Manual of Petroleum Measurement Standards Chapter 2—Tank Calibration

Section 2C—Calibration of Upright Cylindrical Tanks Using the Optical-triangulation Method

ANSI/API MPMS 2.2C
FIRST EDITION, JANUARY 2002

American Petroleum Institute

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CONTENTS

Page

Figures

Tables

Chapter 2—Tank Calibration

SECTION 2C—CALIBRATION OF UPRIGHT CYLINDRICAL TANKS USING THE OPTICAL-TRIANGULATION METHOD

0 Introduction

This method describes the calibration of vertical cylindrical tanks by means of optical triangulation using theodolites. The circumference of the tank is determined at different levels by reference to a base line, which may be either a reference circumference measured by strapping or a base line between two stations of a theodolite measured by means of a tape or by an optical method. External circumferences are corrected to give true internal circumferences. The method is an alternative to other methods such as strapping (Chapter 2, Section 2A) and the optical-reference-line method (Chapter 2, Section 2B).

1 Scope

1.1 This part specifies a calibration procedure for application to tanks above 26 ft in diameter with cylindrical courses that are substantially vertical. It provides a method for determining the volumetric quantity contained within a tank at gauged liquid levels. The measurement required to determine the radius may be made internally (Clause 8) or externally (Clause 9). The external method is applicable only to tanks that are free of insulation.

1.2 Abnormally deformed tanks; e.g., dented or non-circular tanks are excluded from this section, API *MPMS* Chapter 2.

1.3 This method is suitable for tilted tanks up to 3% deviation from the vertical, provided that a correction is applied for the measured tilt as described in API *MPMS* Chapter 2.2A.

2 Normative Reference

The following standard contains provisions which through reference in this text, constitutes provisions of this part of Chapter 2. At the time of publication, the edition indicated was valid. All standards are subject to revision and parties to agreements based on this section of Chapter 2 are encouraged to investigate the possibility of applying the most recent edition of the standard indicated below. Members of API maintain registers of currently valid API Standards.

3 Definitions

For the purposes of this part of Chapter 2, the definitions given in Chapter 2.2A apply.

4 Precautions

The general precautions and safety precautions specified in Chapter 2.2A shall apply to this section of Chapter 2.

5 Equipment

5.1 EQUIPMENT FOR MEASUREMENT OF ANGLES

Equipment for measurement of angles as listed in 5.1.1 to 5.1.4 below.

5.1.1 Theodolites, with angular graduations and a resolution equal to or better than 5 seconds. Each theodolite shall be mounted on a tripod which is firm and stable. The legs of the tripod shall be steadied by means of magnetic bearers when being used for the internal method. Repeat readings shall agree to within 5 seconds.

5.1.2 Low-power laser-beam emitter, equipped with a device such as a fiber-optic light-transfer system and a theodolite-telescope eye-piece connection, by which the laser beam can be transmitted through a theodolite. The laser beam shall be coincident with the optical axis of the telescope.

5.1.3 Heavy weights, to set around the theodolite stations to prevent movement of the tank bottom plate.

5.1.4 Lighting, for use inside the tank to allow measurements to be read accurately.

5.2 STADIA

5.2.1 Stadia, 2 m long, such that the graduated length, between two marks, remains constant to within + 0.02 mm, at the temperature at which it is used.

Note: Conversion to USC units is not recommended for use of the stadia.

5.3 EQUIPMENT FOR BOTTOM CALIBRATION

Either:

a. A liquid method, equipment as specified in Appendix E, or
b. For a survey method, a theodolite, a dumpy level, a surveyor's level or water-filled tubes.

6 Equipment Set-up and Procedure

6.1 PREPARATION OF TANK

Fill the tank to its normal working capacity at least once and allow it to stand for a minimum of 24 hours prior to calibration.

If the tank is calibrated with liquid in it, record the depth, temperature and density of the liquid at the time of calibration. However, if the temperature of the wall surface could differ by more than 18°F (10°C) between the empty part and full part of the tank, the tank shall be completely full or empty. Do not make transfers of liquid during the calibration.

6.2 THEODOLITE SET-UP

6.2.1 Set up each theodolite with care, according to the procedure and instructions given by the manufacturer.

6.2.2 Set up the instrument to be stable.

For the internal method, steady the bottom of the tank near the theodolite station by installing weights or other heavy objects around the station. Mount the legs of the theodolite on magnetic bearers to prevent the legs from sliding on the tank bottom.

For the external method, drive the legs of the tripod fully home into the ground.

6.2.3 Set the bed plate of the instrument as near as possible to the horizontal.

Note: This will ensure verticality of the swivel axis of the theodolite.

6.3 STADIA SET-UP AND PROCEDURE

6.3.1 Mount the stadia on the tripod according to the procedure and instructions given by the manufacturer.

6.3.2 Mount the stadia horizontally and perpendicular to the aiming axis by adjusting the device on the stadia.

6.3.3 Once setting-up is complete, lock the stadia in position and verify the horizontality and the perpendicularity.

7 Measurement of Distance between Two Theodolite Stations

7.1 Take the measurement prior to the commencement of the optical readings. Set up the stadia as described in 6.3.

Measure the horizontal angle 2θ subtended at the theodolite by the two marks on the stadia, using the theodolite.

7.2 Compute the horizontal distance D between the two theodolite stations from the formula.

$$D = \frac{B}{2} \times \cot\theta \qquad (1)$$

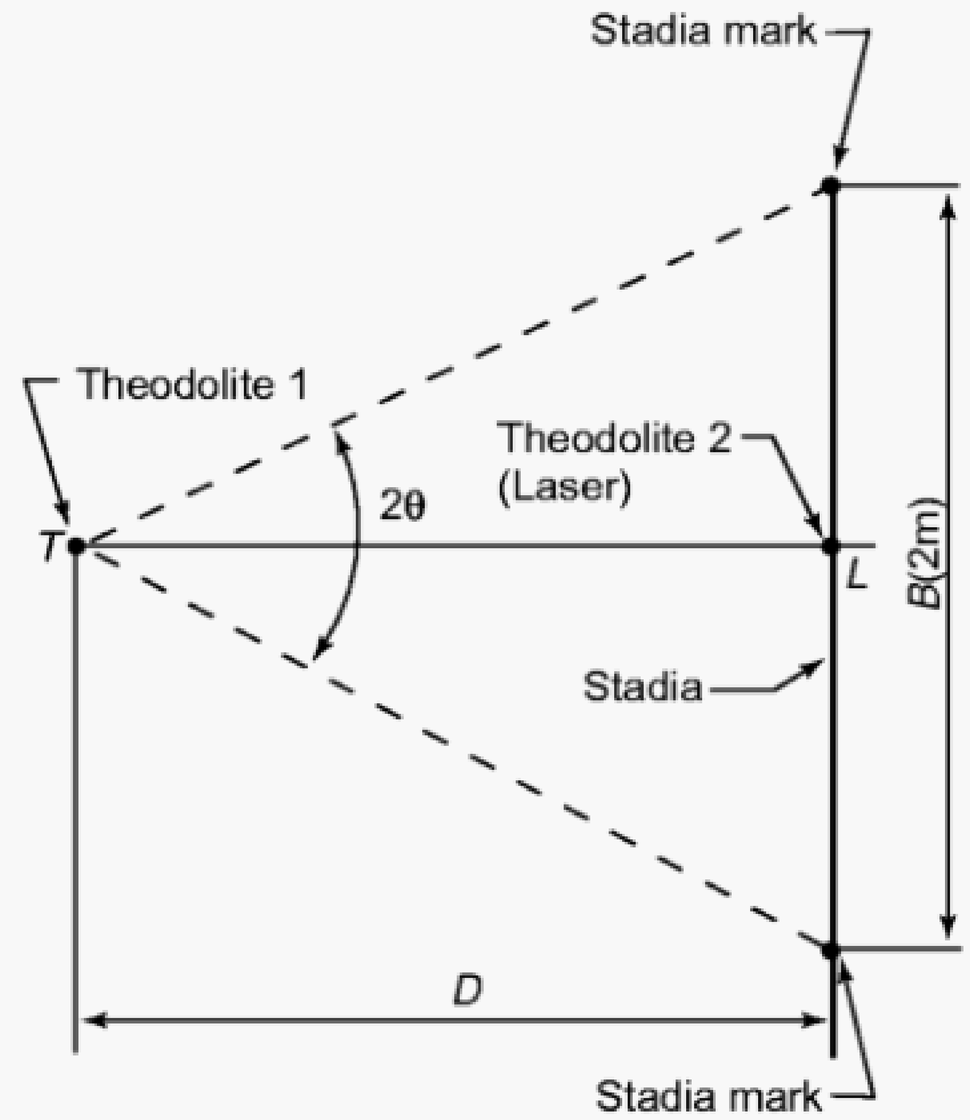


Figure 1—Measurement of Distance between Two Theodolites

where

B = the distance in meters between the two reference marks on the stadia, i.e., 2 meters,

θ = is half the angle in degrees, subtended at theodolite 1, by the two reference marks.

7.3 Carry out the measurement of the angle 2θ and the computation of the distance D a minimum of five times and calculate and record the average value. The computed distance D shall be within the tolerances given in Table 3, or the entire procedure shall be repeated.

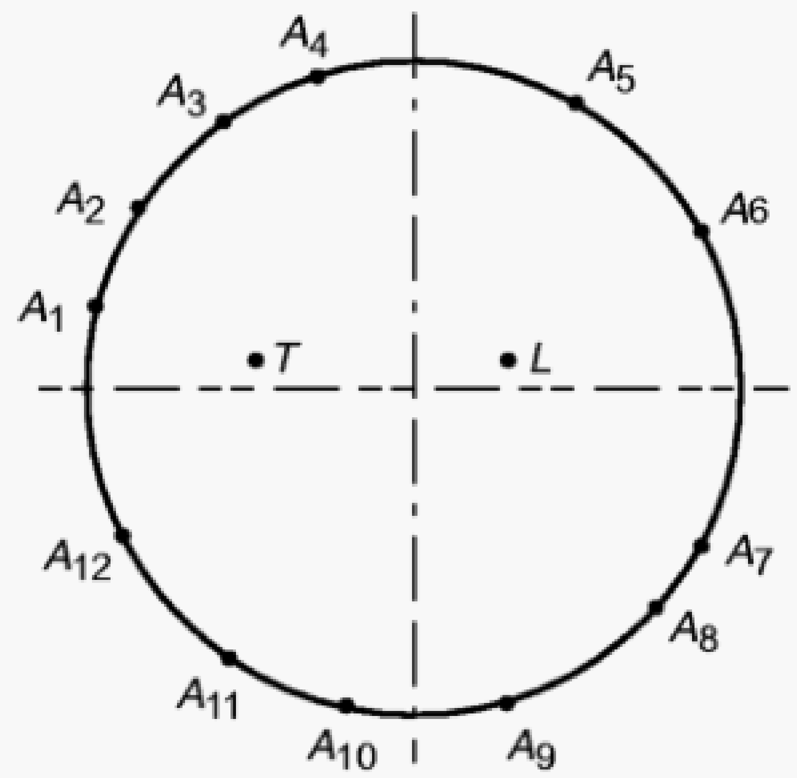
7.4 Redetermine the distance D after completion of all the optical measurements described in 8.13.

The distances computed before and after the optical measurements shall agree within the tolerances given in Table 3. If they do not, repeat the calibration procedure until a set of measurements is obtained with the values for D at the beginning and end in agreement.

8 Procedure for Internal Optical Tank Wall Measurements

8.1 Set up two theodolite stations inside the tank as illustrated in Figure 2 and described in 6.2.

8.2 Locate the two stations approximately on a diametrical plane and at least one quarter diameter apart. Adjust the theodolites and measure the distance TL ($TL = D$) as described in Clause 7.



Notes:

1. The example shows 12 wall points per circumference (see 8.10).
2. *T* and *L* are interchangeable theodolite and laser theodolite stations.
3. Do not locate wall points where the line through *T* and *L* meets the tank wall.

Figure 2—Example of Locations of Theodolite Stations and Wall Points for Internal Procedure

8.3 Set the reference axis *TL* optically on the horizontal planes (circles) of both instruments by sighting from each instrument the vertical graticule wires of the other instrument as described in steps 8.4 to 8.7.

8.4 Shut off the laser beam of the laser theodolite and remove the two filters of the laser theodolite.

8.5 Adjust theodolite *T* to set the telescope to infinity and illuminate the eyepiece of this telescope with a light source.

8.6 Sight the object lens of theodolite from the telescope of the laser theodolite *L* and continue focusing until the graticules become visible. Make the vertical graticule wires coincide by using the adjusting device on the laser theodolite *L*.

Note 1: The example shows 12 wall points per circumference, reference diagram.

Note 2: *T* and *L* are interchangeable theodolite and laser theodolite stations.

Note 3: Do not locate wall points where the line through *T* and *L* meets the tank wall.

8.7 Repeat the operation from theodolite. Repeat the operation as many times as necessary until the vertical graticule wires coincide perfectly.

8.8 The *TL* axis is now set. Record the relative locations of the two theodolites by taking readings of both horizontal scales as the horizontal reference angles.

8.9 Replace the two filters in the laser theodolite and switch on the laser beam. This beam is then used to provide a series of points on the tank wall. Sight these points in turn using the other theodolite; take and record the horizontal-scale readings on both instruments.

Table 1—Minimum Number of Points Per Circumference for Internal Procedure

Circumference		Minimum Number of Points
Meters	Feet	
Up to 50	Up to 164	8
Above 50 up to 100	Above 164 to 328	12
Above 100 up to 150	Above 328 to 492	16
Above 150 up to 200	Above 492 to 656	20
Above 200 up to 250	Above 656 to 820	24
Above 250 up to 300	Above 820 to 894	30
Above 300	Above 894	36

8.10 The minimum number of points on the tank shell wall per circumference shall be as given in Table 1. These points shall not be closer than 12 in. (300 mm) from the vertical weld seam. For each course, there shall be two horizontal sets of points—one set on a circumference at $^1/_5$ to $^1/_4$ of the course height below the upper horizontal seam as shown in Figure 3.

8.11 Sight all the points along a horizontal set, as indicated in Figure 3, by the theodolite and the laser beam; move to the next level.

Note: This will ensure that each set of points on the tank wall is at the same level for a given circumference.

8.12 Calculate by difference, the angles α and β indicated in Figure 4, for each of these points.

8.13 After completion of optical measurement of all points, re-determine the horizontal distance *TL* (*TL* = *D*) if the original and final values of *TL* do not agree as specified; repeat the calibration procedures until such agreement is obtained.

8.14 Check the axis *TL* by switching off the laser removing the filters from the laser theodolite and repeating the operations described in 8.3 to 8.8. The original and final horizontal reference angles shall be within the tolerance specified in 10.2. If not, repeat the calibration procedures until a set of readings ending in such agreement is obtained. Record the average values of the horizontal reference angles.

9 Procedures for External Measurement

9.1 GENERAL

The measurements shall be related either to a reference circumference using the procedure described in 9.2 or to reference distances measured between pairs of theodolite stations as described in 9.3.

Dimensions in millimeters

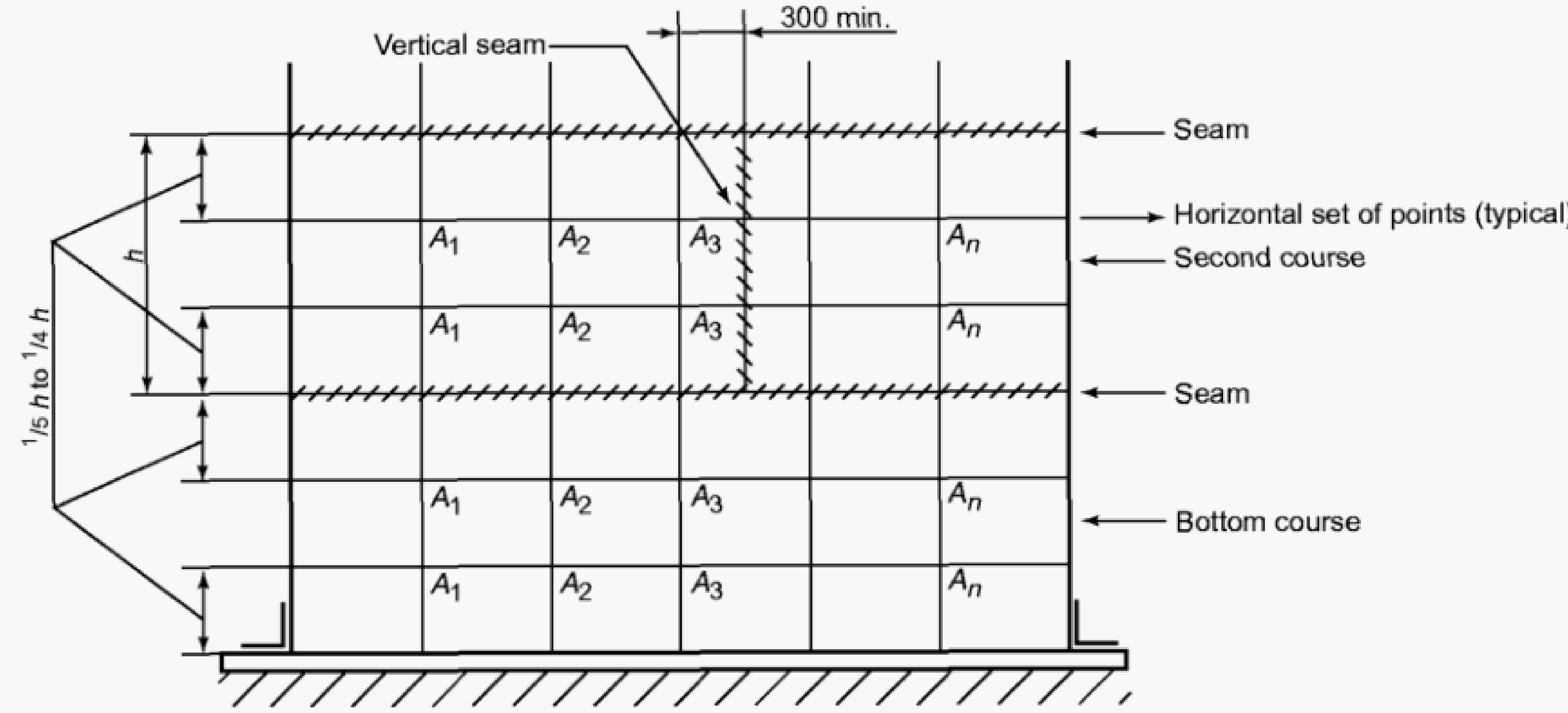
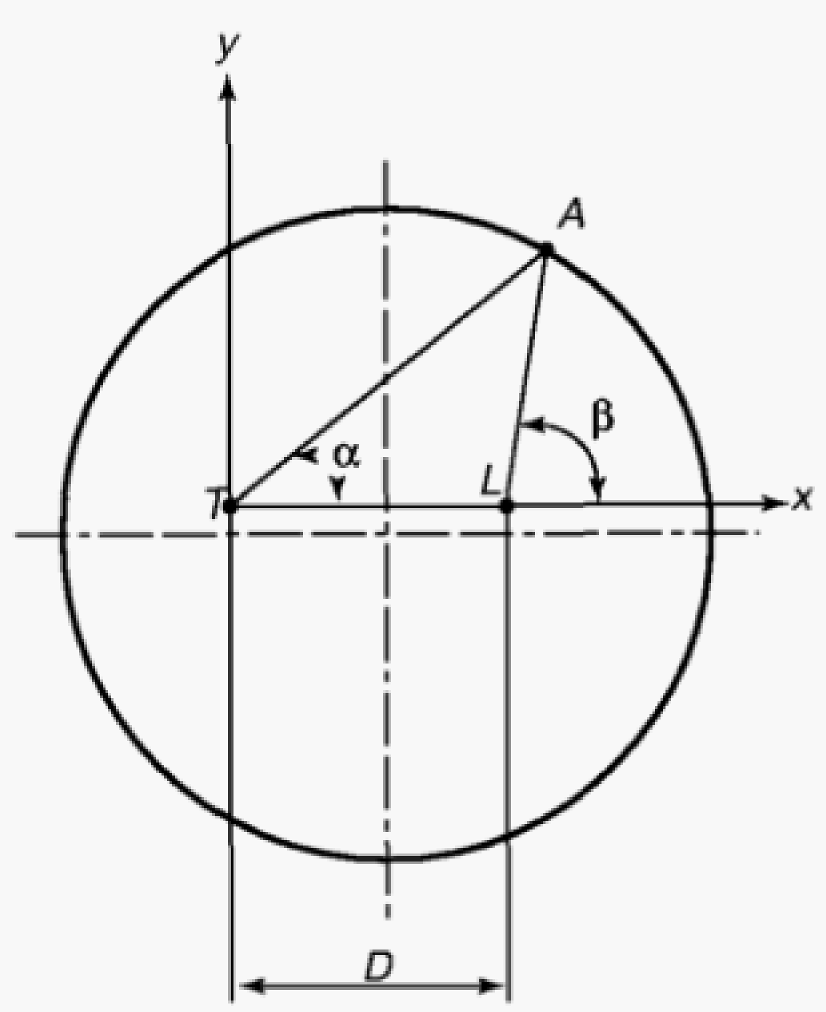


Figure 3—Location of Horizontal Sets of Points on Tank Wall



T = Theodolite station

L = Laser theodolite station

A = An observed point on the tank

Figure 4—Horizontal Angles Between Sightings on Points on Tank Wall and the Reference Axis *TL*

9.2 REFERENCE CIRCUMFERENCE MEASURED BY STRAPPING

9.2.1 Reference Circumference

Determine the reference circumference using the reference method described in Chapter 2.2A and in 9.2.1.2 to 9.2.1.6.

9.2.1.1 Take the measurement of the reference circumference prior to the commencement of the optical readings.

9.2.1.2 Take the measurement of the reference circumference at a position where work conditions allow reliable measurements. Strap the tank at one of the following levels:

a. $^1/_5$ to $^1/_4$ of the course height above the lower horizontal seam;

b. $^1/_5$ to $^1/_4$ of the course height below the upper horizontal seam and repeat the measurement to achieve agreement within the tolerances specified in 10.3.

Note: If worked out beforehand, the measurement of angles can assist in locating the positions in a and b above.

9.2.1.3 After completion of the optical readings, repeat the reference circumference measurement.

9.2.1.4 The measurements referred to in 9.2.1.2 and 9.2.1.4 shall agree within the tolerances specified in 10.3.

9.2.1.5 If agreement is not obtained, further measurements of the reference circumference shall be taken until two consecutive readings do so agree. Record the arithmetic mean of the two measurements as the reference circumference. If consecutive measurements do not agree, determine the reasons for the disagreement and repeat the calibration procedure.

9.2.2 THEODOLITE READINGS

9.2.2.1 Set up the optical theodolite outside the tank, as illustrated in Figure 5 and as described in 6.2. Station locations shall be determined so as to give equal representation around the tank. Increasing the number of stations can minimize any degree of bias to a particular region due to station location.

Note: Two additional stations beyond the minimum are recommended to accommodate any focusing of tangent sightings that may occur when selecting these locations.

The minimum number of stations, T_1, T_2, T_3, etc. per circumference shall be as given in Table 2.

9.2.2.2 From each station and for each level (see 9.2.2.3 and 9.2.2.4), make two sightings tangentially to the tank on either side of the theodolite as shown in Figure 5. Maintain the same vertical angle of the theodolite in both sightings.

Note: This will ensure that the intended targets on the tank are at the same level for a given circumference.

$T_1 \ldots T_8$ = Theodolite Stations

Record the horizontal angles subtended by the tangents at the theodolite.

9.2.2.3 For the reference level, make sightings at the level which the reference circumference was measured, see 9.2.1.

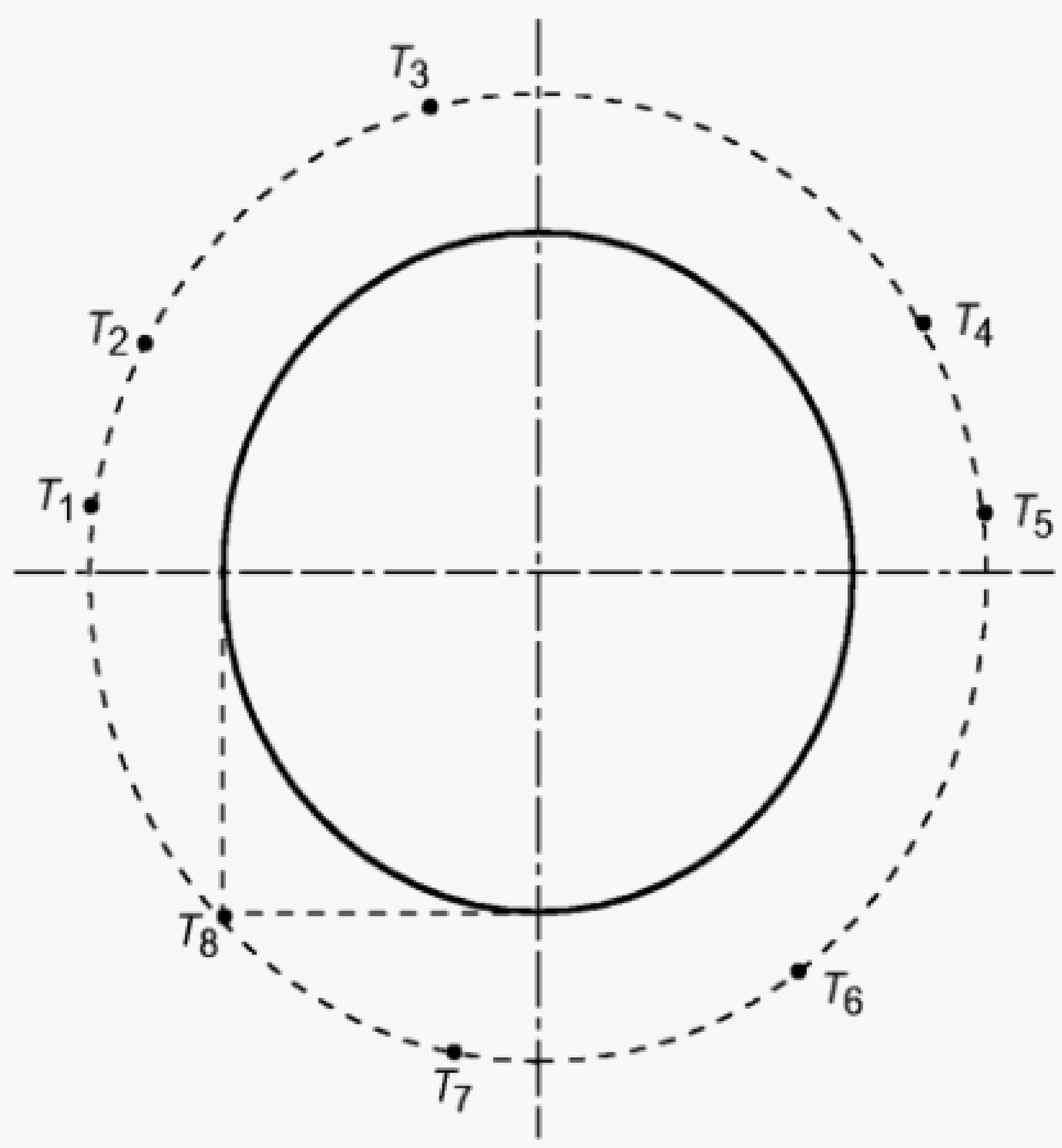
9.2.2.4 For each theodolite station, e.g., T_1; sight each of the courses at two levels, one at 1/5 to 1/4 of course height above the lower horizontal seam; the other at 1/5 to 1/4 of course height below the upper horizontal seam.

9.2.2.5 Move the theodolite from station T_1 to T_2 to T_3, etc., until the entire circumference is covered. Repeat all the described steps at each station, T_1, T_2, T_3, etc., for each level. The repeat readings of the horizontal angles recorded in 9.2.2.2 shall agree within the tolerances specified in 10.2 If they do not, repeat the measurements until two consecutive sets agree within this tolerance. Record the average horizontal angle for each of the points sighted.

9.3 REFERENCE DISTANCES MEASURED BETWEEN PAIRS OF THEODOLITE STATIONS

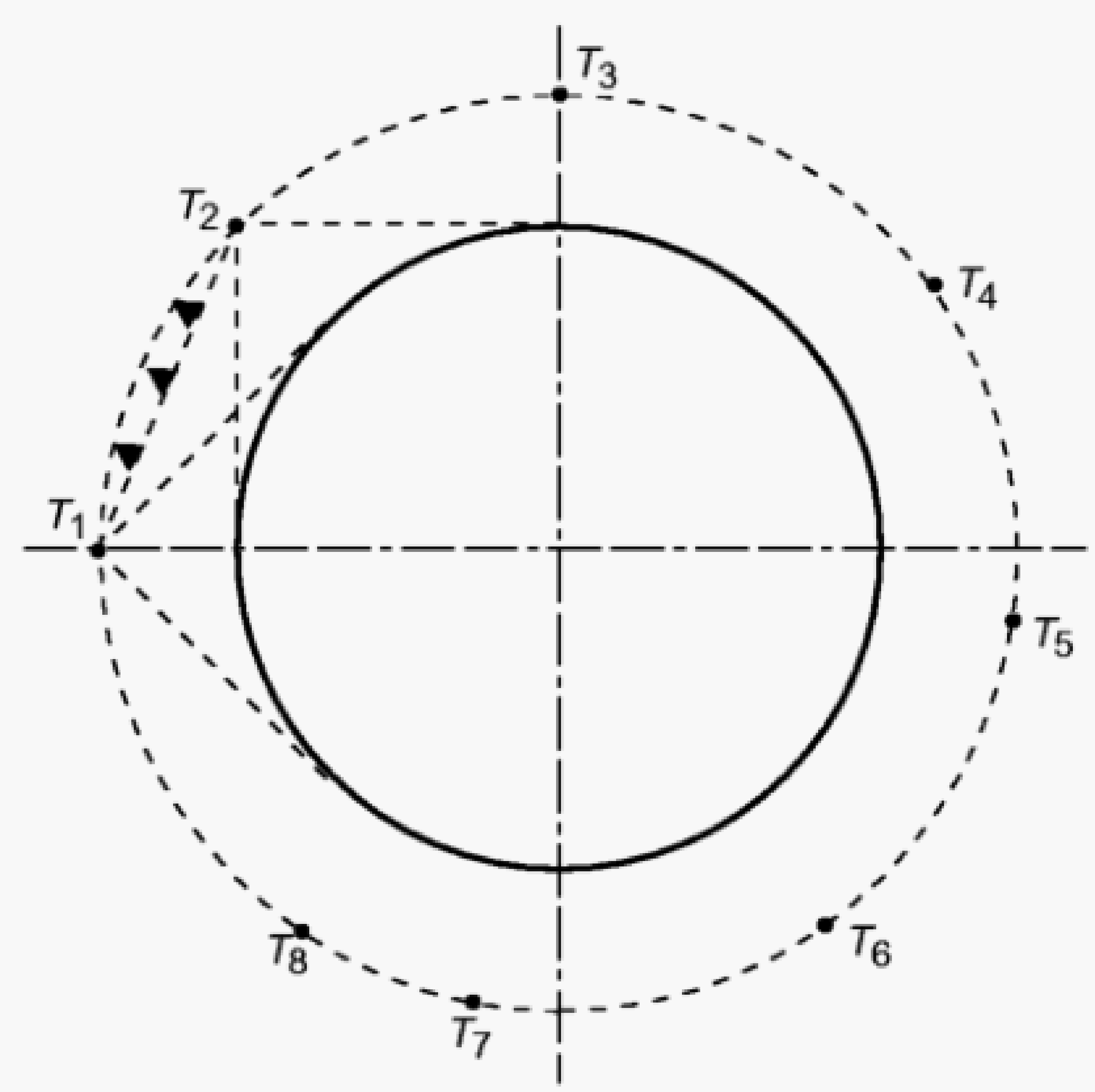
9.3.1 Set up the two theodolite stations outside the tank, Figure 6 for eight stations and as described in 6.2, using an optical theodolite, 5.5.1 and a second tripod. The minimum number of stations, T_1, T_2, etc., per circumference, shall be as referenced in Table 2.

9.3.2 Determine the horizontal distance T_1, T_2; between the two theodolite stations by using the stadia, $T_1T_2 = D$; with the stadia mounted on T_2 as described in 6.3.



$T_1 \ldots T_8$ = Theodolite stations

Figure 5—Example of Theodolite Station Locations for External Procedure Based on a Reference Circumference



$T_1 \ldots T_8$ = Theodolite stations

Figure 6—Example of Theodolite Station Locations for External Procedure Based on Reference Distances between Pairs of Tehodolites

Table 2— Minimum Number of Theodolite Stations for External Procedures

Circumference		Minimum Number of Points
Meters	Feet	
Up to 50	Up to 164	4
Above 50 up to 100	Above 164 to 328	6
Above 100 up to 150	Above 328 to 492	8
Above 150 up to 200	Above 492 to 656	10
Above 200 up to 250	Above 656 to 820	12
Above 250 up to 300	Above 820 to 894	15
Above 300	Above 894	18

9.3.3 From station T_1 sight the tank wall tangentially on either side, maintaining the same vertical angle of the theodolite for the two observations; record the horizontal angle subtended at the theodolite.

9.3.4 Leaving the tripod supports in the same position, interchange the stadia and the optical device, so that the stadia is at location T_1 and the theodolite is at location T_2.

Repeat the determinations described in 9.3.2 and 9.3.3.

9.3.5 The value for D obtained in 9.3.2 shall agree with that obtained in 9.3.4 within the tolerances given in 10.1. If agreement is not obtained, repeat the measurements, starting at station T_1, until two consecutive values do agree. Record the arithmetic mean of the two values as the horizontal distance T_1T_2.

9.3.6 Transfer the tripod set up at T_1 to T_3, leaving the tripod set up at T_2 in place. Apply the procedure in 9.3.2 to 9.3.4 for locations T_1 and T_2 to locations T_2 and T_3.

9.3.7 Continue the procedures outlined above for all subsequent stations around the circumference until station T_1 is reached again.

$T_1 1 \ldots T_8$ = Theodolite Stations

9.3.8 For each course, repeat the procedure described in 9.3.2 to 9.3.7 at two levels, one at 1/5 to 1/4 of the course height above the lower horizontal seam; the other at 1/5 to 1/4 of the course height below the upper horizontal seam.

10 Tolerances

10.1 DISTANCE BETWEEN THEODOLITES

The measurements of the distance D, between the two theodolite stations taken before and after other optical readings, shall not differ by more than the tolerances given in Table 3.

10.2 HORIZONTAL ANGLES

The repeated values for the measurement of horizontal angles using the theodolites shall not differ by more than 0.01 grades[2].

Table 3—Tolerance on Distance Between Theodolites

Distance	Tolerances	Distance	Tolerances
Meters	Millimeters	Feet	Inches
Up to 25	2	Up to 82	3/32
Above 25 and up to 50	4	Above 82 and up to 164	3/16
Above 50 and up to 100	6	Above 164 and up to 328	9/32

Table 4—Tolerance on Reference Circumference

Circumference	Tolerance	Circumference	Tolerance
Meters	Millimeters	Feet	Inches
Up to 25	2	Up to 82	3/32
Above 25 and up to 50	3	Above 82 and up to 164	5/32
Above 50 and up to 100	5	Above 164 and up to 328	1/4
Above 100 and up to 200	6	Above 328 and up to 656	9/32
Above 200	8	Above 656	3/8

10.3 REFERENCE CIRCUMFERENCE

The reference circumference measurements taken before and after the optical readings, see 9.2.1, shall not differ by more than the tolerances given in Table 4.

11 Other Measurements for Tank Calibration

11.1 TANK BOTTOM CALIBRATION

Calibrate the tank bottom by filling with measured quantities of a non-volatile liquid, preferably clean water, as specified in Appendix E, to a minimum level that covers the bottom completely, immersing the dip-plate and eliminating the effect of bottom deformations or, alternatively, calibration by physical survey using a reference plane to determine the shape of the bottom.

11.2 REFERENCE HEIGHT DETERMINATION

Measure the overall height of the reference point on each dip-hatch; upper reference point, above the dip-point, using the dip-tape and dip-weight as specified in Appendix F. Record this overall height to the nearest and smallest graduation mark of the dip-tape and permanently mark it on the tank adjacent to that dip-hatch.

If possible, compare measurements of the reference height with the corresponding dimensions shown on the drawings and investigate any discrepancies.

11.3 OTHER MEASUREMENTS AND DATA

11.3.1 Determine and process the following data as described in Chapter 2.2A.

a. Plate and paint thickness.

b. Height of the courses.

c. Density and working temperature of the liquid to be stored.

d. Maximum filling height.

e. Deadwood.

f. Number, width and thickness of any vertical welds or overlaps.

g. Tilt of the tank.

h. Shape—landing height and apparent mass in air of a floating roof or cover.

11.3.2 It is necessary to refer each tank dip to a dip-point, and this may be in a position different from the datum-point used for the purpose of tank calibration; e.g., a point on the bottom angle.

Determine any difference in level between the datum-point and dip-point, either by normal surveying methods or by other means; record it.

11.3.3 If possible, compare measurements with corresponding dimensions shown in the drawings and verify any measurement which shows a significant discrepancy.

12 Calculations and Development of Tank Capacity Tables

12.1 FROM INTERNAL PROCEDURE (CLAUSE 8)

Compute the internal radius of the tank by the procedures described in Appendices A and B for each level; i.e., two levels per course.

12.2 FROM REFERENCE CIRCUMFERENCE PROCEDURE (CLAUSE 9.2)

Compute the internal radius of the tank by the procedure described in Appendix C for each level; i.e., two levels per course.

12.3 FROM REFERENCE DISTANCES BETWEEN PAIRS OF THEODOLITES (CLAUSE 9.3)

Compute the internal radius of the tank by the procedure described in Appendix D for each level; i.e., two levels per course.

12.4 DEVELOPMENT OF TANK CAPACITY TABLE

The following corrections (described in Chapter 2.2A) shall be applied in the calculation of the Tank Capacity Table:

a. Paint and plate thickness.
b. Vertical seams, if lap-welded.
c. Hydrostatic-head effect during calibration.
d. Hydrostatic-head effect during service.
e. Expansion or contraction of the tank shell due to temperature effects.
f. Tilt of the tank.
g. Apparent mass in air of any floating roof or cover.
h. Deadwood.

12.4.1 Tank Capacity Table

Calculate the tank capacity and prepare the Tank Capacity Table as described in Chapter 2.2A.

APPENDIX A—COMPUTATION OF INTERNAL RADII FROM INTERNAL MEASUREMENTS

A.1 The coordinates (x,y) of a point A on the tank shell wall relative to a system of rectangular axes with center at T as shown in Figure 4 shall be determined from the following two equations:

$$y = x\tan\alpha \quad (2)$$

$$y = (x - D)\tan\beta \quad (3)$$

where

D = is the distance, in meters, between the theodolite stations (see 7.4),

α = is the horizontal angle between the point (i.e., A) on the shell wall and the x-axis at the theodolite station (see 8.12),

b = is the horizontal angle between the point (i.e., A) on the shell wall and the x-axis at the laser theodolite station (see 8.12).

From Equations 2 and 3.

$$x = \frac{D\tan\beta}{\tan\beta - \tan\alpha} \quad (4)$$

A.2 Using Equations 4 and 2, compute the coordinates (x,y) for all points under consideration. Report the following data for each level at which horizontal sets of points were selected (see 8.10):

Course 1:
$A_{1,1}(x,y)$, $A_{1,2}(x,y)$, ... $A_{1,n}(x,y)$
$A_{2,1}(x,y)$, $A_{2,2}(x,y)$,... $A_{2,n}(x,y)$

Course 2:
$A_{1,1}(x,y)$, $A_{1,2}(x,y)$,... $A_{1,n}(x,y)$
$A_{2,1}(x,y)$, $A_{2,2}(x,y)$,... $A_{2,n}(x,y)$

Course N:
$A_{1,1}(x,y)$, $A_{1,2}(x,y)$,... $A_{1,n}(x,y)$
$A_{2,1}(x,y)$, $A_{2,2}(x,y)$,... $A_{2,n}(x,y)$

A.3 Compute the radius for each level using the method described in Appendix B.

APPENDIX B—DETERMINATION OF THE RADIUS OF THE CIRCLE BY THE LEAST-SQUARES METHOD

B.1 Problem

To determine the radius of the circle that best fits the n points (x_i, y_i), where $i = 1, 2, \ldots n$, obtained from the calculation given in Appendix A.

B.2 Principle

The selected criterion for what is the best fit is that the sum of the squares of the distances from the points (x_i, y_i) to the circumference of the circle should be a minimum.

B.3 Theoretical Solution

Distance of point (x_i, y_i) from the circumference of the circle is:

$$[\sqrt{(x_i - a)^2 + (y_i - b)^2}] - r \qquad (5)$$

where (a, b) are the coordinates of the center point of the circle shown in Figure 7.

The sum of the squares of the distances from the n points to the circle is therefore:

$$\sum\{[(x_i - a)^2 + (y_i - b)^2] - r\}^2 \qquad (6)$$

The condition that this is a minimum leads to the following three equations in the three unknown values a, b, and r:

$$na = [\sum x_i] - [r\sum(x_i - a)/r_i] \qquad (7)$$

$$nb = [\sum y_i] - [r\sum(y_i - b)/r_i] \qquad (8)$$

$$nr = \sum r_i \qquad (9)$$

where

$$r_i = \sqrt{(x_i - a)^2 + (y_i - b)^2} \qquad (10)$$

B.4 Calculations

Equations 7, 8 and 9 may be solved by any method. A suggested method for solving these three equations is as follows:

Step 1: Set a, b, and r to zero.

Step 2: Calculate the n values r_i from Equation 10.

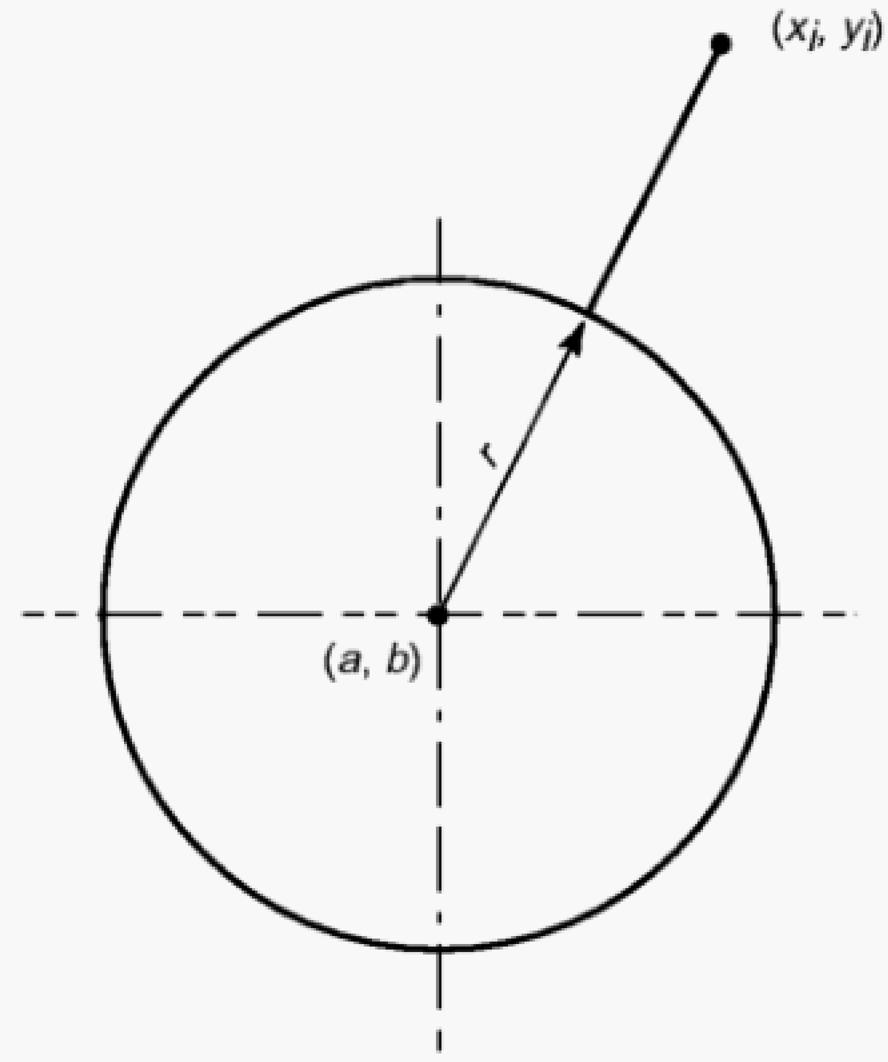


Figure 7—Circle and Coordinates

Step 3: If any of these are zero, replace them by a value of one millimeter (this is to avoid division by zero in the next step).

Step 4: Calculate the new values of a, b and r from Equations 11, 12 and 13 below:

New value of a =

$$[\sum x_i - r\sum(x_i - a)/r_i] \times 1/n \qquad (11)$$

New value of b =

$$[\sum y_i - r\sum(y_i - b)/r_i] \times 1/n \qquad (12)$$

New value of r =

$$r = [\sum r_i] \times 1/n \qquad (13)$$

Step 5: If the new value of r differs from the old value by more than 0.01 mm, replace the old values of a, b and r by the new values and go back to Step 2, otherwise go to Step 6.

Step 6: Round the new value of r to the nearest millimeter as the internal radius for the set of points.

If any other irerative method is used, the intention specified in Step 5, that two successive estimates of r shall differ by no more than 0.01 mm, shall apply.

B.5 Example

B.5.1 DATA

Suppose that the distance D = 15 120 mm and that, at one level, the angles α and β for twelve points on the tank wall for the internal method (see Clause 8) are as shown in Table 5.

Table 5—Data for Example

Point	α grade	β grade
1	24,232 5	60,925 3
2	44,469 4	94,518 8
3	62,808 5	116,561 6
4	82,977 9	136,219 3
5	112,243 4	158,929 9
6	153,578 9	181,888 2
7	247,466 9	217,230 4
8	283,056 2	234,097 1
9	313,856 0	254,419 7
10	345,536 1	285,315 7
11	367,290 3	317,364 3
12	387,338 9	362,361 6

B.5.2 SOLUTION

Calculate coordinates (x,y) for each point as described in Appendix A. The coordinates are shown in Table 6.

Table 6—Calculated Coordinates

Point	x mm	y mm
1	21 057	8 426
2	16 302	13 690
3	10 780	16 304
4	4 535	16 553
5	– 2 596	13 332
6	– 7 357	6 573
7	– 6 495	– 5 997
8	– 2 918	– 10 705
9	3 065	– 13 857
10	11 903	– 13 701
11	17 954	– 10 133
12	21 607	– 4 355

Determine the radius of the best circle, using the least-squares method described in B.3. For the specific example, the radius of the best circle, attained in twelve iterations as shown in Table 7, is 15 558 mm.

Table 7—Solution by Iteration

a mm	b mm	r mm
7 319,613 00	1 344,201 40	16 588,195 00
7 260,352 00	1,239,155 30	15 556,129 00
7 231,926 00	1 200,982 90	15 557,207 00
7 216,363 00	1 184,816 90	15 557,754 00
7 207,766 00	1 178,017 60	15 558,039 00
7 202,992 00	1 175,185 50	15 558,242 00
7 200,328 00	1 174,022 00	15 558,270 00
7 198,836 00	1 173,554 20	15 558,285 00
7 198,000 00	1 173,372 10	15 558,285 00
7 197,523 00	1 173,204 90	15 558,297 00
7 197,258 00	1 173,282 50	15 558,305 00
7 197,109 00	1 173,276 40	15 558,301 00

APPENDIX C—COMPUTATION OF INTERNAL RADII FROM REFERENCE CIRCUMFERENCE AND EXTERNAL MEASUREMENTS

C.1 The horizontal distance T_0 in Figure 8 is constant for all levels at which measurements were taken on the tank. Compute its value from the reference circumference using the equation:

$$T_0 = \frac{C}{2\pi} \times \frac{1}{\sin\phi_1}$$

where

C = the reference circumference as determined in 9.2.1,

2ϕ = the horizontal angle subtended at the theodolite for the reference level as determined in 9.2.2.3.

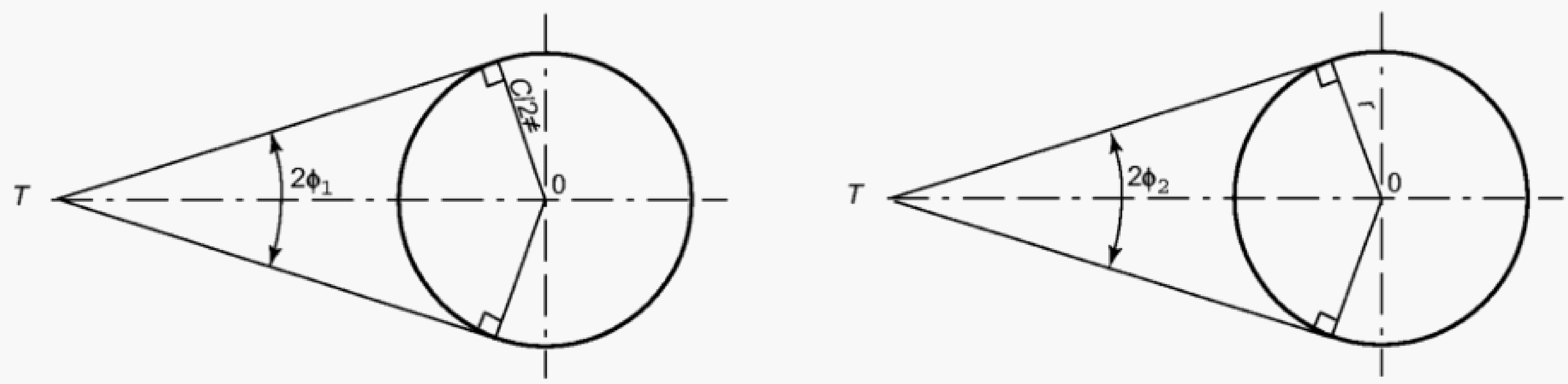
C.2 If r is the external radius at any other level and the corresponding horizontal angle at the theodolite station T is $2\phi_2$ (see 9.2.2.2), then since the distance T_0 is constant,

$$\frac{C}{2\pi} \times \frac{1}{\sin\phi_1} = \frac{R}{\sin\phi_2}$$

$$r = \frac{C}{2\pi} \times \frac{\sin\phi_2}{\sin\phi_1}$$

Calculate the external radius for each of the other theodolite positions in the same way.

C.3 Take the external radius at each level to be the average of the individual radii calculated for that level. Subtract the thickness of the plate and paint (see 11.3.1) to give the corresponding internal radius.



a) A_1 at reference level

b) A_1 at another level

Figure 8—Radii from Reference Circumference

APPENDIX D—COMPUTATION OF INTERNAL RADII FROM REFERENCE DISTANCES BETWEEN PAIRS OF THEODOLITE STATIONS

D.1 The following field measurements, illustrated in Figure 9, are recorded for each set of readings for adjacent theodolite stations (see 9.3):

$T_1T_2 =$ the distance, in meters, between the theodolite stations T_1 and T_2 (9.3.5),

$2\theta_1 =$ the horizontal angle, in grades, subtended by the tangents T_1A and T_1D at theodolite station T_1 (9.3.3),

$2\theta_2 =$ the horizontal angle, in grades, between the tangents T_2B and T_2C,

$\alpha =$ the horizontal angle, in grades, between the tangents T_1A and the line T_1T_2,

$\beta =$ the horizontal angle, in grades, between the tangent T_2C and the T_1T_2.

D.2 To calculate the external radii at points A, B, C and D, it is assumed that $0A = 0D = r_1$ and $0B = 0C = r_2$. Calculate the values of r_1 and r_2, in meters, from Equations 14 and 15, which are derived as follows:

Angle $0T_1T_2 = \alpha + \theta_1$
Angle $0T_1T_2 = \beta + \theta_1$
Angle $T_20T_1 = \pi$ - Angle $0T_1T_2$ – Angle $0T_2T_1$
$= \pi - [\alpha + \beta + \theta_1 + \theta_2] = \phi$
From triangle $0T_1T_2$ using sine rule

$$\frac{T_1T_2}{\sin(T_20T_1)} = \frac{0T_2}{\sin(0T_1T_2)} = \frac{0T_1}{\sin(0T_2T_1)}$$

$$0T_2 = \frac{\sin(\alpha + \theta_1)}{\sin\phi} \times T_1T_2$$

$$0\mathrm{T}_1 = \frac{\sin(\beta + \theta_2)}{\sin\phi} \times \mathrm{T}_1\mathrm{T}_2$$

External radius $r_2 = 0B = 0C$

$$= 0T_2 \sin\theta_2$$

$$= T_1T_2 \sin\theta_2 \left[\frac{\sin(\alpha + \theta_1)}{\sin\phi}\right] \qquad (14)$$

External radius $r_1 = 0A = 0D$

$$= 0T_1 \sin\theta_1$$

$$= T_1T_2 \sin\theta_1 \left[\frac{\sin(\beta + \theta_2)}{\sin\phi}\right] \qquad (15)$$

D.3 Calculate r_1 and r_2 for each of the other pairs of theodolite stations around the tank and at each level. Subtract the thickness of the plate and paint (see 11.3.1) to give the corresponding internal radii.

Take the internal radius for each tank level to be the average of the individual radii calculated for that level.

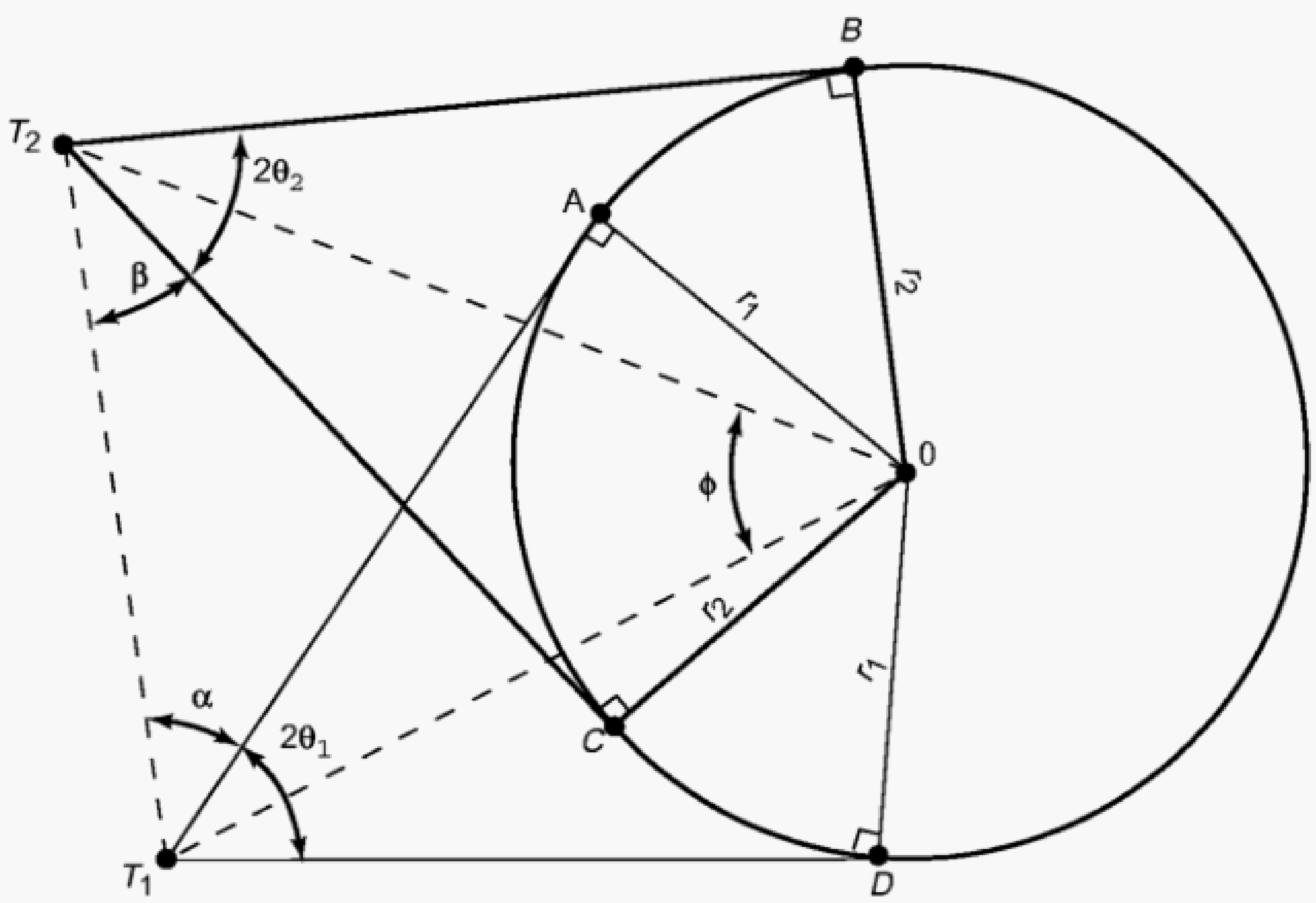


Figure 9—External Radii from Reference Distances between Pairs of Theodolite Stations

APPENDIX E—METHOD FOR CALIBRATING BOTTOMS OF TANKS

E.1 Principle

Bottoms of tanks are calibrated by the introduction into the tank of quantities of water or another nonvolatile liquid, which have been accurately measured, until both the dipping datum-point and the highest point of the tank bottom have been covered.

E.2 Equipment

E.2.1 Meter, either having a known meter factor or with an appropriate means of proving being available on site.

E.2.2 Liquid-tight piping, of suitable length to convey the liquid from its source to the meter and thence to the tank.

E.2.3 Dip-tape and dip-weight, as specific in F.1 and F.2.

E.3 Procedure

E.3.1 Set up the meter (E.2.1) on site and connect it to the calibration-liquid source using the liquid-tight piping (E.2.2). If the meter is to be proved on site, prove it by using an appropriate method, with the liquid to be used in the calibration of the tank, before commencing the tank calibration.

E.3.2 Introduce the liquid into the tank bottom until the liquid just covers the dip-point, ensuring that the piping between the meter and the tank bottom is filled before first delivery. Note, from the meter reading, the volume of liquid transferred to the tank, to obtain the volume of the tank below the datum-point.

E.3.3 Transfer further measured quantities of liquid into the tank until either the highest point of the tank bottom is covered or the liquid level is higher than the lowest point on the tank that will be calibrated by strapping. On completion of the transfer of each measured quantity of liquid, measure the liquid level using the dip-tape and dip-weight (E.2.3).

Note: Suitable water- or oil-finding pastes may be of assistance in determining exact liquid levels.

Record the volumes of liquid introduced and the liquid level measurements.

On completion of the calibration, ensure that the piping between the meter and the tank bottom is full of liquid.

E.3.4 After calibration of the tank bottom, re-prove the meter. If the meter factor has changed such that the volume of the tank bottom would differ by more than 0.3%, eliminate the cause of the variation and repeat the tank bottom calibration.

If the meter factor has changed but not sufficiently for the volume of the tank bottom to differ by more than 0.3%, take the average of the two meter factors and use the average figure in determining the volumes of liquid introduced into the tank.

E.4 Expression of results

After completing the calibration of the tank bottom, introduce the results into the final calculation of the tank capacity table as described in ISO 7507-1 (see 12.4.2).

APPENDIX F—SPECIFICATION FOR DIP-TAPE AND DIP WEIGHT

F.1 Dip-tape

F.1.1 The dip-tape shall be made of high-carbon steel having a carbon content of between 0.7% (m/m) and 1.0% (m/m).

12.4.2 The tape shall have a tensile strength of between 1 600 Nm^{-2} and 1 850 Nm^{-2} and a coefficient of thermal expansion of $(11 \pm 1) \times 10^{-6}\ °C^{-1}$.

F.1.2 The tape shall have been calibrated at 20°C and under an applied tension of 15 N. The calibration conditions shall be marked on the tape at or near the zero end of the tape.

F.1.3 The graduations shall be accurate to within 1,5 mm in each 30 m length when the tape is fully supported on a flat surface at 20°C and subjected to a pull of 15 N.

F.1.4 The tape shall be in one continuous length and graduated on one face only. The tape shall be graduated at intervals of one meter and also at intervals of one decimeter, centimeter and millimeter.

The length of the graduations shall be as follows:

a. At each meter, across the full width of the tape.

b. At each decimeter, across the full width of the tape.

c. At each centimeter, across two-thirds of the full width of the tape.

d. At each fifth millimeter, across one-half of the full width of the tape.

e. At each millimeter, other than each fifth millimeter, across one-third of the full width of the tape.

The distance from the zero mark shall be marked at every meter, on a bright tablet, at every centimeter and at every decimeter. The size of the numbers used to denote the decimeter graduations shall be larger than those used to denote the centimeter graduations.

F.1.5 A swivel hook shall be permanently secured (e.g., by means of riveting) to the front end of the tape to allow the attachment of a dip-weight. The hook shall be such that it will not distort in use and shall be equipped with a device to prevent accidental decoupling of the dip-weight.

Note: Hooks made of brass are preferred.

F.1.6 The tape shall not be varnished or otherwise treated such that it becomes electrically insulated.

Note: The tape should preferably be coated to protect against corrosion during storage.

F.2 The tape shall be wound on to a winding frame made of brass, with a wooden winding handle.

F.3 Dip-weight

Note: The dip-weight is intended to be used in conjunction with and form an integral part of the dip-tape (F.1).

F.3.1 The dip-weight shall be made of brass or another non-spark-producing material of similar density.

F.3.2 The weight shall have a hole drilled into its top lug. The hole shall have a variable diameter dimensioned to accommodate the swivel hook (see F.1.5). When attached to the dip-tape, the weight and tape shall provide a continuous length-measuring device.

Note: The bottom and top sections of the weight should preferably be chamfered. The bottom flat should preferably be approximately 13 mm in diameter.

F.3.3 If the weight is manufactured with a flat face on one side and if this face is graduated at intervals of one centimeter and one millimeter, the graduation marks at each centimeter shall be longer than those at each millimeter and shall be numbered.

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