INTERNATIONAL STANDARD

ISO 12917-1

Second edition
2017-03

Petroleum and liquid petroleum products — Calibration of horizontal cylindrical tanks —

Part 1:
Manual methods

Pétrole et produits pétroliers liquides — Jaugeage des réservoirs cylindriques horizontaux —

Partie 1: Méthodes manuelles

Reference number
ISO 12917-1:2017(E)

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 28, *Petroleum products and lubricants*, Subcommittee SC 2, *Measurement of petroleum and related products*.

This second edition cancels and replaces the first edition (ISO 12917-1:2002), which has been technically revised with the following changes.

— The total length of the tanks has been limited and also only the calibration via ISO 7507-1 is described in order to improve precision.

— Most of the figures have been improved in order to further clarify the measurement procedures. These, in turn, have been described more logically and in a more useful order. For instance, tank shell measurements are no longer described separately and the former Annex on "tilt" has been incorporated in the text.

— A new annex on calibration uncertainties has been added.

— Correction for tank tilt is now calculated rather than read from a figure.

It also incorporates the Technical Corrigendum ISO 12917-1:2002/Cor 1:2009.

A list of parts in the ISO 12917 series can be found on the ISO website.

Introduction

This document forms part of a series on tank calibration methods. In some countries, some or all of the items covered by this document are subject to local regulations. The attention of the user is drawn to the fact that it is possible that differences exist between this document and those regulations.

Petroleum and liquid petroleum products — Calibration of horizontal cylindrical tanks —

Part 1:
Manual methods

1 Scope

This document specifies manual methods for the calibration of nominally horizontal cylindrical tanks, installed at fixed locations.

The methods in this document are applicable to insulated and non-insulated tanks, either when they are above-ground or underground. The methods are applicable to pressurized tanks and to both knuckle-dish-end and flat-end cylindrical tanks as well as elliptical and spherical head tanks.

This document is applicable to tanks inclined from the horizontal, provided a correction is applied for the measured tilt.

Although this document does not impose any limits on the maximum tank diameter and maximum tank tilt to which this document is applicable, the practical limits would be about 4 m in diameter and 10° in tilt.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7507-1:2001, *Petroleum and liquid petroleum products — Calibration of vertical cylindrical tanks — Part 1: Strapping method*

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

4 Precautions

4.1 General

The general and safety precautions specified in ISO 7507-1 shall be applied.

4.2 Internal method

Before a tank which is to be calibrated is entered, a safe-entry certificate shall be obtained. All lines entering the tank shall be disconnected and blanked.

NOTE The attention of the user is drawn to the possible existence of local regulations regarding the safe-entry certificate and entry into tanks, which have contained leaded fuels.

4.3 External method

NOTE The attention of the user is drawn to the possible existence of local regulations regarding entry to the tank area.

5 Equipment

5.1 Equipment as used in ISO 7507-1

Equipment used in the calibration of horizontal tanks shall conform to the specifications laid down in ISO 7507-1. All equipment shall be traceable to a reference standard.

NOTE The equipment required to carry out the calibration is dependent on the method to be employed. This document uses techniques and equipment described in ISO 7507-1.

5.2 Telescopic rod

For the internal method, in addition to the equipment mentioned in 5.1, a telescopic rod may be used. This telescopic rod shall have a scale capable of being read to 1 mm, and shall be calibrated with an uncertainty of less than 1 mm.

5.3 Distance meter

For the internal method, as an alternative to a telescopic rod, a laser-based distance meter may be used. The distance meter may also be used in measurement of tank tilt. This distance meter shall have a scale capable of being read to 1 mm, and shall be calibrated with an uncertainty of less than 1 mm.

5.4 Leveller

Level-measuring instrument used to determine vertical distances between pairs of points. It can be based on either mechanical or optical measurements.

Example Rotating optical/laser instrument that establishes horizontal reference line/plane, with a mechanical height-measuring device.

6 General requirements

6.1 The tank shall be filled to its normal working capacity and working pressure at least once and allowed to stand while full for at least 24 h prior to emptying and preparing it for calibration.

NOTE The hydrostatic test applied to new or repaired tanks will satisfy this requirement when additional pressure tests have been carried out.

6.2 The following parameters shall be determined:

— tilt;

— deadwood;

— temperature;

— pressure;

— position of gauge point, reference height and height of the dip plate, if there is one.

7 Calibration procedures

7.1 General

The calibration procedures for calibration of horizontal cylindrical tanks shall be performed as specified in 7.2 (external measurements) and 7.3 (internal measurements). The remainder of Clause 7 applies to both external and internal measurements.

For both methods, measurements shall be taken at around 1/4 and 3/4 of the length of each segment in accordance with Figure 1.

7.2 Measurement of circumferences — External

7.2.1 Introduction

External measurements may be executed with any depth of liquid and liquid pressure in the tank. The temperature and pressure of the liquid at the time of calibration shall be recorded.

7.2.2 General

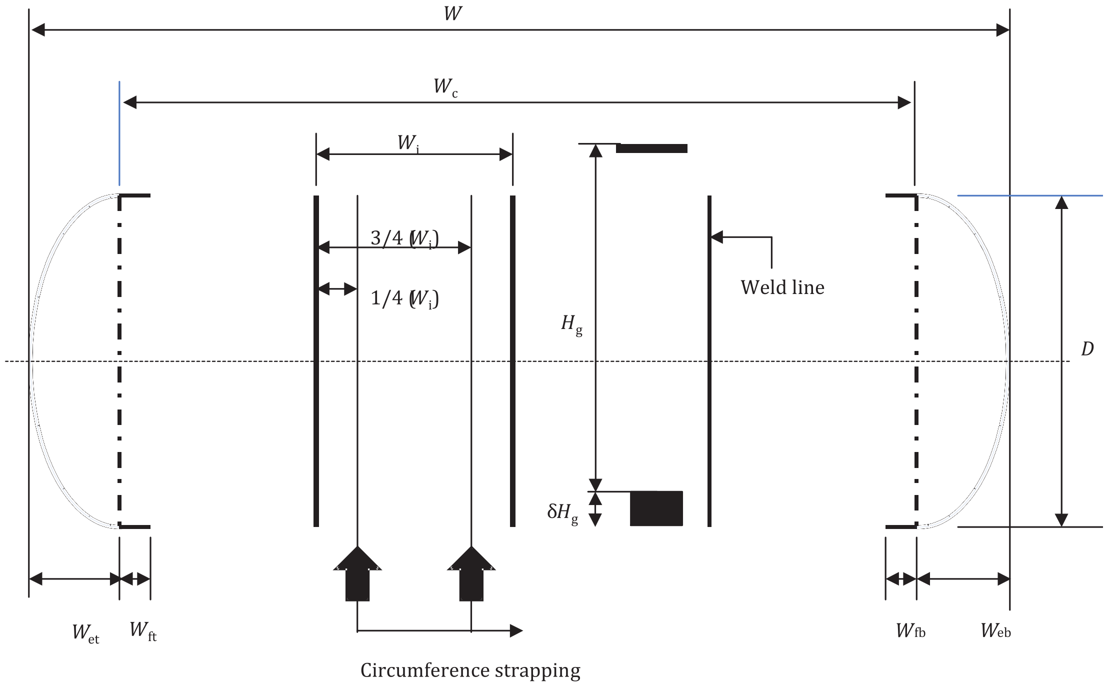
For the measurement procedures, a circumferential tape of sufficient length to completely encircle the tank should be used and measurements of the total circumference shall be taken.

a) In all cases, the tape to be used should be applied to the tank surface at the prescribed locations by the wraparound procedure; i.e. the required length of tape should be applied in a slack condition, positioned, and tightened by the application of the proper tension.

As indicated in Figure 1, strapping should be undertaken around 1/4 and 3/4 of the segment length.

b) In the case in which the circumferential measuring tape is in contact with the tank surface at all points along its path, circumferential measurements should be made and checked in accordance with the relevant procedure given in ISO 7507-1.

c) If the circumferential measuring tape is not in contact with the tank surface, corrections should be made for individual obstructions as specified in ISO 7507-1.



Key

D tank diameter

δH_g dip plate height

H_g reference (gauge) height

W_c cylinder length

W_i segment length

W_{ft} straight flange length (top of tank)

W_{fb} straight flange length (bottom of tank)

W_{et} head length (top of tank)

W_{eb} head length (bottom of tank)

W total tank length

Figure 1 — Measurements of the diameters/circumferences

7.2.3 Repetition of measurements

After the circumference has been measured, the tension shall be released and the tape brought again to the required level and tension. The readings shall then be repeated and recorded.

Take multiple measurements of the circumference. Investigate and, if necessary, remove the perceived outliers. If the first three consecutive measurements agree within ±3 mm, take their average as the circumference and their standard deviation as the standard uncertainty. If they do not agree within this tolerance, repeat the measurements until two standard deviations of the mean of all measurements is less than the half of this tolerance. Use the average as the measured circumference and the standard deviation as the standard uncertainty.

7.3 Measurement of circumferences — Internal

7.3.1 Overview

Internal measurements shall be performed with the tank empty, at ambient temperature and with no pressure in the tank. In-tank temperature at the time of calibration shall be recorded. There is no need to do pressure recording or corrections unless the reference conditions for the tank require it.

7.3.2 General

For the measurement procedures, a telescopic rod (5.2) of sufficient length to completely measure the internal diameter of the tank or the distance meter (5.3) shall be used.

NOTE Distance meter is normally preferable for tanks with diameters exceeding 3 m.

The telescopic rod or the distance meter shall be applied to the tank at the prescribed locations, at four positions, equally divided around the circumference in accordance with Figure 2. The telescopic rod should be at a 90° angle at each touch point. The average of these four measurements shall be recorded as diameter at this particular location within this particular segment. Care should be taken to ensure that the measured diameter is indeed the minimum value in longitudinal direction and maximum value in circumferential direction.

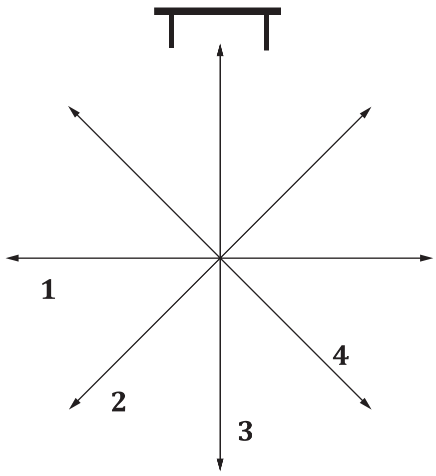


Figure 2 — Internal measurements of diameters

7.4 Measurements of lengths

7.4.1 Method

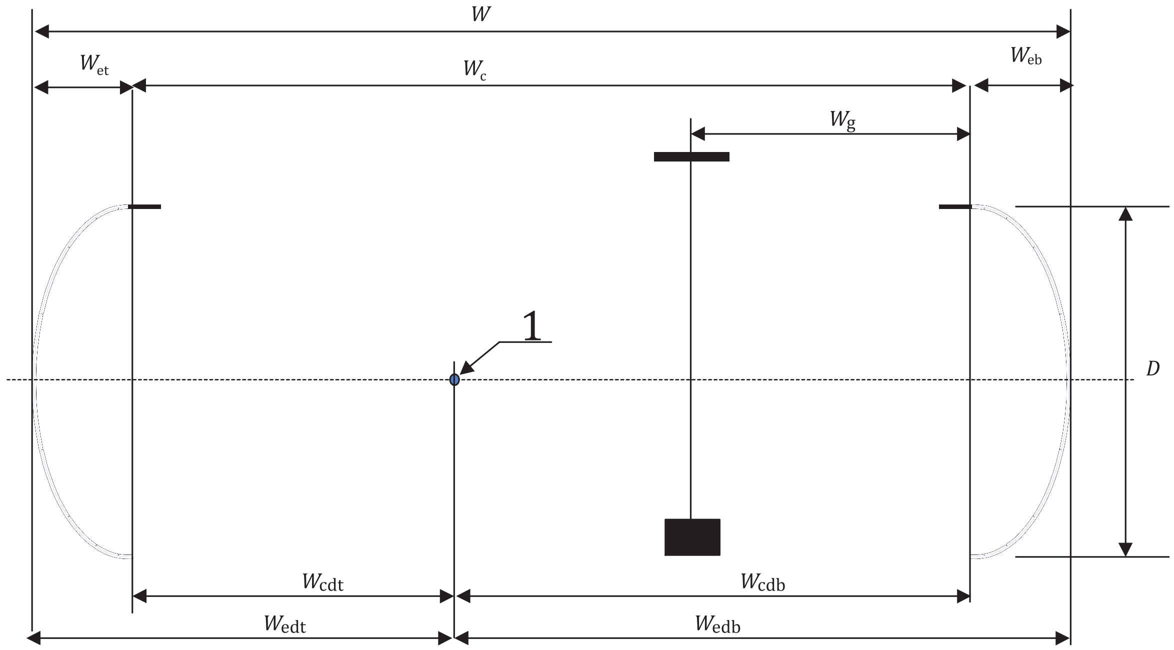
Distance between a single reference point and the extreme points of tank body as well as those of both heads shall be measured in accordance with Figure 3.

NOTE These measurements can be performed using a tape or distance meter, with help of a line or ruler.

The reference point may be anywhere on the body of the tank. Its preferred location is on one of the welds joining the ends to the body of the tank, providing that there are no obstacles.

Repeat all measurements until two consecutive readings agree within a tolerance of ±3 mm.

Considering the uncertain width and location of the welds, the measurements of length should preferably be done to points made on the shell, on or close to the welds.



Key

1 reference
D tank diameter
W_c cylinder length
W_{eb} bottom end length
W_{cdb} bottom cylinder distance
W_{cdt} top cylinder distance
W_{edb} bottom end distance
W_{edt} top end distance
W_{et} top end length
W_{tot} total tank length
W_g gauge length

Figure 3 — Measurements of the lengths

7.4.2 Length of horizontal cylinder

The length of the horizontal tank (cylindrical part) is measured between the extreme welds of the extreme segments (knuckle welds) at two locations at opposite sides of the tank, preferably where there are no obstructions (see Figure 3). Take multiple measurements at each location using measuring tape or distance meter. If the first three consecutive measurements agree within ±3 mm, take their average as the tank length and their standard deviation as the standard uncertainty. If they do not agree within this tolerance, repeat the measurements until two standard deviations of the mean of all measurements is less than the half of this tolerance. Use the average as the measured tank length and the standard deviation as its standard uncertainty.

7.4.3 Lengths of segments

The measurements may be done internally or externally.

Lengths of the individual segments shall be measured between their respective welds at 2 points and taking the average of the two measurements (see Figure 1). If the measurements agree within

±2 mm, take their average as the length of the segment and their standard deviation as the standard uncertainty. If they do not agree within this tolerance, repeat the measurements until they do.

Lengths of the straight flanges connecting the extreme segments to the heads should be measured the same way.

Compare the sum of lengths of all segments including the straight flanges to the total length of the tank and modify length of all segments by their ratio so that the sum of the lengths of the segments is the same as the length of the tank.

7.4.4 Lengths of heads

Length of each head shall be measured as distance between the end plane (mark at the end weld of the cylinder) and the end point of the head (see Figure 3).

7.4.5 Gauge lengths

Gauge length is not measured but defined by the calibrator within the limits of the upper and lower ends of the gauge hatch (see Figure 3).

7.4.6 Measurement/calculations of radii of the heads

To measure the radii using traditional means is difficult and errors (in cm) may result. The tank heads are usually made using pre-manufactured forms, resulting in well-defined and repetitive shapes.

Head radii should be preferably obtained from manufacturer's drawings. If these are not available, other methods should be used.

— Using a theodolite to produce a three-dimensional shape of the head could be the best option.

— The radii of the heads can be determined from the measured lengths in combination with diameters of the extreme segments of the tank body, using the existing manufacturers' standards.

— There are national standards that define the radii of knuckle and dish for the given radius of the tank body. The standard, which the tank end complies with, can be determined by comparing its shape to pre-fabricated templates that conform to the standard. Once this is done, the radii can be read from tables within the standard for the given length of the head and tank diameter. Relevant standards are NF E 81-100 to 104 (French), SMS 483 and 486 (Swedish) and NEN 3350 (Dutch).

Radii of the knuckle are regarded as impossible to measure. They should be obtained from manufacturer's drawings.

NOTE Variations in head radii have very little impact on the measured volumes.

7.5 Tank tilt

If the tank segments vary in diameter and in the alignment of their vertical axes, the tilt should be measured and calculated from multiple measurements of vertical distances from horizontal reference line(s) to the points at the top and/or bottom of the tank. There should be one point in each segment of the tank. If points at both the top and the bottom of the tank are measured, the tilt angle should be calculated as an average of the slopes of fitted straight lines. If points at only one side of the tank (either top or bottom) are measured, the tilt angle should be calculated from the slope of the fitted straight line.

The same method should be used even if the diameters of the segments are regarded as (nearly) identical in order to avoid any unnecessary errors.

A leveller may be used to determine the tilt of the tank by measuring the differences in vertical heights to one or two chosen horizontal reference lines at a number of selected points.

Refer to 10.2.2.3 for a detailed description of the method.

NOTE "top" and "bottom" refer to the ends of the tank that are the highest and lowest positions on the tilted tank. On tanks with no tilt, either end could be "top" or "bottom".

7.6 Plate thickness

The plate thickness shall either be measured for each segment, whenever possible, or taken from the manufacturer's drawings. The plate thickness for each segment shall be recorded to the nearest 0,5 mm. Physical measurements are preferred to readings from drawings.

Normal procedure is to measure two points per segment in any location. Modern ultrasonic instruments can distinguish between metal and paint. If these are not available, the paint shall be scraped off prior to the measurement.

NOTE The thickness of metal is required for pressure correction; combined thickness (metal and paint) is used to calculate internal diameters from external measurements.

7.7 Reference height

Measure the overall height at the reference gauge hatch. If there is a dip plate (datum plate), its height above the bottom of the tank should also be measured in accordance with ISO 7507-1.

7.8 Deadwood

The dimensions and locations of the deadwood shall be measured, whenever possible, or taken from the drawings and the heights of the lowest and highest point of such deadwood measured in relation to the datum point of the tank. The measurements shall be recorded to the nearest 10 mm.

7.9 Measurements of temperature and pressure

Temperature of the tank shell and pressure within the tank shall be used to correct the calculated volume between the calibration and reference conditions.

NOTE Similar corrections are also done between the reference and operating conditions, but these are not the subjects of this document.

Temperature readings should be taken at a minimum of 10 well-distributed points around the tank shell. The temperature of the tank shell should be calculated as the average of these multiple measurements.

If the tank is under pressure when it is being calibrated, the pressure should be measured using the existing pressure gauge.

Corrections to the volume of horizontal cylindrical tanks due to liquid head may be ignored as the effect is minimal due to the limited dimensions, and hence hydrostatic pressures, of tanks of this type.

8 Re-calibration

Tanks shall be re-calibrated whenever the calibration becomes suspect or the tank becomes physically deformed.

Example For example, due to movement of the tank foundations, or as required by national regulations.

If new equipment affecting deadwood volume is fitted or deadwood is removed, the tank calibration table shall be recalculated. If a bigger opening is required in the process, the tank shall be recalibrated.

9 Descriptive data

Descriptive data should be entered on the tank calibration record. It should contain tank description (independent of tank calibration). These would normally include sketches, each completely identified, dated and signed, that show the following:

a) tank number and product ID;

b) location, lengths and thicknesses of segments from which the tank is assembled;

c) number and size of plates per segment;

d) typical vertical and circumferential welding seams;

e) arrangements and sizes of nozzles and manways;

f) locations and sizes of dents and bulges in shell plates, if there are any.

NOTE Further details of the above can be found in ISO 7507-1:2001, Annex D.

Data related to tank calibration that shows the following:

— date of calibration;

— identification of standard used for calibration (e.g. ISO 12917-1);

— method used in bypassing (or correcting for) an obstruction in the path of a circumferential measurement;

— location of the tape path if it is different from that required by this document;

— average tank diameter and corresponding volume of full tank;

— lengths of the tank body and the tank ends;

— tilt angle in degrees or radians;

— location (length from the lowest edge of the tank body) of reference (gauge) point;

— measured value of elevation of dip plate, if there is any;

— measured value of height of the reference point above the dip point (reference height);

— product level and density, pressure and shell temperature when the tank is calibrated;

— pressure and ambient temperature at reference conditions (at which the calibration table is presented);

— type of gauge (innage or ullage) and its direction of measurement (vertical or aligned with the tank ends);

— total measurable level;

— detailed tank calibration table (volume as function of gauged level);

— signature/seal of the certifying authority.

10 Computation of tank capacity table

10.1 General rules

10.1.1 The calculation methods given below lay down minimum requirements for precision, but it is permissible to use alternative procedures, which produce a final tank capacity table of similar or greater precision. Annex A gives a more complex (and more accurate) method of calculating volume. Refer to 10.2 and A.1.2 for an aid in making a decision about which calculation method should be used.

Unless otherwise specified, volume shall be expressed with an accuracy of five significant digits.

10.1.2 Tank capacity tables prepared in accordance with the recommendations set out below shall bear the words “Calibrated by the External/Internal Manual Method in accordance with ISO 12917-1.” Numerical resolution should relate to estimated uncertainties. Reference to GUM should be added.

10.1.3 The standard temperature and standard pressure, for which the tank capacity table has been calculated, shall be recorded at the head of the table.

10.1.4 All deadwood shall be accurately described giving its volume and location, in order to provide adequate allowance for the volume of liquid displaced by the various items and to provide for best estimates of the effects at various elevations within the tank.

10.1.5 All measurements shall be corrected for thermal expansion of the measuring devices as stated in their respective calibration sheets.

10.1.6 Tank calibration table shall also be corrected for expansion of the tank shell at selected reference temperature and pressure.

10.2 Accuracy of volume

10.2.1 General

Calculation of liquid volume may be based on average diameter and total length of the tank body. However, it should be borne in mind that errors in measured volume would result if segment diameters and/or segment lengths vary.

NOTE Refer to A.1.2 for estimate of errors resulting from using average diameter and total length of tank body.

10.2.2 Calculation parameters

10.2.2.1 General

The volume of the tank as function of innage level (relative to the bottom of the tank, ignoring dip-plate (if there is any) shall be calculated from the following:

— average tank diameter (from measured circumferences of each individual segment);

— tank tilt, measured from elevations of each individual segment.

10.2.2.2 Segment diameters

For the external method, the diameters D_i of individual segments shall be calculated from measured circumferences C_i as:

$$D_i = C_i / \pi$$

For the internal method, the diameters D_i shall be measured directly.

Measurements shall be performed as specified above; multiple measurements in each segment shall be averaged as appropriate.

Average diameter of the tank shall be calculated as in accordance with Formula (1):

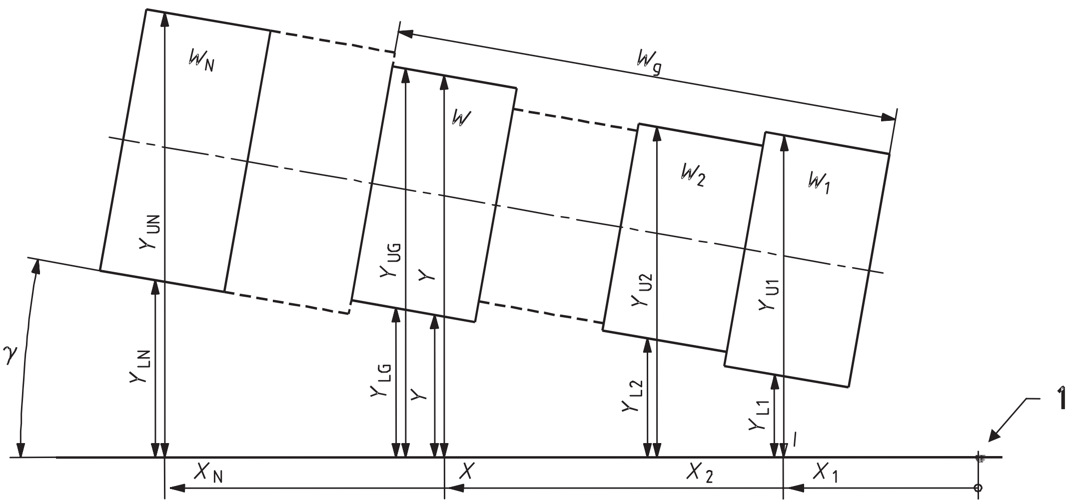
$$D = \frac{\sum_{i=1}^{n} D_i}{n} \quad (1)$$

where

n is the number of segments.

10.2.2.3 Tank tilt

The tilt shall be measured using either one or two horizontal reference lines, as shown in Figures 4 and 5.



Key

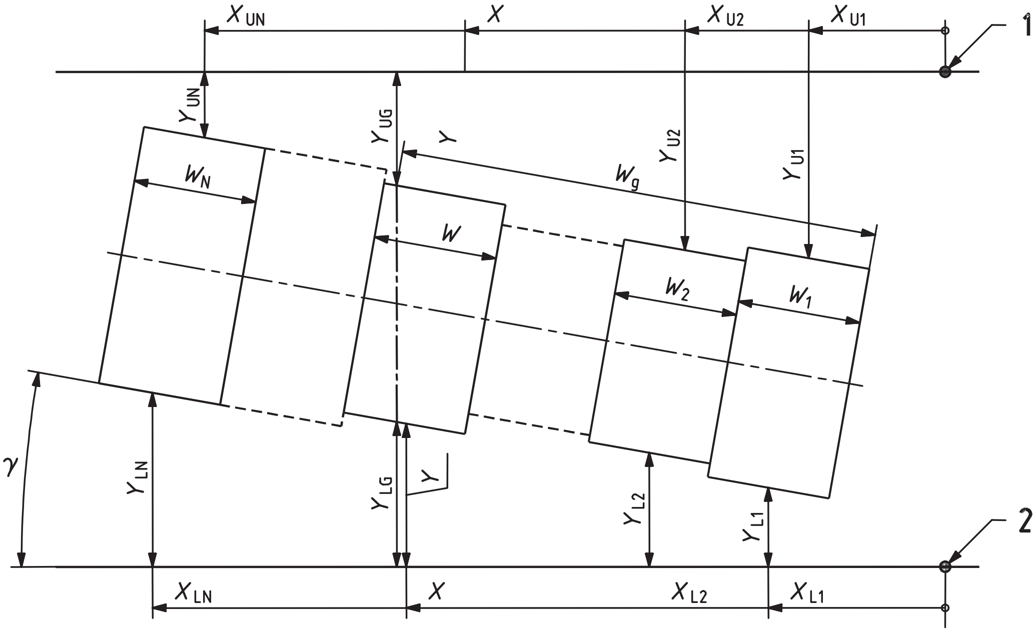
1 reference line

W distances from the lowest point of the tank

X and Y parameters and variables (see text)

γ angle of tilt with reference line

Figure 4 — Angle of tilt (one reference line)



Key

1 top reference line

2 bottom reference line

X and *Y* parameters and variables (see text)

W distances from the lowest point of the tank

γ angle of tilt with reference line

Figure 5 — Angle of tilt (two reference lines)

Resulting equations are as follows.

From measured coordinates of all points, X_i and Y_i, the slope of fitted straight line shall be calculated using the normal formula for linear regression:

$$s = \frac{n \times \sum_{i=1}^{n}(X_i \times Y_i) - \sum_{i=1}^{n}(X_i) - \sum_{i=1}^{n}(Y_i)}{n \times \sum_{i=1}^{n}(X_i)^2 - \left[\sum_{i=1}^{n}(X_i)\right]^2} \qquad (2)$$

where

n is the number of points in one line (top or bottom of the tank);

X_i and Y_i are the coordinates of the points in one line.

The angle of tilt of the tank shall then be calculated for two reference lines as:

$$\gamma = \arctan\left(\frac{s_1 + s_2}{2}\right) \qquad (3)$$

where

s_1 and s_2 are respective slopes of the top and bottom reference lines.

and for one reference line as:

$$\gamma = \arctan(s_1) \tag{4}$$

10.2.3 Volume calculation

10.2.3.1 General

The systematic calculations shall be built up in three sequential parts:

a) calculation of the volume of the cylindrical part of the tank (see 10.2.3.2);

b) calculation of the volume of the tank ends (see 10.2.3.3);

c) additional corrections shall then be made to the volume for deadwood, working pressure and tank shell temperature (see 10.3 and 10.4).

10.2.3.2 Volume of cylindrical body

10.2.3.2.1 Measurements

This method calculates volume of the tank body at any angle of tilt. The tank is assumed to be a single cylinder with one diameter.

Measured (and pre-calculated) parameters and variables, as specified in Figure 5:

D = average diameter of the tank (m)

W = total length of the tank (m)

W_g = distance of the gauge from the lowest point of the tank (m)

γ = angle of tilt (rad)

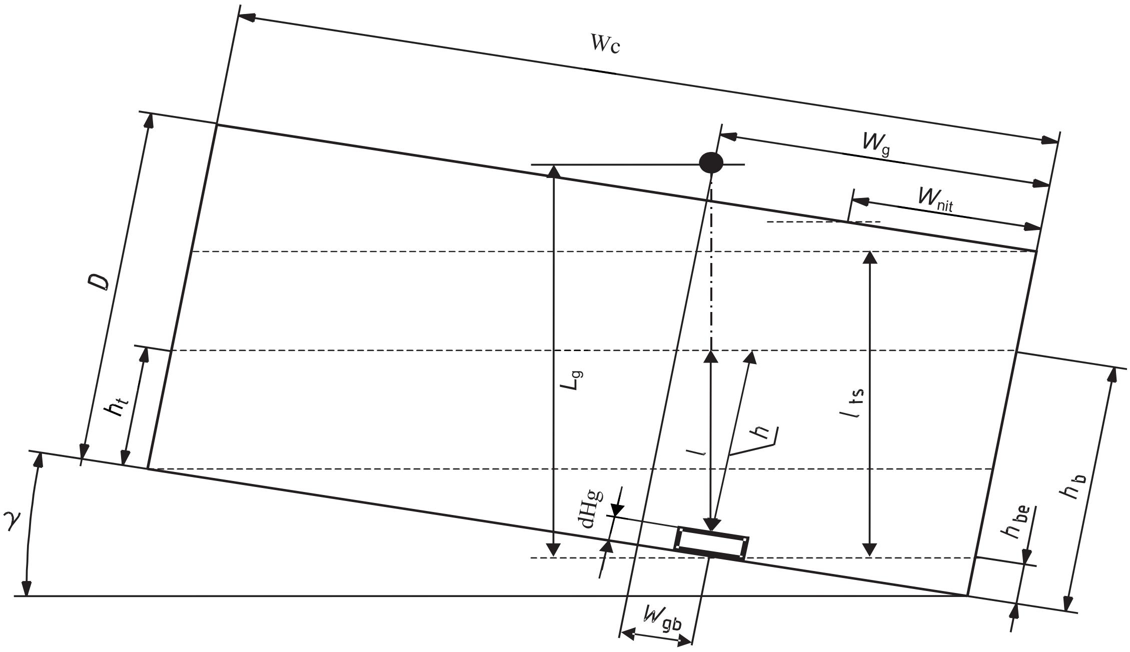
Angle of tilt γ = 0 entered in the following equations would result in zero-divide-by-zero. If the tank has no apparent tilt, a non-zero figure, e.g. γ = 0,000 01 shall be entered into the formulae.

L_g = vertical elevation (vis gravity) of the level gauge above the bottom of the tank (m)

l = gauged (vertical) innage level of the liquid (m)

h = gauged height (parallel to tank ends, derived from gauged liquid level) (m)

10.2.3.2.2 Heights, levels and lengths



Key

D	tank diameter	h_{be}	liquid height at the lower edge of empty tank
l	measured level (includes level of dip plate)	W_c	cylinder length
l_{ts}	measured level with liquid at the top of the lower edge	W_g	gauge length
h	measured height (includes height of dip plate)	W_{gb}	gauge length offset due to tank tilt
δH_g	dip plate height	W_{nit}	length at the top of the tank covered by liquid
L_g	reference (gauge) level		
h_t	liquid height at the upper edge		
h_b	liquid height at the lower edge		

Figure 6 — Heights and lengths in tilted cylindrical tanks

All variables are as specified in Figure 6.

Fixed height:

empty tank ($l = 0$): $h_{be} = (W_g - W_{gb}) \times \tan\gamma = (W_g - D \times \tan\gamma) \times \tan\gamma$ [m] (5)

Calculated variable heights:

height at lower edge: $h_b = h_{be} + (l / \cos\gamma + \delta H_g)$ (m) (6)

height at upper edge: $h_t = h_{be} + (l / \cos\gamma + \delta H_g) - W \times \tan\gamma$ (m) (7)

NOTE 1 The above measured level, l, is, as shown, measured to the dip plate.

NOTE 2 The above calculated heights can be negative or greater than tank diameter.

Calculated width at the top of the tank covered by liquid in near-full-tank state:

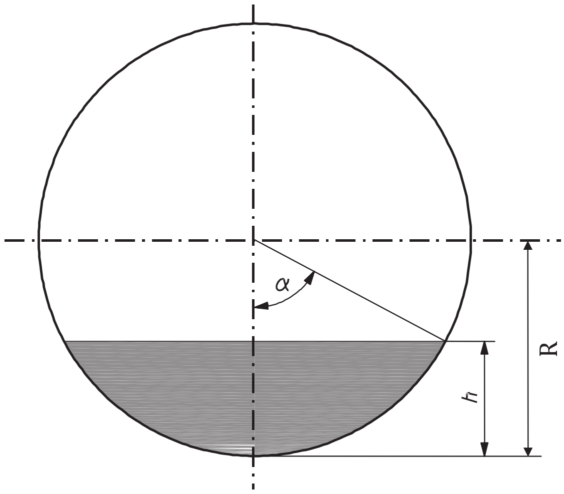
if $h_b < D$ then $W_{nft} = 0$ [m]

if $h_t \geq D$ then $W_{nft} = W$ [m]

else $W_{nft} = (h_b - D) / \tan \gamma$ [m] (8)

10.2.3.2.3 Volume

Angle of coverage is a function of liquid height as specified in Figure 7.



Key

α angle of coverage

h liquid height

R radius

Figure 7 — Angle of coverage

$$\alpha = \arccos (1 - h / R) = \arccos (1 - 2 \times h / D) \text{ (rad)} \quad (9)$$

if calculated $h_b < 0$ then $\alpha_b = 0$

if calculated $h_b > D$ then $\alpha_b = \pi$

if calculated $h_t < 0$ then $\alpha_t = 0$

if calculated $h_t > D$ then $\alpha_t = \pi$

intermediate variable:

$$q = \sin \alpha \times (1 - 1 / 3 \times \sin^2 \alpha) - \alpha \times \cos \alpha \quad (10)$$

Volume up to level l (height h_b at the lower end and h_t at the upper end of the tank):

$$V = R^3 / \tan \gamma \times (q_b - q_t) + \pi \times (D_i / 2)^2 \times W_c \quad (11)$$

where

q_b = f (α_b) = f (h_b)

q_t = f (α_t) = f (h_t)

NOTE Index *b* indicates the bottom and index *t* the top of the tank.

10.2.3.3 Volumes of tank ends

10.2.3.3.1 General

Volumes of tank ends shall be calculated from heights (along the tank ends) of the liquid. See h_b and h_t in 10.2.3.2.2. Alternatively, if the more accurate method of volume calculations is used, the values for h_b and h_t shall be those for extreme tank segments in A.3.2.

These calculations shall be performed on non-tilted tanks. It is assumed that tilt makes only an insignificant difference to the volumes of the tank ends. Tilt corrections are not necessary for tank ends.

NOTE Tank ends include the straight (cylindrical) flange as shown in Figure 1.

10.2.3.3.2 Tori-spherical (knuckle-dish) ends

Calculation of the volume of the knuckle-dish ends shall be based on the following variables as specified in Figure 8:

a) radius of the knuckle, R_k (m);

b) radius of the dish, R_d; or radius of the weld between the dish and the knuckle R_2 (m);

c) radius of the cylinder, $R = D / 2$ (m).

The measured length of the head X_1 shall be used either for calculation of the radius of the dish or for checking the calculations.

If R_d is measured, then:

$$\begin{aligned} \sin\beta &= \frac{(R - R_k)}{(R_d - R_k)} \\ R_2 &= R_d \times \sin\beta \\ X_1 &= R_d - (R_d - R_k) \times \cos\beta \end{aligned} \qquad (12)$$

where

X_1 is the head length.

R_2 (radius of the weld between knuckle and dish) and X_1 (head length) shall be measured, then β shall be calculated (numerically) from Formula (13):

$$(X_1 - R_k \times \cos\beta) \times \sin\beta - R_2 \times (1 - \cos\beta) = 0 \tag{13}$$

and R_d shall be calculated as:

$$R_d = \frac{R_2}{\sin\beta} \tag{14}$$

In either case:

$$X_2 = R_k \times \cos\beta \tag{15}$$

Using this information, the radii of the dish as a function of the distance, R_x, shall be calculated:

$0 \le X \le X_2$ (toroid)

$$R_x = (R - R_k) + \sqrt{R_k^2 - X^2} \tag{16}$$

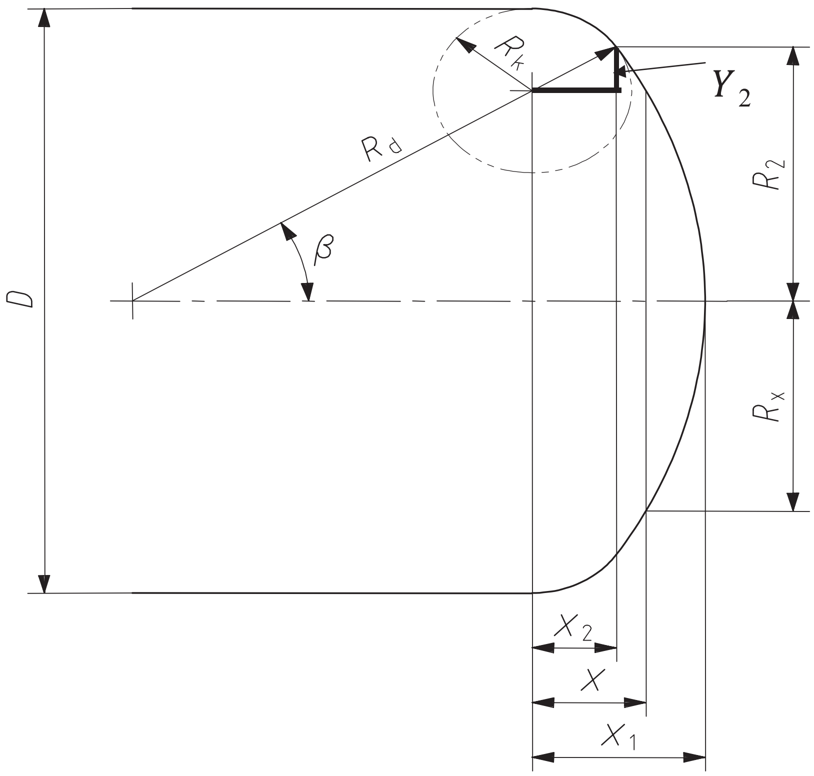
and

$X_2 \le X \le X_1$ (sphere)

$$R_x = \sqrt{R_d^2 - (X_d + X)^2} \tag{17}$$

where

$$X_d = (R_d - R_k) \times \cos\beta = R_d - X_1$$



Key

D tank diameter (= 2 * R)

R_k radius of knuckle

R_d radius of dish

R_2 radius of weld between knuckle and dish

β angle of opening of the weld between knuckle and dish

X_1 X-coordinate of tank head

X_2 X-coordinate of weld between knuckle and dish

Y_2 differential elevation for calculation of β

X X-coordinate of calculated cross-sectional area

R_x radius at point X

Figure 8 — Calculation of volume of the knuckle-dish end

NOTE X_1 is the length of the tank end (either top end or bottom end).

The volume as a function of liquid level (h) of the knuckle dish shall then be calculated by the numerical integration according to Simpson:

$$V_h = \int_0^h A_h(x)dx \tag{18}$$

where

$$A_\mathrm{h}(x) = R_x^2 \times (0{,}5a_x - 0{,}5\sin a_x)$$

where

$$a_x = 2 \times \arccos\left(\frac{R-h}{R_x}\right)$$

leading to:

$$A_\mathrm{h}(x) = R_x^2 \times \arccos\left(\frac{R-h}{R_x}\right) - (R-h) \times \sqrt{R_x^2 - (R-h)^2} \tag{19}$$

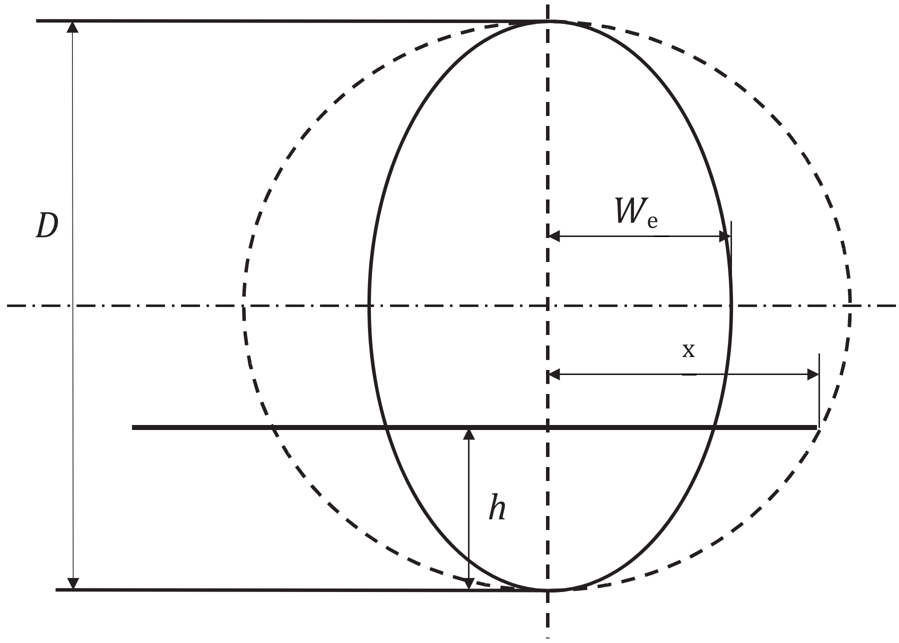
if $x \geq X_1$, $A_\mathrm{h}(x) = 0$

NOTE The integral for volume, V, (Formula 18) can be solved using Simpson's rule or other numerical methods.

10.2.3.3.3 Elliptical and spherical ends

10.2.3.3.3.1 General

Figures 9 and 10 show side view and axial view, respectively, of the tank end for elliptical and spherical ends. These figures should be referred to in 10.2.3.3.3.2 and 10.2.3.3.3.3.



Key

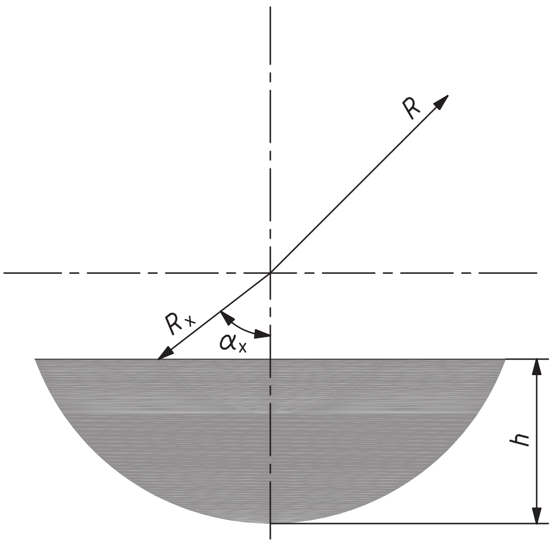
W_e length of the head

h liquid height

$R = D / 2$ radius of the head

x horizontal coordinate of tank end covered with liquid

Figure 9 — Side view of semi-elliptical and semi-spherical tank ends



Key

α_x angle of coverage

h liquid height

R radius of the head

R_x radius of the dish as a function of the distance

Figure 10 — Axial view of tank end

10.2.3.3.3.2 Semi-elliptical ends

The total volume, V_t, shall be calculated from:

$$V_t = \frac{2}{3} \times \pi \times R^2 \times W_e \qquad (20)$$

where

R is the radius of the head (see Figure 10) (m);

W_e is the length of the head (see Figure 9) (m).

The partial volume V_h, at height, h, shall be calculated from:

$$V_h = \frac{\pi \times W_e \times h^2}{2} \times \left(1 - \frac{h}{3R}\right) \qquad (21)$$

10.2.3.3.3.3 Semi-spherical ends

Total volume, V_t, shall be calculated from:

$$V_t = \frac{\pi \times W_e}{6} \times (3R^2 + W_e^2) \qquad (22)$$

Partial volume shall be calculated as knuckle head with knuckle radius = 0 (refer to Figure 8):

$\sin \beta = R / R_d$

$R_2 = R_d \times \sin \beta$

$X_2 = 0$

$X_1 = R_d \times (1\text{-}\cos \beta)$

$$R_x = \sqrt{R_{\mathrm{d}}^2 - (X + R_{\mathrm{d}} \times \cos\beta)^2} \quad (23)$$

The volume as a function of liquid level (h) of the knuckle dish shall then be calculated by the numerical integration according to Simpson:

$$V_{\mathrm{h}} = \int_0^h A_{\mathrm{h}}(x)dx \quad (24)$$

where

$$A_{\mathrm{h}}(x) = R_x^2 \times (0{,}5a_x - 0{,}5\sin a_x)$$

where

$$a_x = 2 \times \arccos\left(\frac{R-h}{R_x}\right)$$

leading to:

$$A_{\mathrm{h}}(x) = R_x^2 \times \arccos\left(\frac{R-h}{R_x}\right) - (R-h) \times \sqrt{R_x^2 - (R-h)^2} \quad (25)$$

if $x \geq X_{\mathrm{h}}$, $A_{\mathrm{h}}(x) = 0$

10.3 Corrections of volume of tank table

10.3.1 General

In most cases, these corrections may be neglected. If products are held at high pressures and high or low temperatures, the corrections on volume of the tank table should be made for:

— working pressure, and

— tank shell temperature.

Due to relatively low hydrostatic pressures, corrections for liquid head need not be made.

10.3.2 Working pressure

10.3.2.1 Principle

NOTE Numerical example in B.3.1 estimates effects of pressure on volume. It is left up to the user to decide whether to do the corrections or not.

Corrections of the volume of the tank for the working pressure within the tank at calibration conditions shall be performed in accordance with the following principle: The stress in one direction causes an extension of the shell in that direction. It also causes a contraction in the perpendicular direction, the size of which depends upon Poisson's ratio for the material.

Pressure at calibration, if there is any, should be measured using existing gauges, and corrections to stated reference conditions should be made as shown below.

No pressure corrections should be attempted for tanks that are declared as "non-pressurized".

10.3.2.2 Tank ends

The combination of the extension of the shell in one direction and the contraction in the perpendicular direction causes a uniform strain in the material of the hemispherical ends of a cylinder given by Formula (26):

$$\frac{(P_r - P) \times R}{2tE}(1 - \sigma) \tag{26}$$

where

P_r is the pressure at reference conditions (Pa);

P is the pressure at which the calibration was performed (Pa);

R is the radius of the tank (m);

t is the shell thickness (m);

E is Young's modulus (Pa);

σ is Poisson's ratio.

This strain corresponds to an increase in the radius of the ends, r_e, given by Formula (27):

$$\frac{\delta r_e}{R} = \frac{(P_r - P) \times R}{2tE}(1 - \sigma) \tag{27}$$

The subscript is used to distinguish the increase in the radius of the hemispherical ends of a cylindrical tank from the increase in the radius of the cylindrical part, which will be denoted by δr_c.

10.3.2.3 Tank body

In the cylindrical part of a tank, the hoop stress is P_r / t and, due to the pull exerted by the hemispherical ends, the longitudinal stress is $(P_r - P) \times R / 2t$.

Hence, it follows that:

$$\text{expansion in longitudinal direction} = \frac{\delta W_c}{W_c} = \frac{(P_r - P) \times R}{2tE}(1 - 2\sigma) \tag{28}$$

$$\text{expansion in circumferential direction} = \frac{\delta r_c}{R} = \frac{(P_r - P) \times R}{2tE}(2 - \sigma) \tag{29}$$

where

W_c is the length of the cylindrical part (m);

δW_c is the increase in this length (m);

δr_c is the increase in the radius of the cylindrical part (m);

P is the working pressure (Pa);

R is the radius of the tank (m);

t is the shell thickness (m);

σ is Poisson's ratio;

E is Young's modulus (Pa).

10.3.2.4 Total volume

Combining these formulae will give the following correction factor to the volume of the tank (Poisson's ratio typically equals 0,3):

$$V_{\text{full}} = V_c \times C_{\text{pvc}} + V_e \times C_{\text{pve}} \quad (30)$$

where

$$C_{\text{pvc}} = \frac{(R + \delta r_c)^2 \times (1 + \delta W_c)}{R^2 \times W_c} \quad (31)$$

$$C_{\text{pve}} = 1 + \frac{3P_r}{2tE} \times (1 - \sigma) \quad (32)$$

V_c is the total cylindrical volume of the tank (m^3);

V_e is the total volume of the ends (m^3).

10.3.3 Tank-shell temperature

Corrections to the volume of the tank due to the fact that the tank-shell temperature is different from the temperature when the tank was calibrated, shall be carried out in accordance with Formula (33).

$$C_{tV} = [1 + \alpha\,(t_1 - t_s)] \times [1 + 2\alpha\,(t_t - t_s)] \quad (33)$$

where

α is the coefficient of linear expansion of the tank shell metal (1/°C);

t_s is the temperature of certification of the tank capacity table (°C);

t_1 is the observed temperature of the dip-tape (same as that of the liquid) (°C);

t_t is the temperature of the tank shell (°C) taken as average of ambient and liquid temperatures.

NOTE For insulated tanks or underground tanks, the shell temperature is assumed to be equal to the liquid temperature.

10.4 Deadwood

The calculation of the volume of the deadwood shall be performed as specified in ISO 7507-1.

10.5 Calibration table at gauged levels

NOTE Tank calibration table calculated above gives volume as a function of level measured vertically from the inside of the tank body, where there is no dip plate. There are several ways the liquid level can be gauged and the client would expect the calibration table to relate to the gauged level.

See Figure 11 for different versions of gauged level. The following modifications should be done to map the vertical level, l, on which the calculations were based to the gauged level:

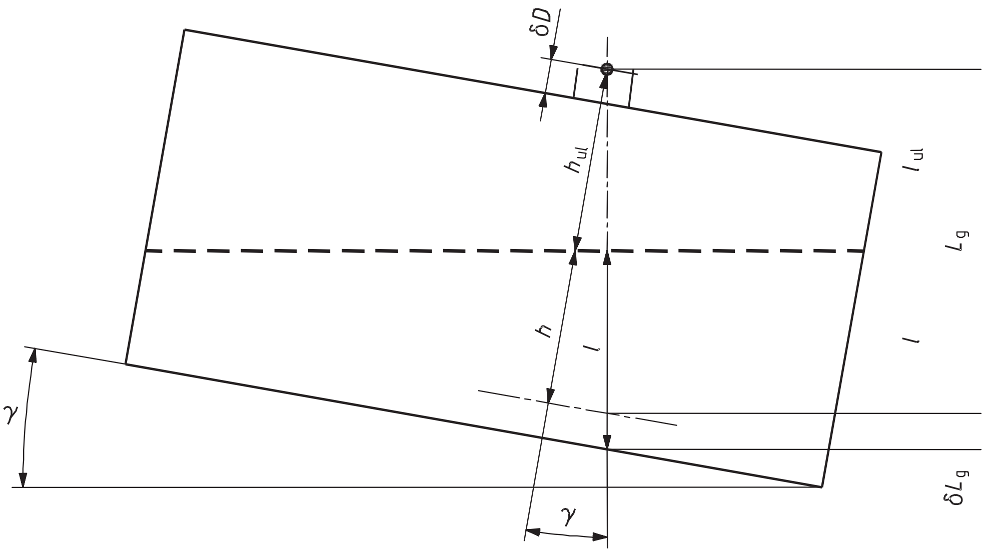
a) gauged level = vertical level, l, (i.e. for tanks with no dip plate): no modifications;

b) gauged level = vertical innage level, l_{in}, (i.e. for tanks with a dip plate at δL_g above the lowest point of the inside of the tank body): volume at δL_g is shown as being the volume of empty tank, levels below δL_g are blanked out;

c) gauged level = vertical ullage level, l_{ul}, (i.e. for tanks with a dip plate at δL_g above the lowest point of the inside of the tank body): same as b). above while the gauged level l_{ul} is mapped onto innage level l_{in} as: $l_{in} = L_g - l_{ul}$;

d) gauged level = aligned innage level (height) h_{in}, parallel with tank ends: the gauged level (height) h_{in} is mapped onto innage level l_{in} as: $h_{in} = l_{in} / \cos \gamma$;

e) gauged level = aligned ullage level (height) h_{ul}, parallel with tank ends: same as d) in which the gauged level (height) h_{in} is mapped onto innage level h_{ul} as: $h_{ul} = L_g / \cos \gamma - h_{in}$.



Key

δD height of reference point above average tank diameter

δL_g increase in vertical elevation

γ angle of tilt

h_{in} aligned innage level

h_{ul} aligned ullage level

L_g vertical elevation

l_{in} vertical innage level

l_{ul} vertical ullage level

Figure 11 — Gauged levels

NOTE Refer to B.5 for a numerical example.

Annex A
(informative)

Computation of tank capacity tables based on individual segment dimensions

A.1 General

A.1.1 Method

This method calculates volumes of liquid in individual segments and obtains the total volume of the tank body as their sum.

Assumptions:

a) Individual segments are concentric, i.e. the differences between their individual diameters (if any) are spread equally around their circumferences.

b) The angle of tilt through all individual segments is the same as the (averaged) angle of tilt of the tank.

The method is valid for any angle of tilt, as above, if tilt = 0 then a small number, e.g. 0,000 01 should be used instead.

A.1.2 Estimate of error

Formula (A.1), based on numerical examples, estimates the worst-case error in volume of tank body as function of maximum difference in segment diameters, average diameter of the tank and the tank tilt:

$$V_{err} = [(0{,}002 \times 88 \times D_{avg} - 0{,}050 \times 6) \times \gamma_d + (0{,}334 \times 98 - 0{,}013 \times 6 \times D_{avg})] \times D_{var} \qquad (A.1)$$

where

V_{err} is the worst-case error in volume [% of full volume];

γ_d is the tank tilt [deg];

D_{avg} is the average diameter of the tank [m];

D_{var} is the worst-case difference between any pair of segment diameters [m].

Typical figures for tanks with diameters 2, 3, 4 and 5 [m] are shown in B.2.

It is recommended that this estimate of error is made. If the error is seen as unacceptable, the following calculations should be performed instead of those shown in Clause 10.

A.2 Measurements

Measured parameters and variables (see for details Figure A.1):

D_i = average internal diameter of segment *i* (*i* = 1 for the lowest segment) [m]

D_g = average internal diameter of the segment where the level gauge is located [m]

W_i = length of segment *i* [m]

W_g = distance of the level gauge from the lowest point of the tank, measured along the axis of the tank [m]

γ = average angle of tilt of the tank [rad]

l = vertical level (innage level measured to the inside of the tank shell) [m]

h = height (corrected gauged level) at right angle to the axis of the tank body [m]

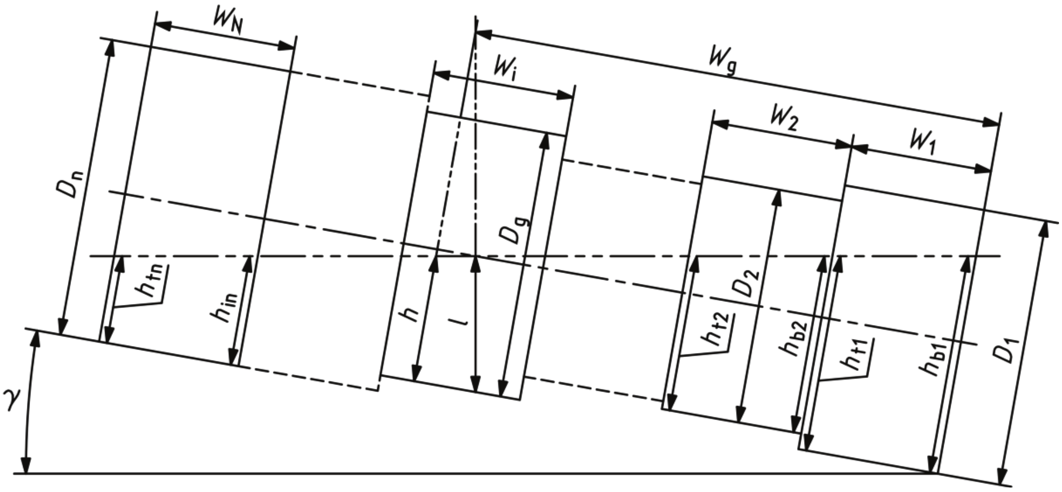


Figure A.1 — Dimensions of individual segments

A.3 Calculations

A.3.1 Fixed heights

Refer to Figure A.1.

Heights at lower segment edges in empty tank (calculated heights could be negative):

height at lowest edge: $h_{b1e} = (W_g - D_g \times \tan \gamma) \times \tan \gamma + (D_1 - D_g) / 2$

height at lower edge of segment 2: $h_{b2e} = h_{b1e} - W_1 \times \tan \gamma + (D_2 - D_1) / 2$

height at lower edge of segment 3: $h_{b3e} = h_{b2e} - W_2 \times \tan \gamma + (D_3 - D_2) / 2$

height at lower edge of segment n: $h_{bne} = h_{bn\text{-}1e} - W_{n\text{-}1} \times \tan \gamma + (D_n - D_{n\text{-}1}) / 2$ (A.2)

A.3.2 Variable heights, levels and widths

Refer to Figure A.1.

Calculated heights at segment edges, with liquid in the tank (calculated heights could be negative or > segment diameter):

heights at lower edges: $h_{bi} = h_{bie} + l / \cos \gamma$ (A.3)

heights at upper edges: $h_{ti} = h_{bie} + l / \cos \gamma - W_i \times \tan \gamma = h_{bi} - W_i * \tan \gamma$ (A.4) where i = segment number

Calculated width of segment at the top covered by liquid in near-full segment:

if $h_{bi} < D_i$, then $W_{ci} = 0$

if $h_{ti} \geq D_i$, then $W_{ci} = W_i$

else $W_{ci} = (h_{ti} - D_i) / \tan \gamma$ (A.4)

NOTE Lowest height h_{b1} (low height in the lowest segment) and highest height h_{tn} (high height in the uppermost segment) are used to calculate volumes in tank ends (see 10.2.3.3).

A.3.3 Volume

Angles of coverage by the liquid in each segment (refer to Figure 7):

lower end of the segment (height h_{bi}):

$\cos \alpha_{bi} = 1 - 2 \times h_{bi} / D_i$

if calculated $h_{bi} < 0$, then $h_{bi} = 0$ and $\cos \alpha_{bi} = 1$

if calculated $h_{bi} > D_i$, then $h_{bi} = D_i$ and $\cos \alpha_{bi} = -1$ (A.5)

upper end of the segment (height h_{ti}):

$\cos \alpha_{ti} = 1 - 2 \times h_{ti} / D_i$

if calculated $h_{ti} < 0$ then $h_{ti} = 0$ and $\cos \alpha_{ti} = 1$

if calculated $h_{ti} > D_i$ then $h_{ti} = D_i$ and $\cos \alpha_{ti} = -1$ (A.6)

Subsets of formulae for segment volumes:

lower end of the segment (height h_{bi}):

$$q_{bi} = \sin \alpha_{bi} \times (1 - \sin^2 \alpha_{bi} / 3) - \alpha_{bi} \times \cos \alpha_{bi} \quad \text{(A.7)}$$

upper end of the segment (height h_{ti}):

$$q_{ti} = \sin \alpha_{ti} \times (1 - \sin^2 \alpha_{ti} / 3) - \alpha_{ti} \times \cos \alpha_{ti} \quad \text{(A.8)}$$

Liquid volume in segment i:

$$V_i = (D_i / 2)^3 \times (q_{bi} - q_{ti}) / \tan \gamma + \pi \times (D_i / 2)^2 \times W_{ci} \quad \text{(A.9)}$$

Liquid volume in the tank:

$$V = \mathrm{SUM}\,(V_i) \quad \text{(A.10)}$$

Annex B
(informative)

Calculation examples

B.1 Volume of tank body

B.1.1 General

This annex shows the results of calculations of the volume of tank body, and a comparison between calculating it as a single cylinder with averaged diameter (Clause 10) and as a set of segments each with individual diameter and width (Annex A).

In the examples presented in B.1.2 and B.1.3, the gauged level was taken up to the point where the inclined tank was completely full. This was L_g = 3,463 m above the lowest point in the segment where the gauge was mounted.

B.1.2 Averaged tank diameter

Input data are as follows:

Davg	=3,358	[m]
W	=15,882	[m]
Wi * tan y	=0,4575	[m]
Ri^3/tan y	=164,28	[m^3]
full volume V	=140,636	[m^3]
gauge width Wg	=8,100	[m]
hbe	=0,231	[m]

Vertical elevation of the level gauge has been set such that the entire tank is gauged. L_g = 3,600 m. This is 0,200 m above the top-most point of the inner surface of the segment where the gauge is mounted.

Calculated data are presented in Table B.1.

Table B.1 — Variables for averaged tank diameter

hb [m]	ht [m]	cos ab	cos at	qb	qt	Wc [m]	Volume [m^3]
0,230	-0,227	0,864	1,000	0,005	0,000	0,000	0,855
0,267	-0,191	0,842	1,000	0,007	0,000	0,000	1,228
0,303	-0,155	0,821	1,000	0,010	0,000	0,000	1,683
0,339	-0,119	0,799	1,000	0,013	0,000	0,000	2,225
0,375	-0,083	0,778	1,000	0,017	0,000	0,000	2,859
0,447	-0,010	0,735	1,000	0,026	0,000	0,000	4,420
0,519	0,062	0,693	0,963	0,038	0,000	0,000	6,363
0,664	0,206	0,607	0,878	0,070	0,004	0,000	11,043
0,808	0,351	0,522	0,792	0,113	0,014	0,000	16,507
0,953	0,495	0,436	0,707	0,169	0,034	0,000	22,571
1,097	0,640	0,351	0,621	0,238	0,064	0,000	29,109
1,242	0,784	0,265	0,536	0,320	0,105	0,000	36,022
1,386	0,929	0,180	0,450	0,417	0,159	0,000	43,230
1,531	1,073	0,094	0,365	0,528	0,225	0,000	50,661
1,675	1,218	0,009	0,279	0,653	0,305	0,000	58,250
1,819	1,362	-0,077	0,194	0,793	0,399	0,000	65,937
1,964	1,506	-0,162	0,108	0,948	0,508	0,000	73,664
2,108	1,651	-0,248	0,023	1,117	0,631	0,000	81,372
2,253	1,795	-0,333	-0,062	1,300	0,769	0,000	89,004
2,397	1,940	-0,419	-0,148	1,497	0,921	0,000	96,501
2,542	2,084	-0,504	-0,233	1,707	1,088	0,000	103,800
2,686	2,229	-0,590	-0,319	1,930	1,269	0,000	110,832
2,831	2,373	-0,675	-0,404	2,165	1,463	0,000	117,519
2,975	2,518	-0,761	-0,490	2,410	1,671	0,000	123,772
3,120	2,662	-0,846	-0,575	2,665	1,892	0,000	129,476
3,264	2,807	-0,932	-0,661	2,928	2,125	0,000	134,475
3,408	2,951	-1,000	-0,746	3,142	2,369	1,003	138,488
3,553	3,095	-1,000	-0,832	3,142	2,622	6,018	141,030
3,589	3,132	-1,000	-0,853	3,142	2,687	7,272	141,442
3,625	3,168	-1,000	-0,875	3,142	2,752	8,526	141,774
3,661	3,204	-1,000	-0,896	3,142	2,817	9,779	142,032
3,697	3,240	-1,000	-0,917	3,142	2,883	11,033	142,222
3,733	3,276	-1,000	-0,939	3,142	2,950	12,287	142,351
3,770	3,312	-1,000	-0,960	3,142	3,016	13,541	142,428
3,806	3,348	-1,000	-0,981	3,142	3,083	14,794	142,462
3,842	3,384	-1,000	-1,000	3,142	3,142	15,882	142,468

B.1.3 Varying tank diameter

The base data are given in Table B.2.

Table B.2 — Calibration for varying tank diameter

Segment	Strapped Circumference Cext1 [m]	Cext2 [m]	Diameter D1 [m]	D2 [m]	Segment Dext avg [m]	length [m]	ac.length [m]		Calib correction DextP [m]	DextT [m]
1	10,663	10,678	3,394	3,399						
	10,675	10,656	3,398	3,392	3,395	1,839	1,839	incl. weld	3,395	3,397
2	10,675	10,729	3,398	3,415						
	10,659	10,697	3,393	3,405	3,399	1,757	3,596		3,399	3,401
3	10,653	10,707	3,391	3,408						
	10,644	10,681	3,388	3,400	3,394	1,752	5,348		3,394	3,396
4	10,647	10,631	3,389	3,384						
	10,675	10,747	3,398	3,421	3,410	1,755	7,103		3,409	3,412
5	10,619	10,703	3,380	3,407						
	10,663	10,817	3,394	3,443	3,419	1,756	8,859	gauge	3,418	3,421
6	10,625	10,795	3,382	3,436						
	10,650	10,751	3,390	3,422	3,406	1,672	10,531		3,406	3,408
7	10,663	10,769	3,394	3,428						
	10,628	10,688	3,383	3,402	3,393	1,755	12,286		3,392	3,395
8	10,659	10,685	3,393	3,401						
	10,669	10,641	3,396	3,387	3,392	1,759	14,045		3,391	3,394
9	10,641	10,644	3,387	3,388						
	10,659	10,641	3,393	3,387	3,390	1,837	15,882	incl. weld	3,390	3,392

Diameters corrected for calibration conditions:

Internal diameter *D*int average: 3,380 [m]

Internal diameter *D*int at gauge: 3,399 [m]

Calculated volumes and comparison with volumes calculated for averaged diameter are given in Table B.3:

Table B.3 — Calculated volumes for varying tank diameter

Varying diameter											Averaged diameter		
Seg. number :	1	2	3	4	5	6	7	8	9				
Avg. diameter [m] :	3,375	3,379	3,374	3,390	3,399	3,386	3,373	3,372	3,370		3,380		
Width [m] :	1,839	1,757	1,752	1,755	1,756	1,672	1,755	1,759	1,837		15,882	max =	0,53%
hbe [m] :	0,242	0,191	0,138	0,095	0,049	-0,007	-0,062	-0,113	-0,165		0,230	min =	-0,01%
Full volume [m3] :	16,452	15,756	15,664	15,836	15,929	15,056	15,677	15,704	16,385		142,468		
gge level [m]	Volume1 [m3]	Volume2 [m3]	Volume3 [m3]	Volume4 [m3]	Volume5 [m3]	Volume6 [m3]	Volume7 [m3]	Volume8 [m3]	Volume9 [m3]	Total Volume [m3]	Total Volume [m]	Variable - averaged Volumes [% max]	
0,000	0,44	0,29	0,16	0,08	0,02	0,00	0,00	0,00	0,00	0,993	0,855	0,096%	
0,217	1,23	0,98	0,79	0,65	0,50	0,32	0,20	0,09	0,02	4,784	4,420	0,255%	
0,289	1,54	1,27	1,05	0,90	0,74	0,52	0,38	0,25	0,14	6,785	6,363	0,296%	
0,433	2,22	1,89	1,65	1,47	1,28	1,01	0,85	0,67	0,52	11,549	11,043	0,355%	
0,578	2,95	2,57	2,31	2,11	1,91	1,57	1,41	1,20	1,04	17,077	16,507	0,400%	
0,722	3,73	3,31	3,02	2,82	2,59	2,21	2,05	1,82	1,66	23,191	22,571	0,435%	
0,866	4,55	4,08	3,78	3,57	3,33	2,89	2,74	2,49	2,34	29,768	29,109	0,463%	
1,011	5,40	4,88	4,57	4,35	4,11	3,61	3,48	3,22	3,08	36,713	36,022	0,485%	
1,155	6,28	5,71	5,38	5,16	4,91	4,37	4,26	3,99	3,87	43,945	43,230	0,502%	
1,300	7,16	6,56	6,22	6,00	5,74	5,15	5,07	4,79	4,70	51,394	50,661	0,514%	
1,444	8,06	7,41	7,07	6,85	6,59	5,95	5,90	5,62	5,55	58,995	58,250	0,523%	
1,588	8,95	8,27	7,92	7,71	7,45	6,76	6,75	6,46	6,42	66,688	65,937	0,527%	
1,733	9,84	9,12	8,77	8,57	8,31	7,58	7,60	7,31	7,31	74,415	73,664	0,527%	
1,877	10,72	9,97	9,62	9,42	9,17	8,39	8,45	8,17	8,20	82,118	81,372	0,524%	
2,022	11,58	10,80	10,45	10,26	10,02	9,21	9,30	9,02	9,10	89,739	89,004	0,516%	
2,166	12,41	11,60	11,26	11,09	10,86	10,00	10,14	9,87	9,98	97,220	96,501	0,504%	
2,310	13,21	12,38	12,05	11,89	11,67	10,78	10,96	10,70	10,86	104,495	103,800	0,488%	
2,455	13,97	13,12	12,80	12,66	12,45	11,53	11,76	11,51	11,71	111,497	110,832	0,467%	
2,599	14,67	13,81	13,50	13,38	13,20	12,25	12,53	12,28	12,53	118,146	117,519	0,440%	
2,743	15,29	14,43	14,15	14,06	13,90	12,93	13,25	13,02	13,32	124,351	123,772	0,407%	
2,888	15,83	14,98	14,72	14,67	14,53	13,56	13,92	13,72	14,06	129,995	129,476	0,364%	
3,032	16,25	15,43	15,21	15,19	15,10	14,11	14,53	14,35	14,74	134,914	134,475	0,308%	
3,177	16,45	15,73	15,56	15,61	15,56	14,58	15,05	14,90	15,36	138,799	138,488	0,218%	
3,321	16,45	15,76	15,66	15,83	15,88	14,94	15,46	15,36	15,87	141,207	141,030	0,125%	
3,465	16,45	15,76	15,66	15,84	15,93	15,06	15,68	15,66	16,25	142,287	142,222	0,046%	
3,610	16,45	15,76	15,66	15,84	15,93	15,06	15,68	15,70	16,39	142,460	142,468	-0,006%	

B.2 Calculation accuracy

Potential errors due to calculating tank volume from averaged tank diameter (for tilted or not-tilted tanks) rather than a sum of volumes of the individual segments.

Formula (A.1) estimates worst-case error in volume as:

$$V_{err} = [(0{,}002\,88 \times D_{avg} - 0{,}050\,6) \times \gamma_d + (0{,}334\,98 - 0{,}013\,6t \times D_{avg})] \times D_{var}$$

The following are values from which this equation has been derived. These are based on worst-case profile of variations of segment diameter, while variations of segment widths are neglected as being insignificant.

Average diameter = 2 m

	tilt [deg] =	0	2	5	10
Dvar [m] =	**0,01**	0,239 %	0,236 %	0,218 %	0,146 %
	0,02	0,478 %	0,472 %	0,436 %	0,292 %
	0,03	0,717 %	0,708 %	0,655 %	0,439 %
	0,04	0,957 %	0,945 %	0,874 %	0,586 %
	0,05	1,197 %	1,182 %	1,093 %	0,733 %

Average diameter = 3 m

	tilt [deg] =	0	2	5	10
Dvar [m] =	**0,01**	0,159 %	0,158 %	0,153 %	0,131 %
	0,02	0,318 %	0,317 %	0,307 %	0,262 %
	0,03	0,478 %	0,475 %	0,460 %	0,394 %
	0,04	0,637 %	0,634 %	0,614 %	0,525 %
	0,05	0,797 %	0,792 %	0,768 %	0,657 %

Average diameter = 4 m

	tilt [deg] =	0	2	5	10
Dvar [m] =	**0,01**	0,119 %	0,119 %	0,117 %	0,109 %
	0,02	0,239 %	0,238 %	0,234 %	0,218 %
	0,03	0,358 %	0,357 %	0,351 %	0,326 %
	0,04	0,478 %	0,476 %	0,468 %	0,435 %
	0,05	0,597 %	0,596 %	0,585 %	0,544 %

Average diameter = 5 m

	tilt [deg] =	0	2	5	10
Dvar [m] =	**0,01**	0,095 %	0,095 %	0,094 %	0,090 %
	0,02	0,191 %	0,191 %	0,189 %	0,181 %
	0,03	0,286 %	0,286 %	0,283 %	0,271 %
	0,04	0,382 %	0,382 %	0,377 %	0,361 %
	0,05	0,478 %	0,477 %	0,472 %	0,452 %

B.3 Corrections for temperature and pressure

The following examples show volume expansion of the tank body due to pressure and temperature.

NOTE Pressure and temperature are in fact the differences between pressures and temperatures at calibration and reference conditions.

B.3.1 Correction for pressure

The thickness of the tank shell [m] is assumed to grow with pressure using Formula (B.1):

$$t = t_0 + K_p \times P \quad \text{(B.1)}$$

where

t_0 = 0,01 [m];

K_p = 1,7E − 05 [1/Pa];

P = (nominal) pressure [Pa].

Parameters:

R = D/2 = 1,689 * 8 [m]

W_c = 15,882 [m]

E = 2E + 11 [Pa]

σ = 0,30 [1]

Volume of full tank:

V = 14,468 [m^3]

Variables and calculation result:

p kPa	**t** m	**R + dR**	W_c **+ d**W_c	**dV** **%full**
10	0,010	1,689 79	15,882 0	**0,002**
50	0,011	1,689 84	15,882 1	**0,007**
100	0,012	1,689 89	15,882 2	**0,014**
200	0,013	1,689 96	15,882 4	**0,024**
500	0,018	1,690 11	15,882 7	**0,044**
1000	0,027	1,690 23	15,883 0	**0,060**
2000	0,044	1,690 34	15,883 2	**0,074**

NOTE p = Pr - P = difference between pressures at reference and at calibration.

B.3.2 Correction for temperature

Parameters:

C_s = 2,1E − 05 expansion coefficient of the tank shell [1/°C]

T_{ref} = 20 temperature at reference [°C]

T_s = tank shell temperature at calibration [°C]

Variables and calculation results:

Ts °C	**Ctv**	**dV** %full
−80	9,9E-01	**-0,63**
−40	1,0E+00	**-0,38**
−20	1,0E+00	**-0,25**
0	1,0E+00	**-0,13**
20	1,0E+00	**0,00**
50	1,0E+00	**0,19**

Ts °C	**Ctv**	**dV** %full
100	1,0E+00	**0,50**
200	1,0E+00	**1,13**
400	1,0E+00	**2,39**

B.4 Volumes of tank ends

B.4.1 Knuckle-dish end

Measured:

R_k = 0,422 [m] = knuckle radius

R_2 = 1,367 [m] = radius of weld between knuckle and dish

X_1 = 0,606 [m] = length of the end

Numerical solution for β:

a) make two estimates of β (β_0, β_1);

b) calculate errors $Er = (X_1 - R_k \times \cos\beta) \times \sin\beta - R_2 \times (1 - \cos\beta)$ for each of these: Er_0, Er_1;

c) calculate the next estimate (i = 2, 3, 4, ...) of $\beta_i = (D_{i-2} \times b_{i-1} - D_{i-1} \times b_{i-2}) / (D_{i-2} - D_{i-1})$ and error (Er_i) for it;

d) carry on with incrementing i until error (Er_i) = 0 (approximately).

Table of calculations:

i =	0 = estim	1 = estim	2	3	4	5	6	7	8	9	10	11
β [rad] =	0,11	0,50	0,1979	0,2662	0,3541	0,3121	0,3171	0,3176	0,3176	0,3176	0,3176	0,3176
Error =	1E-02	−4E-02	1E-02	7E-03	−7E-03	9E-04	8E-05	−1E-06	2E-09	4E-14	0E+00	0E+00

result: β = 0,317 8 [rad]

Calculated:

X_2 = 0,401 [m]

X_d = 3,483 [m]

dX = 0,030 [m] (length of slice X for volume integration)

Volume calculations:

		h-index:	0	1	2	3	4	5	6	7	8	9	10
		h:	0,000	0,338	0,675	1,013	1,351	1,689	2,026	2,364	2,702	3,039	3,377
		*X*h:	0,017	0,414	0,478	0,549	0,592	0,605	0,592	0,549	0,478	0,414	0,017
		*V*h:	0,000	0,137	0,452	0,888	1,409	1,973	2,537	3,059	3,494	3,810	3,947
index	*X*	*R*x	Area (*X*h):										
0	0,000	1,689	0,000 0	0,466 2	1,275 5	2,260 4	3,346 3	4,479 3	Symmetrical with bottom half				
1	0,030	1,688	0,000 0	0,463 9	1,272 1	2,256 1	3,341 3	4,473 5					
2	0,061	1,684	0,000 0	0,456 8	1,261 9	2,243 3	3,326 1	4,456 2					

3	0,091	1,679	0,000 0	0,444 9	1,244 7	2,221 8	3,300 7	4,427 0					
4	0,121	1,671	0,000 0	0,428 3	1,220 5	2,191 4	3,264 7	4,385 7					
5	0,151	1,661	0,000 0	0,406 8	1,188 9	2,151 7	3,217 7	4,331 6					
6	0,182	1,648	0,000 0	0,380 3	1,149 7	2,102 2	3,159 0	4,264 0					
7	0,212	1,632	0,000 0	0,348 8	1,102 3	2,042 2	3,087 6	4,181 8					
8	0,242	1,612	0,000 0	0,312 0	1,046 1	1,970 6	3,002 2	4,083 3					
9	0,272	1,589	0,000 0	0,269 7	0,980 0	1,885 9	2,900 8	3,966 0					
10	0,303	1,561	0,000 0	0,221 7	0,902 5	1,785 6	2,780 3	3,826 3					
11	0,333	1,526	0,000 0	0,167 6	0,810 8	1,665 7	2,635 5	3,657 8					
12	0,363	1,482	0,000 0	0,106 9	0,699 7	1,518 1	2,455 9	3,447 9					
13	0,394	1,419	0,000 0	0,039 8	0,555 6	1,321 8	2,214 5	3,164 1					
14	0,424	1,205	0,000 0	0,000 0	0,169 6	0,742 8	1,477 7	2,280 9					
15	0,454	1,102	0,000 0	0,000 0	0,051 8	0,518 3	1,175 3	1,907 9					
16	0,484	0,988	0,000 0	0,000 0	0,000 0	0,310 8	0,878 2	1,5320					
17	0,515	0,857	0,000 0	0,000 0	0,000 0	0,130 5	0,589 8	1,1533					
18	0,545	0,701	0,000 0	0,000 0	0,000 0	0,006 4	0,317 2	0,7717					
19	0,575	0,497	0,000 0	0,000 0	0,000 0	0,000 0	0,079 9	0,3872					
20	0,606	0,000	0,000 0	0,000 0	0,000 0	0,000 0	0,000 0	0,0000					

B.4.2 Spherical end

Same as knuckle-dish end with Knuckle radius $R_k = 0$.

Measured:

R = 1,689 [m] = radius of tank body

R_d = 3,000 [m] = radius of the sphere

result: β = 0,292 4 [rad]

Calculated:

X_2 = 0 [m]

X_d = 2,494 [m]

dX = 0,026 [m] (length of slice X for volume integration)

Volume calculations:

		h-index:	0	1	2	3	4	5	6	7	8	9	10
		h:	0,000	0,338	0,675	1,013	1,351	1,689	2,026	2,364	2,702	3,039	3,377
		*X*h:	0,007	0,204	0,348	0,447	0,505	0,524	0,505	0,447	0,348	0,204	0,007
		*V*h:	0,000	0,048	0,215	0,498	0,867	1,282	1,697	2,066	2,349	2,516	2,564
index	*X*	*R*x	Area (*X*h):										
0	0,000	1,689	0,000 0	0,466 2	1,275 5	2,260 4	3,346 3	4,479 3	Symmetrical with bottom half				
1	0,026	1,660	0,000 0	0,404 7	1,185 8	2,147 8	3,213 1	4,326 3					
2	0,052	1,619	0,000 0	0,324 8	1,065 8	1,995 8	3,032 3	4,118 0					
3	0,079	1,577	0,000 0	0,249 3	0,947 4	1,843 8	2,850 3	3,907 5					
4	0,105	1,534	0,000 0	0,179 1	0,830 8	1,692 0	2,667 3	3,694 8					
5	0,131	1,489	0,000 0	0,115 7	0,716 5	1,540 5	2,483 3	3,480 0					
6	0,157	1,441	0,000 0	0,060 9	0,605 0	1,389 8	2,298 5	3,263 1					

7	0,183	1,392	0,000 0	0,018 5	0,497 1	1,240 0	2,113 0	3,044 0					
8	0,209	1,341	0,000 0	0,000 0	0,393 5	1,091 6	1,926 9	2,822 7					
9	0,236	1,286	0,000 0	0,000 0	0,295 4	0,945 0	1,740 5	2,599 3					
10	0,262	1,229	0,000 0	0,000 0	0,204 4	0,800 9	1,554 0	2,373 8					
11	0,288	1,169	0,000 0	0,000 0	0,122 6	0,659 9	1,367 6	2,146 1					
12	0,314	1,105	0,000 0	0,000 0	0,054 0	0,523 2	1,181 9	1,916 2					
13	0,340	1,036	0,000 0	0,000 0	0,006 3	0,392 1	0,997 3	1,684 2					
14	0,366	0,961	0,000 0	0,000 0	0,000 0	0,268 7	0,814 6	1,450 0					
15	0,393	0,879	0,000 0	0,000 0	0,000 0	0,156 6	0,634 9	1,213 7					
16	0,419	0,788	0,000 0	0,000 0	0,000 0	0,061 7	0,459 8	0,975 2					
17	0,445	0,684	0,000 0	0,000 0	0,000 0	0,001 2	0,292 2	0,734 6					
18	0,471	0,560	0,000 0	0,000 0	0,000 0	0,000 0	0,138 3	0,491 9					
19	0,497	0,397	0,000 0	0,000 0	0,000 0	0,000 0	0,016 5	0,247 0					
20	0,524	0,000	0,000 0	0,000 0	0,000 0	0,000 0	0,000 0	0,000 0					

B.4.3 Elliptical end

Measured:

X_1 = 0,606 [m] (length of the end = horizontal half-axis of the ellipsoid)

R = 1,689 [m] (radius of tank body = vertical half-axis of the ellipsoid)

Volume calculations:

h m	**Volume** m^3
0,000	0,000
0,338	0,101
0,675	0,376
1,013	0,781
1,351	1,273
1,689	1,808
2,026	2,343
2,364	2,835
2,702	3,240
3,039	3,515
3,377	3,617

B.5 Calibration table with gauged levels

Gauged levels are calculated from vertical level with no dip plate, on which the calculations are based, while the corresponding volumes are maintained. The following example illustrates changes from the original vertical level.

Table B.4 shows an example of a calibration table.

Table B.4 — Calibration table example

Gauged level = Calibration result		Vertical innage		Vertical ullage		Aligned innage		Aligned ullage	
		dLg =	0,29	dD =	0,30	cos y =	0,985		
				Lg =	3,720			Lg / cos y=	3,777
Level	Volume	Level	Volume	Level	Volume	Level	Volume	Level	Volume
0,000	10,178								
0,289	16,403								
0,385	18,846	0,095	18,846	3,625	18,846	0,097	18,846	3,681	18,846
0,578	24,285	0,288	24,285	3,432	24,285	0,292	24,285	3,485	24,285
0,771	30,466	0,481	30,466	3,239	30,466	0,488	30,466	3,289	30,466
0,963	37,359	0,673	37,359	3,047	37,359	0,684	37,359	3,094	37,359
1,156	44,926	0,866	44,926	2,854	44,926	0,879	44,926	2,898	44,926
1,349	53,118	1,059	53,118	2,661	53,118	1,075	53,118	2,702	53,118
1,541	61,876	1,251	61,876	2,469	61,876	1,271	61,876	2,507	61,876
1,734	70,946	1,444	70,946	2,276	70,946	1,466	70,946	2,311	70,946
1,927	80,025	1,637	80,025	2,083	80,025	1,662	80,025	2,116	80,025
2,119	88,811	1,829	88,811	1,891	88,811	1,857	88,811	1,920	88,811
2,312	97,040	2,022	97,040	1,698	97,040	2,053	97,040	1,724	97,040
2,505	104,646	2,215	104,646	1,506	104,646	2,249	104,646	1,529	104,646
2,697	111,581	2,407	111,581	1,313	111,581	2,444	111,581	1,333	111,581
2,890	117,807	2,600	117,807	1,120	117,807	2,640	117,807	1,137	117,807
3,082	123,291	2,792	123,291	0,928	123,291	2,836	123,291	0,942	123,291
3,275	128,034	2,985	128,034	0,735	128,034	3,031	128,034	0,746	128,034
3,468	132,046	3,178	132,046	0,542	132,046	3,227	132,046	0,551	132,046
3,660	135,354	3,370	135,354	0,350	135,354	3,422	135,354	0,355	135,354
3,853	137,974	3,563	137,974	0,157	137,974	3,618	137,974	0,159	137,974
4,046	139,939	3,756	139,939	-0,036	139,939	3,814	139,939	-0,036	139,939
4,238	141,279	3,948	141,279	-0,228	141,279	4,009	141,279	-0,232	141,279
4,431	142,066	4,141	142,066	-0,421	142,066	4,205	142,066	-0,428	142,066
4,624	142,398	4,334	142,398	-0,614	142,398	4,401	142,398	-0,623	142,398
4,816	142,444	4,526	142,444	-0,806	142,444	4,596	142,444	-0,819	142,444

Annex C
(informative)

Calibration uncertainties

C.1 Uncertainties of tank body

C.1.1 Diameter — External method

Uncertainties of the circumferences measured by the external method (strapping tape) are the same as described in ISO 7507-1:2001, F.3.

Result = uD = uncertainty of the (averaged) diameter of the body of the tank with no corrections for temperature or pressure.

C.1.2 Diameter — Internal method

Uncertainties of the measured diameter shall be estimated as follows:

— uD_{ir} = uncertainty of telescopic rod or the distance meter [m], includes the rod precision and uncertainties of read-out;

— uD_{ip} = position uncertainty of the rod [m] from following table:

Tank internal diameter	Uncertainty
up to 3 m	±1 mm (0,001 m)
above 3 m	±2 mm (0,002 m)

Uncertainty of averaging, assuming the equation below yields (very approximately) the standard deviation:

$$uD_{av} = \text{abs}\ [\text{MAX}\ (D_{ir}) - \text{AVG}\ (D_{ir})]\ /\ \text{sqrt}\ (n)\ [\text{m}] \qquad (C.1)$$

where n is the number of diameters measured in one location in one segment.

Uncertainty (standard deviation) of averaged diameter in one location in one segment:

$$uD_{im} = (uD_{ir}^2 + uD_{ip}^2 + uD_{av}^2)^{1/2}\ [\text{m}] \qquad (C.2)$$

Uncertainty (standard deviation) of averaged diameter for the tank body:

$$uD = uD_{im}\ /\ \text{sqrt}\ (m)\ [\text{m}] \qquad (C.3)$$

where m is the number of locations in all segment of the tank.

C.1.3 Lengths

C.1.3.1 General uncertainties

Uncertainties of the tank length measured strapping tape are similar to those described in ISO 7507-1:2001, D.4.

The following are figures for worst cases:

— tape calibration certificate = 0,5 mm;

— tape resolution = 1 mm;

— tape tension and position = 3 mm (in case of horizontal tanks).

Further uncertainties are due to

— deformation of tank heads = 10 mm.

C.1.3.2 Tank body

As the length is measured as sum of two measurements, both subject to the above uncertainties, the resulting standard uncertainty

uW = [sqrt (2) × sqrt (0,5 ^2 + 1^2 + 3^2 + 10^2)] / [2 × sqrt (3)] = 4,4 mm = 0,004 4 m

C.1.3.3 Gauge location

Location of tank gauge (length along the top of the tank body away from its lowest point) is measured only once. Its standard uncertainty is:

uW_g = sqrt (0,5 ^2 + 1^2 + 3^2 + 10^2) / [2 × sqrt (3)] = 3,1 [mm] = 0,003 1 [m]

C.1.4 Angle of tilt

The tilt is measured by repeated measurements of distance X and Y (see 10.2.2.3 above).

Uncertainty of tilt is derived from that of slope of line fitted to pairs of X and Y points. uX and uY are identical for all points.

Uncertainty of slope is derived from its equation (see 10.2.2.3) as:

$us^2 = uX^2 \times \text{SUM}\ (ds\ /\ dX_i)^2 + uY^2 \times \text{SUM}\ (ds\ /\ dY_i)^2$

where

$ds\ /\ dX_i = [n \times Y_i - 1 - s \times (2 \times n \times X_i - 2 \times \text{SUM}\ (X_i)]\ /\ \{n \times \text{SUM}\ (X_i^2) - [\text{SUM}\ (X_i)]^2\};$

$ds\ /\ dY_i = \{n \times X_i - 1\}\ /\ \{n * \text{SUM}\ (X_i^2) - [\text{SUM}\ (X_i)]^2\}.$

Assuming that the uncertainties of measured X and Y are as above, i.e. 0,003 1 m each, the uncertainties us can be estimated.

a) Uncertainty of tilt is derived as:

$u\gamma = us \times \cos^2\gamma$ for one fitted line

$u\gamma = us\ /\ \text{sqrt}\ (2) \times \cos^2\gamma$ for two fitted lines

b) Uncertainty of calculated slope (typical figure, based on the above uncertainties, for tank with nine segments):

us = 0,000 4 [1] for one fitted line

us = 0,000 3 [1] for two fitted lines

c) Uncertainty of angle of tilt derived from the slope:

$u\gamma$ = 0,000 4 [rad] = 0,025 [deg] for one fitted line

$u\gamma$ = 0,000 3 [rad] = 0,017 [deg] for two fitted lines

C.1.5 Volume

Uncertainties are estimated for the numerical method outlined in Clause 10 (using averaged diameter of the tank), for heights (levels) not exceeding low (0) or high (D) limits for the entire lengths of the tank.

The tank is assumed to be an ideal cylinder, with cross-sections of all segments being co-axial circles. Potential deformations in the tank and any misalignments of tank segments are neglected.

Volume of the tank body is a function of: h (gauged height), R (tank radius), γ (angle of tilt), W (tank length) and W_g (length between the lowest point of the tank body and the gauge position).

$$V = f(R, W, W_g, \gamma)$$

$$uV^2 = (uR \times \delta V / \delta R)^2 + (uW \times \delta V / \delta W)^2 + (uW_g \times \delta V / \delta W_g)^2 + (u\gamma \times \delta V / \delta \gamma)^2 \quad \text{(C.4)}$$

Derivatives of volume:

$$\delta V / \delta R = 3 \times V / R + [R \times (Z_b \times h_b - Z_t \times h_t)] / \tan \gamma \quad \text{(C.5)}$$

$$\delta V / \delta W = (V \times H) / (W^2 \times \sin \gamma \times \cos^2 \gamma) - R^2 \times Z_t \quad \text{(C.6)}$$

$$\delta V / \delta W_g = R^2 \times (Z_b - Z_t) \quad \text{(C.7)}$$

$$\delta V / \delta \gamma = R^2 \times (Z_b - Z_t) / \sin \gamma \quad \text{(C.8)}$$

where intermediate variables are:

$Z_b = \alpha_b - \sin \alpha_b \times \cos \alpha_b$

$Z_t = \alpha_t - \sin \alpha_t \times \cos \alpha_t$

$\alpha_b = \arccos [(R - h_b) / R]$

$\alpha_t = \arccos [(R - h_t) / R]$

$h_b = (h + W_g \times \sin \gamma) / \cos \gamma$ = height (level) at the lowest point of the tank [m]

$h_t = [h + (W_g - W) \times \sin \gamma] / \cos \gamma$ = height (level) at the highest point of the tank [m]

γ = angle of tilt of the tank [rad]

$R = D / 2$ = internal radius of the tank body [m]

C.1.6 Correction for temperature

Assuming zero uncertainties of the reference temperature, the additional uncertainty of the volume of the tank body is:

$$uC_{tv} = \{[3 \times (T_s - T_r) \times uC_1]^2 + [2 \times C_1 \times uT_s]^2\}^{1/2} \qquad (C.9)$$

C.1.7 Correction for pressure

Assuming that all components of the equation in B.3.1 are subject to uncertainties, the following formula applies:

$$uC_{pve} = \{[3 \times (1 - \sigma) \; / \; (2tE)]^2 \times [(R \times uP)^2 + (P \times uR)^2 + (P_r \times ut \; / \; t)^2 + (P_r \times uE \; / \; E)^2] + [3P_r \times u\sigma \; / \; (2tE)]^2\}^{1/2} \qquad (C.10)$$

where

P = internal pressure of the tank at calibration conditions, with uncertainty uP [Pa];

P_r = pressure at reference conditions;

R = $D / 2$ = radius of the tank body, with uncertainty $ur = uD / 2$ [m];

t = thickness of the tank shell, with uncertainty ut [m];

E = Young's modulus of the tank shell material, with uncertainty uE [Pa];

σ = Poisson's ratio of the tank shell material, with uncertainty $u\,\sigma$ [1].

Uncertainty of pressure at calibration may be difficult to establish. It is recommended that if in doubt, this particular uncertainty should be neglected.

C.1.8 Corrected volume

Assuming that the total volume in the tank is calculated as:

$$V_{total} = (C_{pvc} \times V_c + C_{pve} \times V_e) \times C_{tv}$$

its uncertainty is

$$uV_{total} = \{[(C_{pvc} \times uV_c)^2 + (V_c \times uC_{pvc})^2 + (C_{pve} \times uV_e)^2 + (V_e \times uC_{pve})^2] \times C_{tv}^2 + (V_c \times C_{pvc} + V_e \times C_{pve})^2 \times uC_{tv}^2\}^{1/2} \qquad (C.11)$$

NOTE Uncertainties of tank ends may normally be neglected, i.e. $uC_{tv} = 0$.

C.1.9 Numerical examples

C.1.9.1 Basics

Calculated for approximate calibration table, based on assumption that all segments have the same diameters. Uncertainties of corrections for temperature and pressure are neglected.

C.1.9.2 Tank diameter

Based on the same calibration data (see above) with the following uncertainties of source data.

Strap tape:			Uncertainties:				
a-st =	2,00E-05	[1/°C]		ent,value	type		
*T*stc =	20,0	[°C]	length =	0,001 5	max	0,000 43	[m]
Tank body:			Read-out =	0,001	max	0,000 29	[m]
straps/segment =	4		position =	0,009	max	0,002 60	[m], from table
number of straps =	36		T tape/tank =	5	max	1,443	[°C]
STD of straps =	0,047 2		T-exp, =	2,0E-06	max	5,8E-07	[1/°C]
a-tk =	5,77E-07	[1/°C]	thick-m+*P* =	0,000 5	max	0,000 14	[m]
Temperature reference:							
*T*ref =	15	[°C]					

Values and uncertainties of measured circumferences and diameter at calibration conditions, corrected to reference temperature:

Outputs:	values	std. uncert's
	[m]	[m]
Average:		
Avg Cem =	10,678	0,047 2
Cet =	10,677	0,047 2
Ci =	10,608	0,047 2
Di =	3,3776	0,0150

C.1.9.3 Tank body volume

Source parameters:

	value	std. uncertainty	
avg. int. diameter *D*irc:	**3,378**	**0,003 0**	[m]
tilt angle *y*:	0,175	0,000 4	[rad]
body length *W*:	15,882	0,004 4	[m]
gauge length *W*g:	8,100	0,003 1	[m]
thick metal + paint:	0,011	0,000 1	[m]

uL = 0 [m] - level uncertainty is normally included in gauging

gge height [m]	Zb	Zt	dV/dy	dV/dR	dV/dW	dV/dWg	uVolume [m^3]	[%full]
0,433	0,436	0,079	35,40	20,92	−0,20	1,02	0,035 6	0,02 %
0,578	0,577	0,173	40,09	31,13	−0,46	1,15	0,050 8	0,04 %
0,722	0,727	0,286	43,76	42,35	−0,77	1,26	0,067 7	0,05 %
0,866	0,884	0,413	46,68	54,31	−1,13	1,34	0,085 8	0,06 %
1,011	1,047	0,553	48,99	66,80	−1,51	1,41	0,104 7	0,07 %
1,155	1,213	0,701	50,77	79,64	−1,93	1,46	0,124 2	0,09 %
1,300	1,383	0,857	52,08	92,66	−2,37	1,50	0,144 1	0,10 %

1,444	1,553	1,019	52,97	105,69	−2,82	1,53	0,163 9	0,12 %
1,588	1,724	1,185	53,44	118,59	−3,28	1,54	0,183 7	0,13 %
1,733	1,894	1,354	53,51	131,21	−3,76	1,54	0,202 9	0,14 %
1,877	2,061	1,525	53,19	143,38	−4,24	1,53	0,221 5	0,16 %
2,022	2,225	1,696	52,46	154,92	−4,72	1,51	0,239 2	0,17 %
2,166	2,383	1,866	51,31	165,66	−5,19	1,48	0,255 7	0,18 %
2,310	2,535	2,033	49,71	175,38	−5,66	1,43	0,270 5	0,19 %
2,455	2,678	2,198	47,60	183,81	−6,12	1,37	0,283 5	0,20 %
2,599	2,810	2,357	44,92	190,64	−6,57	1,29	0,294 0	0,21 %
2,743	2,929	2,510	41,55	195,42	−6,99	1,20	0,301 3	0,21 %
2,888	3,030	2,655	37,28	197,51	−7,40	1,07	0,304 6	0,21 %
3,032	3,108	2,789	31,68	195,69	−7,77	0,91	0,301 9	0,21 %
3,177	3,142	2,910	22,95	189,84	−8,11	0,66	0,293 0	0,21 %
3,321	3,142	3,015	12,56	193,87	−8,40	0,36	0,299 2	0,21 %

NOTE If one of the simplifications mentioned above is used in measurements and/or calculations, additional error will result that has to be added to these uncertainties.

As shown above, if the tank tilt is only measured at two points (lowest points at the lowest and uppermost segments, the added error could be of the order of 0,1 %. If the tank volume is calculated from the averaged diameter, the added error could be as much as 1 % or even more. The size of the errors depends on the variations in elevations of individual segments and in their diameters.

C.2 Uncertainties of tank ends

Uncertainties of volumes of tank ends are normally neglected.

C.3 Errors in calculation of tank body volume

Errors in calculations of volume of tank body may result if the method based on average diameter and total tank length is applied to a tank where the segment diameters vary.

Worst-case errors in calculations, estimated in 10.2, should be added to the estimated uncertainties to yield:

$$uV_{totalC} = \{(uV_{total})^2 + [V_{err} / \mathrm{sqrt}\ (3)]^2\}^{1/2} \quad \text{(C.12)}$$

where

uV_{total} = total uncertainty of volume of tank body calculated in C.1.9;

V_{err} = worst-case error due to simplified calculations of tank body volume estimated in 10.2.

NOTE Distribution of worst case errors is normally either fully positive or fully negative. Hence only sqrt (3) rather than [2 * sqrt (3)] is used in the above equation.

Numerical example:

uV_{total} = 0,21 % of full volume (see C.1.9.2)

uV_{err} = 0,64 % of full volume (see B.2) for tilt angle

γ_d = 1,65 deg

D_{avg} = 3,38 m

D_{var} = 0,029 m

uV_{totalC} = 0,43 % of full volume

Bibliography

[1] ISO 1998 (all parts), *Petroleum industry — Terminology*

ICS 75.180.30
Price based on 46 pages