265.533	2.376	2.66	397.278	2.878
2.17	267.918	2.385	2.67	400.166	2.888
2.18	270.314	2.396	2.68	403.063	2.897
2.19	272.720	2.406	2.69	405.970	2.907
2.20	275.136	2.416	2.70	408.887	2.917
2.21	277.562	2.426	2.71	411.813	2.926
2.22	279.997	2.435	2.72	414.750	2.937
2.23	282.443	2.446	2.73	417.695	2.945
2.24	284.899	2.456	2.74	420.651	2.956
2.25	287.365	2.466	2.75	423.616	2.965
2.26	289.840	2.475	2.76	426.591	2.975
2.27	292.326	2.486	2.77	429.575	2.984
2.28	294.821	2.495	2.78	432.569	2.994
2.29	297.327	2.506	2.79	435.573	3.004
2.30	299.842	2.515	2.80	438.586	3.013
2.31	302.367	2.525	2.81	441.609	3.023
2.32	304.906	2.539	2.82	444.641	3.032
2.33	307.461	2.555	2.83	447.683	3.042
2.34	310.025	2.564	2.84	450.735	3.052
2.35	312.600	2.575	2.85	453.796	3.061
2.36	315.184	2.584	2.86	456.867	3.071
2.37	317.778	2.594	2.87	459.948	3.081
2.38	320.382	2.604	2.88	463.038	3.090
2.39	322.996	2.614	2.89	466.137	3.099
2.40	325.619	2.623	2.90	469.246	3.109
2.41	328.253	2.634	2.91	472.365	3.119
2.42	330.896	2.643	2.92	475.493	3.128
2.43	333.549	2.653	2.93	478.631	3.138
2.44	336.213	2.664	2.94	481.778	3.147
2.45	338.885	2.672	2.95	484.935	3.157
2.46	341.568	2.683	2.96	488.101	3.166
2.47	344.261	2.693	2.97	491.277	3.176
2.48	346.963	2.702	2.98	494.462	3.185
2.49	349.675	2.712	2.99	497.657	3.195

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
4.00	868.218	4.123	4.50	1085.605	4.561
4.01	872.351	4.133	4.51	1090.174	4.569
4.02	876.492	4.141	4.52	1094.752	4.578
4.03	880.643	4.151	4.53	1099.338	4.586
4.04	884.802	4.159	4.54	1103.933	4.595
4.05	888.970	4.168	4.55	1108.537	4.604
4.06	893.146	4.176	4.56	1113.149	4.612
4.07	897.332	4.186	4.57	1117.770	4.621
4.08	901.527	4.195	4.58	1122.399	4.629
4.09	905.730	4.203	4.59	1127.036	4.637
4.10	909.942	4.212	4.60	1131.683	4.647
4.11	914.163	4.221	4.61	1136.337	4.654
4.12	918.393	4.230	4.62	1141.001	4.664
4.13	922.632	4.239	4.63	1145.672	4.671
4.14	926.879	4.247	4.64	1150.353	4.681
4.15	931.135	4.256	4.65	1155.042	4.689
4.16	935.400	4.265	4.66	1159.739	4.697
4.17	939.674	4.274	4.67	1164.445	4.706
4.18	943.957	4.283	4.68	1169.159	4.714
4.19	948.248	4.291	4.69	1173.882	4.723
4.20	952.549	4.301	4.70	1178.613	4.731
4.21	956.858	4.309	4.71	1183.352	4.739
4.22	961.175	4.317	4.72	1188.101	4.749
4.23	965.502	4.327	4.73	1192.857	4.756
4.24	969.837	4.335	4.74	1197.622	4.765
4.25	974.181	4.344	4.75	1202.396	4.774
4.26	978.534	4.353	4.76	1207.178	4.782
4.27	982.895	4.361	4.77	1211.968	4.790
4.28	987.265	4.370	4.78	1216.767	4.799
4.29	991.644	4.379	4.79	1221.574	4.807
4.30	996.032	4.388	4.80	1226.389	4.815
4.31	1000.428	4.396	4.81	1231.213	4.824
4.32	1004.833	4.405	4.82	1236.046	4.833
4.33	1009.247	4.414	4.83	1240.887	4.841
4.34	1013.670	4.423	4.84	1245.736	4.849
4.35	1018.101	4.431	4.85	1250.593	4.857
4.36	1022.540	4.439	4.86	1255.459	4.866
4.37	1026.989	4.449	4.87	1260.334	4.875
4.38	1031.446	4.457	4.88	1265.216	4.882
4.39	1035.912	4.466	4.89	1270.107	4.891
4.40	1040.386	4.474	4.90	1275.007	4.900
4.41	1044.869	4.483	4.91	1279.914	4.907
4.42	1049.361	4.492	4.92	1284.830	4.916
4.43	1053.861	4.500	4.93	1289.755	4.925
4.44	1058.370	4.509	4.94	1294.687	4.932
4.45	1062.888	4.518	4.95	1299.628	4.941
4.46	1067.414	4.526	4.96	1304.578	4.950
4.47	1071.949	4.535	4.97	1309.535	4.957
4.48	1076.492	4.543	4.98	1314.501	4.966
4.49	1081.044	4.552	4.99	1319.475	4.974

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
6.00	1863.497	5.780	6.50	2162.125	6.155
6.01	1869.285	5.788	6.51	2168.288	6.163
6.02	1875.080	5.795	6.52	2174.457	6.169
6.03	1880.883	5.803	6.53	2180.634	6.177
6.04	1886.693	5.810	6.54	2186.819	6.185
6.05	1892.512	5.819	6.55	2193.010	6.191
6.06	1898.337	5.825	6.56	2199.209	6.199
6.07	1904.171	5.834	6.57	2205.416	6.207
6.08	1910.012	5.841	6.58	2211.629	6.213
6.09	1915.860	5.848	6.59	2217.850	6.221
6.10	1921.717	5.857	6.60	2224.078	6.228
6.11	1927.580	5.863	6.61	2230.314	6.236
6.12	1933.452	5.872	6.62	2236.557	6.243
6.13	1939.331	5.879	6.63	2242.807	6.250
6.14	1945.217	5.886	6.64	2249.064	6.257
6.15	1951.111	5.894	6.65	2255.328	6.264
6.16	1957.013	5.902	6.66	2261.600	6.272
6.17	1962.922	5.909	6.67	2267.879	6.279
6.18	1968.839	5.917	6.68	2274.165	6.286
6.19	1974.763	5.924	6.69	2280.459	6.294
6.20	1980.695	5.932	6.70	2286.759	6.300
6.21	1986.635	5.940	6.71	2293.067	6.308
6.22	1992.582	5.947	6.72	2299.382	6.315
6.23	1998.536	5.954	6.73	2305.704	6.322
6.24	2004.498	5.962	6.74	2312.034	6.330
6.25	2010.468	5.970	6.75	2318.371	6.337
6.26	2016.444	5.976	6.76	2324.714	6.343
6.27	2022.429	5.985	6.77	2331.065	6.351
6.28	2028.421	5.992	6.78	2337.424	6.359
6.29	2034.420	5.999	6.79	2343.789	6.365
6.30	2040.427	6.007	6.80	2350.161	6.372
6.31	2046.442	6.015	6.81	2356.541	6.380
6.32	2052.463	6.021	6.82	2362.928	6.387
6.33	2058.493	6.030	6.83	2369.322	6.394
6.34	2064.529	6.036	6.84	2375.723	6.401
6.35	2070.574	6.045	6.85	2382.131	6.408
6.36	2076.625	6.051	6.86	2388.546	6.415
6.37	2082.684	6.059	6.87	2394.969	6.423
6.38	2088.751	6.067	6.88	2401.398	6.429
6.39	2094.825	6.074	6.89	2407.835	6.437
6.40	2100.906	6.081	6.90	2414.279	6.444
6.41	2106.995	6.089	6.91	2420.729	6.450
6.42	2113.091	6.096	6.92	2427.187	6.458
6.43	2119.194	6.103	6.93	2433.652	6.465
6.44	2125.305	6.111	6.94	2440.124	6.472
6.45	2131.423	6.118	6.95	2446.603	6.479
6.46	2137.549	6.126	6.96	2453.089	6.486
6.47	2143.682	6.133	6.97	2459.582	6.493
6.48	2149.822	6.140	6.98	2466.083	6.501
6.49	2155.970	6.148	6.99	2472.590	6.507

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
8.00	3164.911	7.184	8.50	3532.129	7.495
8.01	3172.102	7.191	8.51	3539.631	7.502
8.02	3179.299	7.197	8.52	3547.138	7.507
8.03	3186.503	7.204	8.53	3554.652	7.514
8.04	3193.713	7.210	8.54	3562.171	7.519
8.05	3200.929	7.216	8.55	3569.697	7.526
8.06	3208.152	7.223	8.56	3577.229	7.532
8.07	3215.381	7.229	8.57	3584.766	7.537
8.08	3222.616	7.235	8.58	3592.310	7.544
8.09	3229.857	7.241	8.59	3599.859	7.549
8.10	3237.105	7.248	8.60	3607.415	7.556
8.11	3244.360	7.255	8.61	3614.977	7.562
8.12	3251.620	7.260	8.62	3622.544	7.567
8.13	3258.887	7.267	8.63	3630.118	7.574
8.14	3266.160	7.273	8.64	3637.697	7.579
8.15	3273.440	7.280	8.65	3645.283	7.586
8.16	3280.725	7.285	8.66	3652.874	7.591
8.17	3288.017	7.292	8.67	3660.472	7.598
8.18	3295.315	7.298	8.68	3668.075	7.603
8.19	3302.620	7.305	8.69	3675.684	7.609
8.20	3309.931	7.311	8.70	3683.300	7.616
8.21	3317.248	7.317	8.71	3690.921	7.621
8.22	3324.571	7.323	8.72	3698.548	7.627
8.23	3331.900	7.329	8.73	3706.181	7.633
8.24	3339.236	7.336	8.74	3713.820	7.639
8.25	3346.578	7.342	8.75	3721.464	7.644
8.26	3353.926	7.348	8.76	3729.115	7.651
8.27	3361.281	7.355	8.77	3736.772	7.657
8.28	3368.641	7.360	8.78	3744.434	7.662
8.29	3376.008	7.367	8.79	3752.103	7.669
8.30	3383.381	7.373	8.80	3759.777	7.674
8.31	3390.760	7.379	8.81	3767.457	7.680
8.32	3398.145	7.385	8.82	3775.143	7.686
8.33	3405.537	7.392	8.83	3782.834	7.691
8.34	3412.934	7.397	8.84	3790.532	7.698
8.35	3420.338	7.404	8.85	3798.235	7.703
8.36	3427.748	7.410	8.86	3805.945	7.710
8.37	3435.164	7.416	8.87	3813.660	7.715
8.38	3442.586	7.422	8.88	3821.381	7.721
8.39	3450.015	7.429	8.89	3829.107	7.726
8.40	3457.449	7.434	8.90	3836.840	7.733
8.41	3464.890	7.441	8.91	3844.578	7.738
8.42	3472.336	7.446	8.92	3852.322	7.744
8.43	3479.789	7.453	8.93	3860.072	7.750
8.44	3487.248	7.459	8.94	3867.828	7.756
8.45	3494.713	7.465	8.95	3875.589	7.761
8.46	3502.184	7.471	8.96	3883.357	7.768
8.47	3509.661	7.477	8.97	3891.130	7.773
8.48	3517.145	7.484	8.98	3898.908	7.778
8.49	3524.634	7.489	8.99	3906.693	7.785

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
10.00	4721.386	8.332	10.50	5144.340	8.579
10.01	4729.723	8.337	10.51	5152.924	8.584
10.02	4738.065	8.342	10.52	5161.512	8.588
10.03	4746.412	8.347	10.53	5170.105	8.593
10.04	4754.764	8.352	10.54	5178.703	8.598
10.05	4763.121	8.357	10.55	5187.306	8.603
10.06	4771.484	8.363	10.56	5195.913	8.607
10.07	4779.851	8.367	10.57	5204.525	8.612
10.08	4788.223	8.372	10.58	5213.142	8.617
10.09	4796.601	8.378	10.59	5221.764	8.622
10.10	4804.983	8.382	10.60	5230.390	8.626
10.11	4813.371	8.388	10.61	5239.021	8.631
10.12	4821.763	8.392	10.62	5247.657	8.636
10.13	4830.161	8.398	10.63	5256.297	8.640
10.14	4838.563	8.402	10.64	5264.942	8.645
10.15	4846.971	8.408	10.65	5273.592	8.650
10.16	4855.384	8.413	10.66	5282.246	8.654
10.17	4863.801	8.417	10.67	5290.905	8.659
10.18	4872.224	8.423	10.68	5299.569	8.664
10.19	4880.651	8.427	10.69	5308.238	8.669
10.20	4889.084	8.433	10.70	5316.911	8.673
10.21	4897.521	8.437	10.71	5325.589	8.678
10.22	4905.964	8.443	10.72	5334.271	8.682
10.23	4914.411	8.447	10.73	5342.958	8.687
10.24	4922.863	8.452	10.74	5351.650	8.692
10.25	4931.321	8.458	10.75	5360.346	8.696
10.26	4939.783	8.462	10.76	5369.047	8.701
10.27	4948.250	8.467	10.77	5377.753	8.706
10.28	4956.722	8.472	10.78	5386.463	8.710
10.29	4965.199	8.477	10.79	5395.178	8.715
10.30	4973.681	8.482	10.80	5403.897	8.719
10.31	4982.168	8.487	10.81	5412.621	8.724
10.32	4990.659	8.491	10.82	5421.350	8.729
10.33	4999.156	8.497	10.83	5430.083	8.733
10.34	5007.657	8.501	10.84	5438.821	8.738
10.35	5016.164	8.507	10.85	5447.563	8.742
10.36	5024.675	8.511	10.86	5456.310	8.747
10.37	5033.191	8.516	10.87	5465.061	8.751
10.38	5041.712	8.521	10.88	5473.817	8.756
10.39	5050.238	8.526	10.89	5482.577	8.760
10.40	5058.769	8.531	10.90	5491.342	8.765
10.41	5067.304	8.535	10.91	5500.112	8.770
10.42	5075.844	8.540	10.92	5508.886	8.774
10.43	5084.389	8.545	10.93	5517.665	8.779
10.44	5092.939	8.550	10.94	5526.448	8.783
10.45	5101.494	8.555	10.95	5535.235	8.787
10.46	5110.054	8.560	10.96	5544.027	8.792
10.47	5118.618	8.564	10.97	5552.824	8.797
10.48	5127.187	8.569	10.98	5561.625	8.801
10.49	5135.761	8.574	10.99	5570.430	8.805

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
12.00	6481.737	9.226	12.50	6947.772	9.410
12.01	6490.966	9.229	12.51	6957.185	9.413
12.02	6500.199	9.233	12.52	6966.602	9.417
12.03	6509.436	9.237	12.53	6976.022	9.420
12.04	6518.677	9.241	12.54	6985.446	9.424
12.05	6527.921	9.244	12.55	6994.873	9.427
12.06	6537.169	9.248	12.56	7004.304	9.431
12.07	6546.422	9.253	12.57	7013.739	9.435
12.08	6555.678	9.256	12.58	7023.176	9.437
12.09	6564.937	9.259	12.59	7032.618	9.442
12.10	6574.201	9.264	12.60	7042.062	9.444
12.11	6583.468	9.267	12.61	7051.511	9.449
12.12	6592.739	9.271	12.62	7060.962	9.451
12.13	6602.014	9.275	12.63	7070.417	9.455
12.14	6611.292	9.278	12.64	7079.876	9.459
12.15	6620.575	9.283	12.65	7089.338	9.462
12.16	6629.861	9.286	12.66	7098.803	9.465
12.17	6639.151	9.290	12.67	7108.272	9.469
12.18	6648.444	9.293	12.68	7117.745	9.473
12.19	6657.742	9.298	12.69	7127.220	9.475
12.20	6667.043	9.301	12.70	7136.700	9.480
12.21	6676.347	9.304	12.71	7146.182	9.482
12.22	6685.656	9.309	12.72	7155.668	9.486
12.23	6694.968	9.312	12.73	7165.157	9.489
12.24	6704.284	9.316	12.74	7174.650	9.493
12.25	6713.603	9.319	12.75	7184.146	9.496
12.26	6722.926	9.323	12.76	7193.646	9.500
12.27	6732.253	9.327	12.77	7203.148	9.502
12.28	6741.584	9.331	12.78	7212.655	9.507
12.29	6750.918	9.334	12.79	7222.164	9.509
12.30	6760.256	9.338	12.80	7231.677	9.513
12.31	6769.597	9.341	12.81	7241.193	9.516
12.32	6778.942	9.345	12.82	7250.713	9.520
12.33	6788.291	9.349	12.83	7260.236	9.523
12.34	6797.644	9.353	12.84	7269.762	9.526
12.35	6807.000	9.356	12.85	7279.292	9.530
12.36	6816.359	9.359	12.86	7288.825	9.533
12.37	6825.723	9.364	12.87	7298.361	9.536
12.38	6835.090	9.367	12.88	7307.900	9.539
12.39	6844.460	9.370	12.89	7317.443	9.543
12.40	6853.834	9.374	12.90	7326.989	9.546
12.41	6863.212	9.378	12.91	7336.538	9.549
12.42	6872.593	9.381	12.92	7346.091	9.553
12.43	6881.978	9.385	12.93	7355.647	9.556
12.44	6891.367	9.389	12.94	7365.206	9.559
12.45	6900.759	9.392	12.95	7374.768	9.562
12.46	6910.154	9.395	12.96	7384.334	9.566
12.47	6919.553	9.399	12.97	7393.903	9.569
12.48	6928.956	9.403	12.98	7403.475	9.572
12.49	6938.362	9.406	12.99	7413.050	9.575

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
14.00	8395.708	9.870	14.50	8892.379	9.992
14.01	8405.580	9.872	14.51	8902.373	9.994
14.02	8415.455	9.875	14.52	8912.370	9.997
14.03	8425.332	9.877	14.53	8922.369	9.999
14.04	8435.212	9.880	14.54	8932.370	10.001
14.05	8445.095	9.883	14.55	8942.373	10.003
14.06	8454.980	9.885	14.56	8952.379	10.006
14.07	8464.868	9.888	14.57	8962.387	10.008
14.08	8474.759	9.891	14.58	8972.397	10.010
14.09	8484.651	9.892	14.59	8982.410	10.013
14.10	8494.547	9.896	14.60	8992.424	10.014
14.11	8504.445	9.898	14.61	9002.441	10.017
14.12	8514.345	9.900	14.62	9012.460	10.019
14.13	8524.249	9.904	14.63	9022.482	10.022
14.14	8534.154	9.905	14.64	9032.505	10.023
14.15	8544.062	9.908	14.65	9042.531	10.026
14.16	8553.973	9.911	14.66	9052.559	10.028
14.17	8563.886	9.913	14.67	9062.589	10.030
14.18	8573.801	9.915	14.68	9072.621	10.032
14.19	8583.719	9.918	14.69	9082.656	10.035
14.20	8593.640	9.921	14.70	9092.692	10.036
14.21	8603.563	9.923	14.71	9102.731	10.039
14.22	8613.488	9.925	14.72	9112.772	10.041
14.23	8623.416	9.928	14.73	9122.815	10.043
14.24	8633.347	9.931	14.74	9132.860	10.045
14.25	8643.280	9.933	14.75	9142.908	10.048
14.26	8653.215	9.935	14.76	9152.957	10.049
14.27	8663.153	9.938	14.77	9163.009	10.052
14.28	8673.093	9.940	14.78	9173.063	10.054
14.29	8683.035	9.942	14.79	9183.119	10.056
14.30	8692.980	9.945	14.80	9193.177	10.058
14.31	8702.928	9.948	14.81	9203.237	10.060
14.32	8712.878	9.950	14.82	9213.299	10.062
14.33	8722.830	9.952	14.83	9223.363	10.064
14.34	8732.785	9.955	14.84	9233.430	10.067
14.35	8742.742	9.957	14.85	9243.498	10.068
14.36	8752.701	9.959	14.86	9253.569	10.071
14.37	8762.663	9.962	14.87	9263.641	10.072
14.38	8772.627	9.964	14.88	9273.716	10.075
14.39	8782.593	9.966	14.89	9283.792	10.076
14.40	8792.562	9.969	14.90	9293.871	10.079
14.41	8802.533	9.971	14.91	9303.952	10.081
14.42	8812.507	9.974	14.92	9314.035	10.083
14.43	8822.483	9.976	14.93	9324.120	10.085
14.44	8832.461	9.978	14.94	9334.206	10.086
14.45	8842.442	9.981	14.95	9344.295	10.089
14.46	8852.424	9.982	14.96	9354.386	10.091
14.47	8862.410	9.986	14.97	9364.479	10.093
14.48	8872.397	9.987	14.98	9374.574	10.095
14.49	8882.387	9.990	14.99	9384.671	10.097

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
16.00	10413.592	10.266	16.50	10928.460	10.325
16.01	10423.859	10.267	16.51	10938.786	10.326
16.02	10434.127	10.268	16.52	10949.114	10.328
16.03	10444.397	10.270	16.53	10959.442	10.328
16.04	10454.668	10.271	16.54	10969.772	10.330
16.05	10464.940	10.272	16.55	10980.102	10.330
16.06	10475.213	10.273	16.56	10990.434	10.332
16.07	10485.488	10.275	16.57	11000.766	10.332
16.08	10495.764	10.276	16.58	11011.100	10.334
16.09	10506.042	10.278	16.59	11021.434	10.334
16.10	10516.321	10.279	16.60	11031.770	10.336
16.11	10526.601	10.280	16.61	11042.106	10.336
16.12	10536.882	10.281	16.62	11052.444	10.338
16.13	10547.164	10.282	16.63	11062.782	10.338
16.14	10557.448	10.284	16.64	11073.121	10.339
16.15	10567.733	10.285	16.65	11083.462	10.341
16.16	10578.020	10.287	16.66	11093.803	10.341
16.17	10588.308	10.288	16.67	11104.145	10.342
16.18	10598.596	10.288	16.68	11114.488	10.343
16.19	10608.887	10.291	16.69	11124.832	10.344
16.20	10619.178	10.291	16.70	11135.177	10.345
16.21	10629.470	10.292	16.71	11145.523	10.346
16.22	10639.764	10.294	16.72	11155.869	10.346
16.23	10650.059	10.295	16.73	11166.217	10.348
16.24	10660.355	10.296	16.74	11176.566	10.349
16.25	10670.653	10.298	16.75	11186.915	10.349
16.26	10680.952	10.299	16.76	11197.265	10.350
16.27	10691.251	10.299	16.77	11207.616	10.351
16.28	10701.552	10.301	16.78	11217.968	10.352
16.29	10711.854	10.302	16.79	11228.321	10.353
16.30	10722.158	10.304	16.80	11238.675	10.354
16.31	10732.462	10.304	16.81	11249.030	10.355
16.32	10742.768	10.306	16.82	11259.385	10.355
16.33	10753.075	10.307	16.83	11269.741	10.356
16.34	10763.383	10.308	16.84	11280.098	10.357
16.35	10773.692	10.309	16.85	11290.456	10.358
16.36	10784.002	10.310	16.86	11300.815	10.359
16.37	10794.313	10.311	16.87	11311.175	10.360
16.38	10804.626	10.313	16.88	11321.535	10.360
16.39	10814.939	10.313	16.89	11331.896	10.361
16.40	10825.254	10.315	16.90	11342.258	10.362
16.41	10835.570	10.316	16.91	11352.621	10.363
16.42	10845.887	10.317	16.92	11362.984	10.363
16.43	10856.204	10.317	16.93	11373.349	10.365
16.44	10866.523	10.319	16.94	11383.714	10.365
16.45	10876.844	10.321	16.95	11394.079	10.365
16.46	10887.165	10.321	16.96	11404.446	10.367
16.47	10897.487	10.322	16.97	11414.813	10.367
16.48	10907.810	10.323	16.98	11425.181	10.368
16.49	10918.135	10.325	16.99	11435.550	10.369

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
18.00	12485.112	10.395	18.50	13004.686	10.393
18.01	12495.507	10.395	18.51	13015.077	10.391
18.02	12505.903	10.396	18.52	13025.469	10.392
18.03	12516.298	10.395	18.53	13035.860	10.391
18.04	12526.694	10.396	18.54	13046.251	10.391
18.05	12537.089	10.395	18.55	13056.642	10.391
18.06	12547.485	10.396	18.56	13067.033	10.391
18.07	12557.881	10.396	18.57	13077.423	10.390
18.08	12568.277	10.396	18.58	13087.813	10.390
18.09	12578.672	10.395	18.59	13098.203	10.390
18.10	12589.068	10.396	18.60	13108.593	10.390
18.11	12599.464	10.396	18.61	13118.982	10.389
18.12	12609.860	10.396	18.62	13129.371	10.389
18.13	12620.256	10.396	18.63	13139.759	10.388
18.14	12630.652	10.396	18.64	13150.148	10.389
18.15	12641.048	10.396	18.65	13160.536	10.388
18.16	12651.442	10.394	18.66	13170.923	10.387
18.17	12661.825	10.383	18.67	13181.311	10.388
18.18	12672.207	10.382	18.68	13191.698	10.387
18.19	12682.590	10.383	18.69	13202.100	10.402
18.20	12692.973	10.383	18.70	13212.501	10.401
18.21	12703.356	10.383	18.71	13222.903	10.402
18.22	12713.738	10.382	18.72	13233.303	10.400
18.23	12724.121	10.383	18.73	13243.704	10.401
18.24	12734.504	10.383	18.74	13254.104	10.400
18.25	12744.886	10.382	18.75	13264.504	10.400
18.26	12755.269	10.383	18.76	13274.903	10.399
18.27	12765.651	10.382	18.77	13285.302	10.399
18.28	12776.033	10.382	18.78	13295.701	10.399
18.29	12786.416	10.383	18.79	13306.099	10.398
18.30	12796.811	10.395	18.80	13316.497	10.398
18.31	12807.206	10.395	18.81	13326.895	10.398
18.32	12817.601	10.395	18.82	13337.292	10.397
18.33	12827.996	10.395	18.83	13347.688	10.396
18.34	12838.390	10.394	18.84	13358.084	10.396
18.35	12848.785	10.395	18.85	13368.480	10.396
18.36	12859.179	10.394	18.86	13378.875	10.395
18.37	12869.574	10.395	18.87	13389.270	10.395
18.38	12879.968	10.394	18.88	13399.664	10.394
18.39	12890.362	10.394	18.89	13410.058	10.394
18.40	12900.756	10.394	18.90	13420.452	10.394
18.41	12911.150	10.394	18.91	13430.844	10.392
18.42	12921.543	10.393	18.92	13441.237	10.393
18.43	12931.937	10.394	18.93	13451.629	10.392
18.44	12942.330	10.393	18.94	13462.020	10.391
18.45	12952.723	10.393	18.95	13472.411	10.391
18.46	12963.116	10.393	18.96	13482.802	10.391
18.47	12973.509	10.393	18.97	13493.192	10.390
18.48	12983.901	10.392	18.98	13503.581	10.389
18.49	12994.293	10.392	18.99	13513.970	10.389

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
20.00	14559.417	10.303	20.50	15072.956	10.237
20.01	14569.719	10.302	20.51	15083.192	10.236
20.02	14580.020	10.301	20.52	15093.426	10.234
20.03	14590.320	10.300	20.53	15103.658	10.232
20.04	14600.618	10.298	20.54	15113.889	10.231
20.05	14610.916	10.298	20.55	15124.119	10.230
20.06	14621.212	10.296	20.56	15134.347	10.228
20.07	14631.507	10.295	20.57	15144.573	10.226
20.08	14641.800	10.293	20.58	15154.798	10.225
20.09	14652.093	10.293	20.59	15165.022	10.224
20.10	14662.384	10.291	20.60	15175.244	10.222
20.11	14672.674	10.290	20.61	15185.464	10.220
20.12	14682.963	10.289	20.62	15195.683	10.219
20.13	14693.250	10.287	20.63	15205.900	10.217
20.14	14703.537	10.287	20.64	15216.116	10.216
20.15	14713.822	10.285	20.65	15226.330	10.214
20.16	14724.105	10.283	20.66	15236.543	10.213
20.17	14734.388	10.283	20.67	15246.754	10.211
20.18	14744.669	10.281	20.68	15256.963	10.209
20.19	14754.949	10.280	20.69	15267.171	10.208
20.20	14765.227	10.278	20.70	15277.377	10.206
20.21	14775.505	10.278	20.71	15287.582	10.205
20.22	14785.781	10.276	20.72	15297.785	10.203
20.23	14796.056	10.275	20.73	15307.986	10.201
20.24	14806.329	10.273	20.74	15318.186	10.200
20.25	14816.601	10.272	20.75	15328.384	10.198
20.26	14826.872	10.271	20.76	15338.581	10.197
20.27	14837.141	10.269	20.77	15348.775	10.194
20.28	14847.409	10.268	20.78	15358.969	10.194
20.29	14857.676	10.267	20.79	15369.160	10.191
20.30	14867.941	10.265	20.80	15379.350	10.190
20.31	14878.206	10.265	20.81	15389.538	10.188
20.32	14888.468	10.262	20.82	15399.725	10.187
20.33	14898.729	10.261	20.83	15409.909	10.184
20.34	14908.989	10.260	20.84	15420.093	10.184
20.35	14919.248	10.259	20.85	15430.274	10.181
20.36	14929.505	10.257	20.86	15440.454	10.180
20.37	14939.761	10.256	20.87	15450.632	10.178
20.38	14950.015	10.254	20.88	15460.808	10.176
20.39	14960.268	10.253	20.89	15470.983	10.175
20.40	14970.520	10.252	20.90	15481.155	10.172
20.41	14980.770	10.250	20.91	15491.327	10.172
20.42	14991.019	10.249	20.92	15501.496	10.169
20.43	15001.266	10.247	20.93	15511.664	10.168
20.44	15011.512	10.246	20.94	15521.830	10.166
20.45	15021.756	10.244	20.95	15531.994	10.164
20.46	15031.999	10.243	20.96	15542.156	10.162
20.47	15042.240	10.241	20.97	15552.317	10.161
20.48	15052.480	10.240	20.98	15562.475	10.158
20.49	15062.719	10.239	20.99	15572.632	10.157

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
22.00	16588.203	9.945	22.50	17082.225	9.816
22.01	16598.145	9.942	22.51	17092.039	9.814
22.02	16608.085	9.940	22.52	17101.850	9.811
22.03	16618.022	9.937	22.53	17111.657	9.807
22.04	16627.958	9.936	22.54	17121.463	9.806
22.05	16637.890	9.932	22.55	17131.265	9.802
22.06	16647.820	9.930	22.56	17141.065	9.800
22.07	16657.748	9.928	22.57	17150.862	9.797
22.08	16667.673	9.925	22.58	17160.656	9.794
22.09	16677.596	9.923	22.59	17170.447	9.791
22.10	16687.516	9.920	22.60	17180.235	9.788
22.11	16697.434	9.918	22.61	17190.021	9.786
22.12	16707.349	9.915	22.62	17199.804	9.783
22.13	16717.262	9.913	22.63	17209.584	9.780
22.14	16727.172	9.910	22.64	17219.362	9.778
22.15	16737.080	9.908	22.65	17229.136	9.774
22.16	16746.986	9.906	22.66	17238.908	9.772
22.17	16756.888	9.902	22.67	17248.677	9.769
22.18	16766.789	9.901	22.68	17258.443	9.766
22.19	16776.686	9.897	22.69	17268.206	9.763
22.20	16786.581	9.895	22.70	17277.966	9.760
22.21	16796.474	9.893	22.71	17287.724	9.758
22.22	16806.364	9.890	22.72	17297.478	9.754
22.23	16816.252	9.888	22.73	17307.230	9.752
22.24	16826.137	9.885	22.74	17316.979	9.749
22.25	16836.019	9.882	22.75	17326.725	9.746
22.26	16845.899	9.880	22.76	17336.468	9.743
22.27	16855.776	9.877	22.77	17346.208	9.740
22.28	16865.651	9.875	22.78	17355.945	9.737
22.29	16875.523	9.872	22.79	17365.680	9.735
22.30	16885.392	9.869	22.80	17375.411	9.731
22.31	16895.259	9.867	22.81	17385.140	9.729
22.32	16905.123	9.864	22.82	17394.865	9.725
22.33	16914.985	9.862	22.83	17404.588	9.723
22.34	16924.844	9.859	22.84	17414.308	9.720
22.35	16934.700	9.856	22.85	17424.025	9.717
22.36	16944.554	9.854	22.86	17433.738	9.713
22.37	16954.405	9.851	22.87	17443.449	9.711
22.38	16964.253	9.848	22.88	17453.157	9.708
22.39	16974.099	9.846	22.89	17462.862	9.705
22.40	16983.942	9.843	22.90	17472.564	9.702
22.41	16993.783	9.841	22.91	17482.263	9.699
22.42	17003.621	9.838	22.92	17491.959	9.696
22.43	17013.456	9.835	22.93	17501.652	9.693
22.44	17023.288	9.832	22.94	17511.342	9.690
22.45	17033.118	9.830	22.95	17521.029	9.687
22.46	17042.945	9.827	22.96	17530.713	9.684
22.47	17052.769	9.824	22.97	17540.394	9.681
22.48	17062.591	9.822	22.98	17550.072	9.678
22.49	17072.409	9.818	22.99	17559.747	9.675

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
24.00	18520.203	9.337	24.50	18982.231	9.145
24.01	18529.536	9.333	24.51	18991.373	9.142
24.02	18538.865	9.329	24.52	19000.511	9.138
24.03	18548.191	9.326	24.53	19009.644	9.133
24.04	18557.513	9.322	24.54	19018.774	9.130
24.05	18566.831	9.318	24.55	19027.900	9.126
24.06	18576.146	9.315	24.56	19037.021	9.121
24.07	18585.457	9.311	24.57	19046.139	9.118
24.08	18594.764	9.307	24.58	19055.252	9.113
24.09	18604.068	9.304	24.59	19064.362	9.110
24.10	18613.367	9.299	24.60	19073.468	9.106
24.11	18622.663	9.296	24.61	19082.569	9.101
24.12	18631.956	9.293	24.62	19091.667	9.098
24.13	18641.244	9.288	24.63	19100.760	9.093
24.14	18650.529	9.285	24.64	19109.849	9.089
24.15	18659.810	9.281	24.65	19118.934	9.085
24.16	18669.087	9.277	24.66	19128.016	9.082
24.17	18678.361	9.274	24.67	19137.093	9.077
24.18	18687.630	9.269	24.68	19146.166	9.073
24.19	18696.896	9.266	24.69	19155.235	9.069
24.20	18706.159	9.263	24.70	19164.299	9.064
24.21	18715.417	9.258	24.71	19173.360	9.061
24.22	18724.671	9.254	24.72	19182.417	9.057
24.23	18733.922	9.251	24.73	19191.469	9.052
24.24	18743.169	9.247	24.74	19200.518	9.049
24.25	18752.412	9.243	24.75	19209.562	9.044
24.26	18761.652	9.240	24.76	19218.602	9.040
24.27	18770.887	9.235	24.77	19227.638	9.036
24.28	18780.119	9.232	24.78	19236.670	9.032
24.29	18789.346	9.227	24.79	19245.697	9.027
24.30	18798.570	9.224	24.80	19254.721	9.024
24.31	18807.791	9.221	24.81	19263.740	9.019
24.32	18817.007	9.216	24.82	19272.755	9.015
24.33	18826.219	9.212	24.83	19281.766	9.011
24.34	18835.428	9.209	24.84	19290.773	9.007
24.35	18844.632	9.204	24.85	19299.775	9.002
24.36	18853.833	9.201	24.86	19308.774	8.999
24.37	18863.030	9.197	24.87	19317.768	8.994
24.38	18872.223	9.193	24.88	19326.758	8.990
24.39	18881.412	9.189	24.89	19335.743	8.985
24.40	18890.597	9.185	24.90	19344.725	8.982
24.41	18899.778	9.181	24.91	19353.702	8.977
24.42	18908.955	9.177	24.92	19362.675	8.973
24.43	18918.129	9.174	24.93	19371.644	8.969
24.44	18927.298	9.169	24.94	19380.608	8.964
24.45	18936.463	9.165	24.95	19389.569	8.961
24.46	18945.625	9.162	24.96	19398.525	8.956
24.47	18954.782	9.157	24.97	19407.476	8.951
24.48	18963.936	9.154	24.98	19416.424	8.948
24.49	18973.086	9.150	24.99	19425.367	8.943

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
26.00	20305.443	8.478	26.50	20722.922	8.223
26.01	20313.916	8.473	26.51	20731.141	8.219
26.02	20322.384	8.468	26.52	20739.354	8.213
26.03	20330.847	8.463	26.53	20747.562	8.208
26.04	20339.306	8.459	26.54	20755.764	8.202
26.05	20347.759	8.453	26.55	20763.962	8.198
26.06	20356.207	8.448	26.56	20772.154	8.192
26.07	20364.650	8.443	26.57	20780.341	8.187
26.08	20373.089	8.439	26.58	20788.522	8.181
26.09	20381.522	8.433	26.59	20796.698	8.176
26.10	20389.950	8.428	26.60	20804.869	8.171
26.11	20398.374	8.424	26.61	20813.035	8.166
26.12	20406.792	8.418	26.62	20821.195	8.160
26.13	20415.206	8.414	26.63	20829.350	8.155
26.14	20423.614	8.408	26.64	20837.500	8.150
26.15	20432.017	8.403	26.65	20845.644	8.144
26.16	20440.416	8.399	26.66	20853.783	8.139
26.17	20448.809	8.393	26.67	20861.916	8.133
26.18	20457.197	8.388	26.68	20870.045	8.129
26.19	20465.580	8.383	26.69	20878.167	8.122
26.20	20473.958	8.378	26.70	20886.285	8.118
26.21	20482.331	8.373	26.71	20894.397	8.112
26.22	20490.699	8.368	26.72	20902.504	8.107
26.23	20499.062	8.363	26.73	20910.605	8.101
26.24	20507.420	8.358	26.74	20918.701	8.096
26.25	20515.773	8.353	26.75	20926.791	8.090
26.26	20524.121	8.348	26.76	20934.877	8.086
26.27	20532.463	8.342	26.77	20942.956	8.079
26.28	20540.801	8.338	26.78	20951.031	8.075
26.29	20549.133	8.332	26.79	20959.099	8.068
26.30	20557.461	8.328	26.80	20967.163	8.064
26.31	20565.783	8.322	26.81	20975.221	8.058
26.32	20574.100	8.317	26.82	20983.273	8.052
26.33	20582.412	8.312	26.83	20991.321	8.048
26.34	20590.718	8.306	26.84	20999.362	8.041
26.35	20599.020	8.302	26.85	21007.398	8.036
26.36	20607.316	8.296	26.86	21015.429	8.031
26.37	20615.608	8.292	26.87	21023.454	8.025
26.38	20623.894	8.286	26.88	21031.474	8.020
26.39	20632.175	8.281	26.89	21039.488	8.014
26.40	20640.451	8.276	26.90	21047.497	8.009
26.41	20648.721	8.270	26.91	21055.500	8.003
26.42	20656.987	8.266	26.92	21063.498	7.998
26.43	20665.247	8.260	26.93	21071.490	7.992
26.44	20673.502	8.255	26.94	21079.477	7.987
26.45	20681.752	8.250	26.95	21087.458	7.981
26.46	20689.996	8.244	26.96	21095.434	7.976
26.47	20698.236	8.240	26.97	21103.404	7.970
26.48	20706.470	8.234	26.98	21111.368	7.964
26.49	20714.699	8.229	26.99	21119.327	7.959

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.
28.00	21893.436	7.364
28.01	21900.795	7.359
28.02	21908.148	7.353
28.03	21915.494	7.346
28.04	21922.834	7.340
28.05	21930.168	7.334
28.06	21937.495	7.327
28.07	21944.817	7.322
28.08	21952.132	7.315
28.09	21959.440	7.308
28.10	21966.743	7.303
28.11	21974.039	7.296
28.12	21981.329	7.290
28.13	21988.613	7.284
28.14	21995.890	7.277
28.15	22003.162	7.272
28.16	22010.426	7.264
28.17	22017.685	7.259
28.18	22024.937	7.252
28.19	22032.183	7.246
28.20	22039.422	7.239
28.21	22046.656	7.234
28.22	22053.882	7.226
28.23	22061.103	7.221
28.24	22068.317	7.214
28.25	22075.525	7.208
28.26	22082.726	7.201
28.27	22089.921	7.195
28.28	22097.110	7.189
28.29	22104.292	7.182
28.30	22111.468	7.176
28.31	22118.638	7.170
28.32	22125.801	7.163
28.33	22132.957	7.156
28.34	22140.107	7.150
28.35	22147.251	7.144
28.36	22154.389	7.138
28.37	22161.520	7.131
28.38	22168.644	7.124
28.39	22175.762	7.118
28.40	22182.874	7.112
28.41	22189.979	7.105
28.42	22197.077	7.098
28.43	22204.170	7.093
28.44	22211.255	7.085
28.45	22218.335	7.080
28.46	22225.407	7.072
28.47	22232.473	7.066
28.48	22239.533	7.060
28.49	22246.586	7.053
28.50	22253.633	7.047
28.51	22260.673	7.040
28.52	22267.707	7.034
28.53	22274.734	7.027
28.54	22281.754	7.020
28.55	22288.768	7.014
28.56	22295.776	7.008
28.57	22302.776	7.000
28.58	22309.771	6.995
28.59	22316.758	6.987
28.60	22323.739	6.981
28.61	22330.714	6.975
28.62	22337.682	6.968
28.63	22344.643	6.961
28.64	22351.598	6.955
28.65	22358.546	6.948
28.66	22365.487	6.941
28.67	22372.422	6.935
28.68	22379.350	6.928
28.69	22386.272	6.922
28.70	22393.186	6.914
28.71	22400.095	6.909
28.72	22406.996	6.901
28.73	22413.891	6.895
28.74	22420.779	6.888
28.75	22427.661	6.882
28.76	22434.536	6.875
28.77	22441.404	6.868
28.78	22448.265	6.861
28.79	22455.120	6.855
28.80	22461.968	6.848
28.81	22468.809	6.841
28.82	22475.644	6.835
28.83	22482.472	6.828
28.84	22489.293	6.821
28.85	22496.107	6.814
28.86	22502.915	6.808
28.87	22509.716	6.801
28.88	22516.510	6.794
28.89	22523.297	6.787
28.90	22530.078	6.781
28.91	22536.852	6.774
28.92	22543.618	6.766
28.93	22550.379	6.761
28.94	22557.132	6.753
28.95	22563.879	6.747
28.96	22570.618	6.739
28.97	22577.351	6.733
28.98	22584.077	6.726
28.99	22590.797	6.720

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
30.00	23233.122	5.997	30.50	23523.282	5.615
30.01	23239.111	5.989	30.51	23528.890	5.608
30.02	23245.092	5.981	30.52	23534.489	5.599
30.03	23251.066	5.974	30.53	23540.081	5.592
30.04	23257.033	5.967	30.54	23545.664	5.583
30.05	23262.992	5.959	30.55	23551.240	5.576
30.06	23268.943	5.951	30.56	23556.809	5.569
30.07	23274.887	5.944	30.57	23562.369	5.560
30.08	23280.824	5.937	30.58	23567.921	5.552
30.09	23286.753	5.929	30.59	23573.466	5.545
30.10	23292.674	5.921	30.60	23579.003	5.537
30.11	23298.588	5.914	30.61	23584.532	5.529
30.12	23304.494	5.906	30.62	23590.053	5.521
30.13	23310.393	5.899	30.63	23595.566	5.513
30.14	23316.284	5.891	30.64	23601.072	5.506
30.15	23322.168	5.884	30.65	23606.569	5.497
30.16	23328.044	5.876	30.66	23612.059	5.490
30.17	23333.913	5.869	30.67	23617.541	5.482
30.18	23339.774	5.861	30.68	23623.015	5.474
30.19	23345.627	5.853	30.69	23628.481	5.466
30.20	23351.473	5.846	30.70	23633.939	5.458
30.21	23357.311	5.838	30.71	23639.389	5.450
30.22	23363.141	5.830	30.72	23644.831	5.442
30.23	23368.964	5.823	30.73	23650.265	5.434
30.24	23374.780	5.816	30.74	23655.692	5.427
30.25	23380.587	5.807	30.75	23661.110	5.418
30.26	23386.387	5.800	30.76	23666.521	5.411
30.27	23392.180	5.793	30.77	23671.923	5.402
30.28	23397.964	5.784	30.78	23677.318	5.395
30.29	23403.742	5.778	30.79	23682.704	5.386
30.30	23409.511	5.769	30.80	23688.083	5.379
30.31	23415.273	5.762	30.81	23693.454	5.371
30.32	23421.027	5.754	30.82	23698.817	5.363
30.33	23426.773	5.746	30.83	23704.171	5.354
30.34	23432.512	5.739	30.84	23709.518	5.347
30.35	23438.243	5.731	30.85	23714.857	5.339
30.36	23443.967	5.724	30.86	23720.188	5.331
30.37	23449.682	5.715	30.87	23725.510	5.322
30.38	23455.390	5.708	30.88	23730.825	5.315
30.39	23461.090	5.700	30.89	23736.132	5.307
30.40	23466.783	5.693	30.90	23741.430	5.298
30.41	23472.468	5.685	30.91	23746.721	5.291
30.42	23478.145	5.677	30.92	23752.004	5.283
30.43	23483.814	5.669	30.93	23757.278	5.274
30.44	23489.476	5.662	30.94	23762.545	5.267
30.45	23495.130	5.654	30.95	23767.803	5.258
30.46	23500.776	5.646	30.96	23773.053	5.250
30.47	23506.414	5.638	30.97	23778.296	5.243
30.48	23512.045	5.631	30.98	23783.530	5.234
30.49	23517.667	5.622	30.99	23788.756	5.226

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
32.00	24273.879	4.379	32.50	24481.571	3.936
32.01	24278.248	4.369	32.51	24485.498	3.927
32.02	24282.609	4.361	32.52	24489.416	3.918
32.03	24286.961	4.352	32.53	24493.324	3.908
32.04	24291.305	4.344	32.54	24497.224	3.900
32.05	24295.640	4.335	32.55	24501.115	3.891
32.06	24299.966	4.326	32.56	24504.996	3.881
32.07	24304.283	4.317	32.57	24508.869	3.873
32.08	24308.591	4.308	32.58	24512.732	3.863
32.09	24312.891	4.300	32.59	24516.587	3.855
32.10	24317.182	4.291	32.60	24520.432	3.845
32.11	24321.464	4.282	32.61	24524.268	3.836
32.12	24325.738	4.274	32.62	24528.096	3.828
32.13	24330.003	4.265	32.63	24531.914	3.818
32.14	24334.258	4.255	32.64	24535.723	3.809
32.15	24338.506	4.248	32.65	24539.523	3.800
32.16	24342.744	4.238	32.66	24543.314	3.791
32.17	24346.973	4.229	32.67	24547.096	3.782
32.18	24351.194	4.221	32.68	24550.868	3.772
32.19	24355.406	4.212	32.69	24554.632	3.764
32.20	24359.609	4.203	32.70	24558.386	3.754
32.21	24363.803	4.194	32.71	24562.132	3.746
32.22	24367.989	4.186	32.72	24565.868	3.736
32.23	24372.165	4.176	32.73	24569.595	3.727
32.24	24376.333	4.168	32.74	24573.313	3.718
32.25	24380.492	4.159	32.75	24577.022	3.709
32.26	24384.642	4.150	32.76	24580.721	3.699
32.27	24388.783	4.141	32.77	24584.412	3.691
32.28	24392.916	4.133	32.78	24588.093	3.681
32.29	24397.039	4.123	32.79	24591.765	3.672
32.30	24401.154	4.115	32.80	24595.428	3.663
32.31	24405.259	4.105	32.81	24599.082	3.654
32.32	24409.356	4.097	32.82	24602.726	3.644
32.33	24413.444	4.088	32.83	24606.361	3.635
32.34	24417.523	4.079	32.84	24609.987	3.626
32.35	24421.593	4.070	32.85	24613.604	3.617
32.36	24425.654	4.061	32.86	24617.212	3.608
32.37	24429.707	4.053	32.87	24620.811	3.599
32.38	24433.750	4.043	32.88	24624.400	3.589
32.39	24437.784	4.034	32.89	24627.980	3.580
32.40	24441.810	4.026	32.90	24631.551	3.571
32.41	24445.826	4.016	32.91	24635.112	3.561
32.42	24449.834	4.008	32.92	24638.664	3.552
32.43	24453.832	3.998	32.93	24642.207	3.543
32.44	24457.822	3.990	32.94	24645.741	3.534
32.45	24461.803	3.981	32.95	24649.265	3.524
32.46	24465.774	3.971	32.96	24652.781	3.516
32.47	24469.737	3.963	32.97	24656.286	3.505
32.48	24473.691	3.954	32.98	24659.783	3.497
32.49	24477.635	3.944	32.99	24663.270	3.487

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
34.00	24966.509	2.516	34.50	25079.539	2.012
34.01	24969.016	2.507	34.51	25081.541	2.002
34.02	24971.513	2.497	34.52	25083.532	1.991
34.03	24973.999	2.486	34.53	25085.514	1.982
34.04	24976.476	2.477	34.54	25087.485	1.971
34.05	24978.943	2.467	34.55	25089.445	1.960
34.06	24981.400	2.457	34.56	25091.396	1.951
34.07	24983.846	2.446	34.57	25093.336	1.940
34.08	24986.283	2.437	34.58	25095.266	1.930
34.09	24988.710	2.427	34.59	25097.185	1.919
34.10	24991.127	2.417	34.60	25099.095	1.910
34.11	24993.534	2.407	34.61	25100.993	1.898
34.12	24995.931	2.397	34.62	25102.882	1.889
34.13	24998.318	2.387	34.63	25104.760	1.878
34.14	25000.695	2.377	34.64	25106.628	1.868
34.15	25003.062	2.367	34.65	25108.486	1.858
34.16	25005.418	2.356	34.66	25110.333	1.847
34.17	25007.765	2.347	34.67	25112.170	1.837
34.18	25010.102	2.337	34.68	25113.996	1.826
34.19	25012.429	2.327	34.69	25115.812	1.816
34.20	25014.745	2.316	34.70	25117.618	1.806
34.21	25017.052	2.307	34.71	25119.413	1.795
34.22	25019.349	2.297	34.72	25121.198	1.785
34.23	25021.635	2.286	34.73	25122.973	1.775
34.24	25023.911	2.276	34.74	25124.737	1.764
34.25	25026.178	2.267	34.75	25126.491	1.754
34.26	25028.434	2.256	34.76	25128.234	1.743
34.27	25030.680	2.246	34.77	25129.967	1.733
34.28	25032.916	2.236	34.78	25131.689	1.722
34.29	25035.142	2.226	34.79	25133.401	1.712
34.30	25037.358	2.216	34.80	25135.103	1.702
34.31	25039.563	2.205	34.81	25136.794	1.691
34.32	25041.759	2.196	34.82	25138.475	1.681
34.33	25043.944	2.185	34.83	25140.145	1.670
34.34	25046.120	2.176	34.84	25141.805	1.660
34.35	25048.285	2.165	34.85	25143.454	1.649
34.36	25050.440	2.155	34.86	25145.093	1.639
34.37	25052.584	2.144	34.87	25146.721	1.628
34.38	25054.719	2.135	34.88	25148.338	1.617
34.39	25056.844	2.125	34.89	25149.946	1.608
34.40	25058.958	2.114	34.90	25151.542	1.596
34.41	25061.062	2.104	34.91	25153.129	1.587
34.42	25063.156	2.094	34.92	25154.704	1.575
34.43	25065.239	2.083	34.93	25156.269	1.565
34.44	25067.313	2.074	34.94	25157.824	1.555
34.45	25069.376	2.063	34.95	25159.368	1.544
34.46	25071.429	2.053	34.96	25160.901	1.533
34.47	25073.472	2.043	34.97	25162.424	1.523
34.48	25075.505	2.033	34.98	25163.937	1.513
34.49	25077.527	2.022	34.99	25165.438	1.501

SOUNDING TABLE AT -160 DEGREES C, TANK NO. 4

ELEV.(M)	VOL. (S)	DIFF.	ELEV.(M)	VOL. (S)	DIFF.
36.00	25261.639	.397			
36.01	25262.023	.384			
36.02	25262.395	.372			
36.03	25262.755	.360			
36.04	25263.103	.348			
36.05	25263.439	.336			
36.06	25263.763	.324			
36.07	25264.074	.311			
36.08	25264.374	.300			
36.09	25264.661	.287			
36.10	25264.936	.275			
36.11	25265.198	.262			
36.12	25265.449	.251			
36.13	25265.687	.238			
36.14	25265.914	.227			
36.15	25266.128	.214			
36.16	25266.329	.201			
36.17	25266.519	.190			
36.18	25266.696	.177			
36.19	25266.861	.165			
36.20	25267.012	.151			
36.21	25267.143	.131			
36.22	25267.261	.118			
36.23	25267.376	.115			
36.24	25267.481	.105			
36.25	25267.575	.094			
36.26	25267.656	.081			
36.27	25267.725	.069			
36.28	25267.781	.056			
36.29	25267.825	.044			
36.30	25267.857	.032			
36.31	25267.877	.020			
36.32	25267.884	.007			
TOP 36.3209	25267.884	.000			

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM.
BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO.
NBSIR 79-1751

2. Gov't Accession No.

3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Custody Transfer Systems for LNG Ships: Tank Survey Techniques and Sounding Tables

5. Publication Date
May 1979

6. Performing Organization Code

7. AUTHOR(S)

R. H. F. Jackson, R. S. Collier, S. Haber, P. V. Tryon

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

The Maritime Administration
Department of Commerce
Washington, DC

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Static measurements of liquefied natural gas (LNG) for custody transfer purposes require an accurate and precise knowledge of the container volume and the volume-height relationship. The extremely low temperatures of LNG (less than 150° K) preclude in situ surveys; however, the increasing value of the cargo requires more precise and accurate measurements than previously used for bulk marine cargoes.

A description and assessment of the application of photogrammetric techniques to the ambient temperature survey of a 35-meter diameter spherical aluminum container are presented. Sample sounding tables (height-volume) are calculated, and an estimate of error is given.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Accuracy; statistical analysis; cryogenic; error estimation; liquefied natural gas; LNG; marine; mathematical modeling; measurement; photogrammetric; precision; ship cargo; strapping; survey

18. AVAILABILITY ☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☒ Order From Sup. of Doc., U.S. Government Printing Office, Washington, DC 20402, SD Stock No. SN003-003-

☐ Order From National Technical Information Service (NTIS), Springfield, VA, 22161

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PRINTED PAGES
84

22. Price
$6.00

USCOMM-DC