Bilateral Comparison in the Calibration of Atmospheric Tank Provers by Volumetric and Gravimetric Methods

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Abstract

Calibration of liquid quantity meters may be carried out volumetrically by collecting a known volume of liquid in a standard vessel. In this volumetric method, the standard vessel often known as atmospheric tank prover takes the form of a container with a calibrated volume. In its turn, calibration of the tank prover volume can be carried out by weighing the water contained in the vessel, or carried out using smaller volumetric measures which are themselves traceable to national standards by weighing methods. This paper presents a bilateral interlaboratory comparison in the calibration service of atmospheric tank provers carried out by Institute for Technological Research of the State of Sao Paulo (IPT) and Weights and Measures Institute of the State of São Paulo (IPEM-SP). The main objectives of the comparison were to validate the calibration results of two accredited laboratories and to comply with the requirements established by the accreditation standards regarding the participation of calibration laboratories in proficiency tests. Another important objective was to evaluate the comparability of the calibration methods used by the laboratories. IPT used the gravimetric weighting method and IPEM-SP used the volumetric method. The performances of the laboratories in the calibrations were quite satisfactory for both atmospheric tank provers used in the comparison. The normalized errors obtained were between 0.08 and 0.15 for the 20 L tank prover and 0.05 to 0.22 for the 1 000 L tank prover, indicating a very satisfactory comparability between the two calibration methods.

1. Introduction

Atmospheric tank provers are measurement standards often used in the calibration of liquid volume provers, which in turn are used in the calibration of oil flow meters installed in petroleum fiscal and production allocation measurement systems, in hydrocarbon custody transfer metering stations and also in the verification of volume totalizers of liquid fuels sold directly to consumers in gas stations. These devices are fundamental standards for establishing traceability in the measurement of these products and thus must have their volumes determined with accuracy and reliability. In Brazil, this equipment must be calibrated by accredited calibration laboratories at maximum intervals of three years.

In turn, the satisfactory participation of calibration laboratories in proficiency testing activities and in other types of interlaboratorial comparisons consists in a mechanism established by the ISO/IEC 17025 [1] standard for the laboratories to ensure the validity of their measurement results. Among the many benefits of a laboratory participation in interlaboratory comparisons, it is worth mentioning the possibility of the laboratory comparing its metrological performance in measuring the value of a given quantity with another similar laboratory. Another benefit is the opportunity for the results obtained in the comparison to serve as a subsidy to improve the quality and reliability of the services provided by the laboratory.

2. Bilateral interlaboratory comparison

Based on the context presented previously and under a common interest and agreement, the Institute for Technological Research of the State of São Paulo (IPT) and the Weights and Measures Institute of the State of Sao Paulo (IPEM-SP) planned and carried out a bilateral interlaboratory comparison in the calibration service of atmospheric tank provers.

2.1 Objectives

The main objectives of the comparison were to validate the calibration results of both conformity assessment bodies and to comply with the requirements established by the accreditation standards regarding the regular participation of calibration laboratories in proficiency testing activities. Another important objective was to evaluate the comparability of the different calibration methods used by the laboratories.

Considering that it was a bilateral comparison between two public laboratories accredited by the Cgcre-General Coordination of Accreditation, the Brazilian ILAC member laboratory accreditation body, it was decided not to define a reference laboratory. Thus, the results obtained by one laboratory were directly compared with the results obtained by the other.

2.2 The tank provers used in the comparison

Two atmospheric tank provers with the characteristics presented in Table 1 were used for the comparison:

Table 1: Tank provers used in the comparison.

Tank prover	Characteristics
Tank prover of 20 L	Stainless steel atmospheric tank prover of 20 L, mark Impar, with carrying handle, identification number IE-02361, indication interval of ±200 cm³ and resolution of the scale of 20 cm³.
Tank prover of 1 000 L	Stainless steel atmospheric tank prover of 1 000 L, unmarked, mounted on tripod, ball drain valve for discharge, identification number IE-09644, indication interval of ±15 L and resolution of the scale of 0.5 L.

Figures 1 and 2 show the two tank provers.

Figure 1: Tank prover of 20 L.

Figure 2: Tank prover of 1 000 L.

According to the guidelines defined in the comparison protocol, the laboratories were not allowed to make any type of adjustment in the tank provers and, to provide independence and impartiality, they should not know the results of the other laboratory until the calibrations were finished.

2.3 Calibrated scale points

Calibrations were performed in three points of the tank provers scales: the zero point corresponding to the nominal volume of the tank prover, an upper point and a lower point as shown in the Table 2.

Table 2: Chosen scale points for each calibrated tank prover.

Scale point	20 L tank prover		1 000 L tank prover	
	Scale mark	Nominal volume	Scale mark	Nominal volume
Lower	-200 mL	19.8 L	-10 L	990 L
Zero	0 mL	20.0 L	0 L	1 000 L
Upper	+200 mL	20.2 L	+10 L	1 010 L

After calibration, each participating laboratory prepared a calibration certificate for each tank prover, including the calibrated items data, calibration procedure used and the results obtained. After that, a technical meeting was held at IPEM-SP with representatives from both laboratories in order to disclose and compare the results.

The performance evaluation of the participants of the interlaboratory comparison was made using the criterion of normalized error calculated for the measurement bias quantity determined by the laboratories for each artifact.

3. Calibration methods

For the calibration of the tank provers each laboratory used its own method of calibration and calculation of results and uncertainties. IPEM-SP used the volumetric method and IPT used the gravimetric method of static weighing of the water contained in the tank prover.

3.1 Volumetric method

Calibration of an atmospheric tank prover by volumetric method consists on transfers of liquids (usually water) from standard volume measures from which the transferred volume and its measurement uncertainty required for calibration is known [2]. Since the volume of the transferred liquid is known, the scale of the atmospheric tank prover under calibration is compared with the meniscus of liquid formed during the calibration.

3.1.1 Preparing the tank prover for calibration

Before carrying out the measurements, the atmospheric tank prover must be filled with clean water and after this water is poured (small prover) or drained through the drain discharge valve (large prover). After most of the water is released from the tank, a period of 30 seconds must be taken so that the discharge valve is opened and closed three times so as to deplete the residual water that has drained from the inner walls of the reservoir.

3.1.2 Measurements on the neck scale reading of zero of the tank provers

For the 1 000 L tank prover under calibration, a standard volume measure with nominal volume of 100 L was used ten times in order to transfer about 1 000 L of water into it. For the 20 L tank prover under calibration, a standard volume measure with nominal volume of 20 L was used once. Then the meniscus of water in both tank provers were adjusted to the respective zero point of the scale using standard glasswares.

The volumes of water transferred by the standard volume measures and by the standard glasswares give the reference volumes of the tank provers scales at zero point.

3.1.3 Measurements on the upper point

Since the zero point was measured, standard glasswares were used to provide more water into each tank prover until the meniscus of water reaches the chosen upper point of the scale. So its volume is calculated from the reference volume determined at zero point plus the volumes transferred by the standard glasswares.

3.1.4 Measurements on the lower point

Once the volume of upper point is calculated, standard glasswares were used to remove water from each tank prover until the meniscus of water reaches de chosen lower point. Thus the volume of lower point is calculated by the volume determined on the upper point minus the volume of water removed by the standard glasswares.

For each point measured, the temperature of water is determined using a digital thermometer. Once the measurements of the three points are finished, the steps described from 3.1.1 to 3.1.4 are repeated twice in order to determine the average volumes and their uncertainties.

3.1.5 Environmental parameters

The environmental parameters prevailing during the execution of both calibrations are shown in Table 3.

Table 3: Environmental parameters during calibrations.

Tank prover	Water temperature (°C)	Air temperature (°C)	Relative humidity (%)
1 000 L	19,1 ± 0,6	19,8 ± 0,4	63,7 ± 2,9
20 L	20,0 ± 0,2	19,7 ± 0,2	61,6 ± 1,4

3.1.6 Corrections on the volume determinations

Environmental parameters, especially temperature, are able to modify the volume of liquids and containers. The volume of a tank prover is usually referred as it is used at 20 °C, so the reference volume results should correspond to the volumes of the tank provers at 20 °C. Since the calibrations are generally performed at temperatures other than 20 °C, the measured volumes must be corrected to 20 °C as follows:

$$V_{Pt1} = V_{P20}.[1 + \gamma_P.(t_1 - 20)] \qquad (1)$$

$$V_{ob20} = V_{Pt1}.[1 - \gamma_{ob}.(t_2 - 20)] \qquad (2)$$

where:

V_{Pt1} : liquid volume in the standard at temperature t_1;
V_{P20} : liquid volume in the standard at 20 °C;
V_{ob20} : corrected liquid volume on the object at 20 °C;
t_1 : water temperature on the standard;
t_2 : water temperature on the tank prover;
γ_P : thermal expansion coefficient of the standard;
γ_{ob} : thermal expansion coefficient of the tank prover.

Equation (1) corrects the volume of water delivered by the standard measures when its temperature is different from 20 °C. Then Equation (2) corrects the volume of the tank prover under calibration as it should be at 20 °C [3].

3.1.7 Sources of measurement uncertainties

Basically, the measurement uncertainties of each calibration results consider the standard deviation of the three volume measurements and the uncertainties from the standard volume measures, standard glasswares and temperature measurements. The uncertainties are calculated as described in reference [4].

3.2 Gravimetric method

The gravimetric method of calibration of atmospheric tank provers used by IPT is based on the static weighing of the mass of water contained in the tank prover using an electronic scale. The reference volume is determined from the value of the measured mass of water and its density at measuring conditions [6].

At IPT, calibration of tank provers with volumetric capacity up to 500 L is carried out in a single weighing. For vessels of capacities above 500 L, calibration is performed by means of multiple weighing and where the sum of the collected weighing matches the total volume of the tank prover. In this case, it is recommended to use the lowest number of weighing to minimize the final uncertainty associated to the measured volume.

3.2.1 Calibration assembly

Assemblies presented in Figures 3 and 4 were used for the calibration of the 20 L and the 1 000 L tank provers according to the gravimetric method.

3.2.2 Preparation for calibration

Tank provers are used to measure volumes of various types of liquid products that can contaminate the clean water used in the calibration. In order to avoid this type of problem, tank provers were checked for cleanliness before being calibrated. After that, tank provers were filled with clean water and inspected to check for leaks.

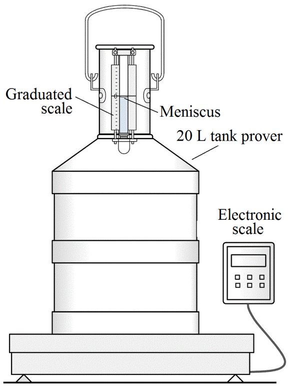

Figure 3: Schematic for calibration of the 20 L tank prover.

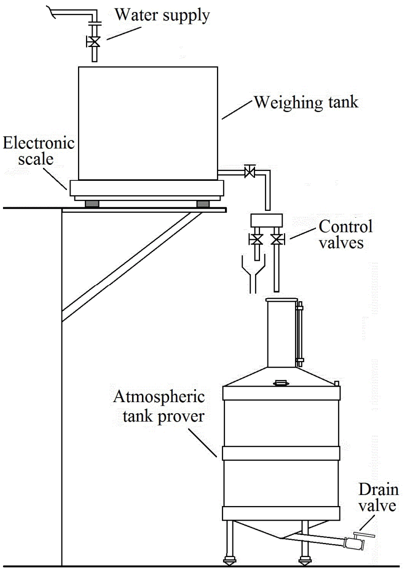

Figure 4: Schematic for calibration of the 1000 L tank prover.

The stability of the water temperature is a key factor for the success of the calibration. So, the water temperature during calibration should remain as stable as possible. The ideal calibration condition occurs with a maximum difference between the ambient air temperature and the water temperature of ±1 °C.

3.2.3 Calibration of the tank prover nominal volume

Calibration of the 20 L tank prover was performed by directly comparing the volume of water collected in the prover and the mass of water measured using an electronic scale. For that, the dry tank prover was carefully filled with water to the point of the scale to be calibrated. The water density at the calibration temperature was used for determination of the tank prover volume.

Calibration of the 1000 L tank prover was carried out according to the following steps:

- The scale was reset after verifying its normal operation.
- Carefully, place the weighing tank on the scale.
- Level the tank prover.
- Fill the tank prover with clean water up to the neck.
- Drain the tank prover by observing the flow of the water in the drain valve; when the drain is no longer a continuous water fillet, that is when the water begins to drip at the outlet of the drain valve, start timing with a stopwatch, and after 30 seconds close the drain.
- Take note of the initial mass value indicated in the scale (Important: the scale should not be zeroed).
- Fill the tank prover with water to the point of the scale to be calibrated; use a pipette when the water level is close to the mark to minimize the effect of the meniscus that is normally formed during the filling process.
- Wait for a period of stabilization of the temperatures of the water and the tank prover wall; start reading the parameters by entering the following values:
  - volume indicated in the tank prover,
  - initial mass value indicated in the scale with tank prover empty,
  - final mass value indicated in the scale with tank prover filled with water,
  - tank prover wall temperature,
  - water temperature inside the tank prover,
  - atmospheric pressure and
  - ambient air temperature and relative humidity.
- Empty the tank prover and repeat the procedure twice.
- Enter the data obtained in the three measurements in the calculation software and analyse the results.

3.2.4 Calculation Methodology

The volume of water contained in the tank prover by the gravimetric method is determined by equation (3):

$$V_{\text{water}} = \frac{m_{\text{water}}}{\rho_{\text{water}}} \quad (3)$$

where:

V_{water} : volume of water contained in the tank prover [m³];
m_{water} : mass of water measured by the scale [kg];
ρ_{water} : density of the water in the tank prover temperature when filled with water [kg/m^3].

- *Correction of the apparent initial mass indicated on the scale according to its calibration certificate*

$$m_{\text{init\_ind\_corr}} = m_{\text{init\_ind}} + k_1 \quad (4)$$

where:

$m_{\text{init\_ind\_corr}}$: initial mass indicated on the scale and corrected by its calibration certificate [kg];
$m_{\text{init\_ind}}$: initial mass indicated on the scale [kg];
k_1 : initial mass correction value, obtained from the scale calibration certificate [kg].

The method of calculating the apparent final mass indicated on the scale follows the same procedure.

- *Determination of the initial reference mass*

Correction of apparent initial mass of water for air buoyancy effect:

$$m_{\text{init\_refer}} = (m_{\text{init\_ind\_corr}}) \cdot \frac{\rho_{\text{water\_scale}} \cdot (\rho_{\text{std\_mass}} - \rho_{\text{air\_scale\_cal}})}{\rho_{\text{std\_mass}} \cdot (\rho_{\text{water\_scale}} - \rho_{\text{air\_tank\_cal}})} \quad (5)$$

where:
$m_{\text{init\_refer}}$: initial reference mass [kg];
$\rho_{\text{water\_scale}}$: density of the water at the temperature inside the weighing tank [kg/m³];
$\rho_{\text{std\_mass}}$: density of the standard mass used in the calibration of the scale [8000 kg/m³];
$\rho_{\text{air\_scale\_cal}}$: density of the ambient air during calibration of the scale [1.2 kg/m³];
$\rho_{\text{air\_tank\_cal}}$: density of the ambient air during tank prover calibration [kg/m³].

The method of calculating the final reference mass follows the same procedure.

- *Determination of the net reference mass of water*

$$m_{\text{ref}} = m_{\text{final\_refer}} - m_{\text{init\_refer}} \quad (6)$$

where:
m_{ref} : reference mass [kg];
$m_{\text{final\_refer}}$: final reference mass [kg];
$m_{\text{init\_refer}}$: initial reference mass [kg].

- *Density of water used in tank prover calibration*

Calibration of the 20 L tank prover was performed using distilled water. Density of the distilled water used to convert the mass of water to an equivalent volume of the liquid is given by the following state equation [5]:

$$\begin{aligned}\rho_{\text{dist\_water}} &= 999{,}8395639 + 0{,}06798299989 \cdot T_{\text{tank}} \\ &- 0{,}009106025564 \cdot T_{\text{tank}}^2 + 0{,}0001005272999 \cdot T_{\text{tank}}^3 \\ &- 0{,}000001126713526 \cdot T_{\text{tank}}^4 + 0{,}000000006591795606 \cdot T_{\text{tank}}^5\end{aligned} \quad (7)$$

where:
T_{tank} : water temperature at the tank prover temperature [ºC];
$\rho_{\text{dist\_water}}$: density of water at the tank prover temperature [kg/m³].

Calibration of the 1 000 L tank prover was carried out using clean water and the water density was determined using a calibrated density meter.

- *Determination of the tank prover reference volume at the calibration temperature*

Reference volume of the tank prover at the calibration temperature is calculated using the following equation:

$$V_{\text{refer}} = \frac{m_{\text{refer}}}{\rho_{\text{water\_tank}}} \quad (8)$$

where:
V_{refer} : reference volume at tank prover temperature [m³];
$\rho_{\text{water\_tank}}$: water density at the tank prover temperature [kg/m³].

- *Calculation of the volume of the tank prover referred to the temperature of 20 °C*

$$V_{20\,°\text{C}} = \frac{V_{\text{refer}}}{CTS} \quad (9)$$

where:
$V_{20\,°\text{C}}$: volume of the tank prover at the reference temperature of 20 °C [L];
V_{refer} : volume of the tank prover at the tank prover temperature [m³];
CTS : correction factor by thermal expansion of the tank prover material.

- *Correction factor by thermal expansion of the tank prover material (CTS)*

$$CTS = 1 + G_c \cdot (T_{\text{tank}} - 20) \quad (10)$$

where:
CTS : thermal expansion correction factor of the tank prover material;
G_c : volumetric thermal expansion coefficient of the tank prover material [1/ ºC];
T_{tank} : tank prover temperature [ºC];
20 : reference temperature of 20 ºC.

- *Measurement bias calculation*

$$E = 100 \cdot \left(\frac{V_{\text{nom\_vol}} - V_{\text{refer (20 °C)}}}{V_{\text{refer (20 °C)}}} \right) \quad (11)$$

where:
E : measurement bias of volume indication of the tank prover [L];
$V_{\text{refer (20 °C)}}$: reference volume of tank prover corrected for the reference condition of 20 °C [L];
$V_{\text{nom\_vol}}$: volume indicated on the mark scale [L].

3.2.5 Sources of measurement uncertainties

In the gravimetric method, the measurement uncertainties of each calibration results consider the standard deviation of the three volume measurements and the uncertainties associated to the reference mass measurements, water density, air density, tank material expansion factor and temperature measurements. The uncertainties are calculated according to the guidelines of reference [4].

4. Calibration results

Tables 4 to 7 present the results obtained by IPEM-SP and IPT in the calibration of the two tank provers.

Table 4: Results of IPEM-SP for calibration of 20 L tank prover.

(Mark scale) Nominal volume (L)	Reference volume (L)	Measurement bias (L)	Expanded uncertainty (L)	Coverage factor *k*
(-02) 19,8	19,805	-0,005	0,005	2,0
(0) 20,0	20,003	-0,003	0,005	2,0
(+0,2) 20,2	20,202	-0,002	0,005	2,0

Table 5: Results of IPT for calibration of 20 L tank prover.

(Mark scale) Nominal volume (L)	Reference volume (L)	Measurement bias (L)	Expanded uncertainty (L)	Coverage factor *k*
(-02) 19,8	19,804	-0,004	0,012	2,02
(0) 20,0	20,004	-0,004	0,012	2,02
(+0,2) 20,2	20,204	-0,004	0,012	2,02

Table 6: Results of IPEM-SP for calibration of 1 000 L tank prover.

(Mark scale) Nominal volume (L)	Reference volume (L)	Measurement bias (L)	Expanded uncertainty (L)	Coverage factor *k*
(-10) 990	989,79	0,21	0,12	2,0
(0) 1 000	1 000,04	-0,04	0,12	2,0
(+10) 1 010	1 010,48	-0,48	0,12	2,0

Table 7: Results of IPT for calibration of 1 000 L tank prover.

(Mark scale) Nominal volume (L)	Reference volume (L)	Measurement bias (L)	Expanded uncertainty (L)	Coverage factor *k*
(-10) 990	989,7	0,3	0,4	2,03
(0) 1 000	1 000,1	-0,1	0,4	2,03
(+10) 1 010	1 010,5	-0,5	0,4	2,03

5. Evaluation of the results

The evaluation of the performance of the participants in the interlaboratory comparison was performed using the normalized error (*NE*) criterion calculated for the measurement bias parameter, according to the expression:

$$NE = \left| \frac{E_{IPEM} - E_{IPT}}{\sqrt{U_{IPEM}^2 + U_{IPT}^2}} \right| \qquad (12)$$

where:

E_{IPEM} : result obtained by IPEM-SP laboratory;
E_{IPT} : result obtained by IPT laboratory;
U_{IPEM} : expanded uncertainty associated to the results of IPEM-SP laboratory;
U_{IPT} : expanded uncertainty associated to the results of IPT laboratory.

Tables 8 and 9 show the results of the evaluation of normalized error obtained in the comparison of the results of the calibrations carried out by IPEM-SP and IPT for the tank provers of 20 L and 1 000 L.

Table 8: Normalized error for the results of 20 L tank prover.

(Mark scale) Nominal volume (L)	Difference between measurement bias Values (L)	Normalized error *NE*
(-02) 19,8	-0,001	0,08
(0) 20,0	0,001	0,08
(+0,2) 20,2	0,002	0,15

Table 9: Normalized error for the results of 1 000 L tank prover.

(Mark scale) Nominal volume (L)	Difference between measurement bias Values (L)	Normalized error *NE*
(-10) 990	-0,094	0,22
(0) 1 000	0,064	0,14
(+10) 1 010	0,019	0,05

6. Conclusion

In summary, results presented in Tables 4 to 9 show that the performance of the laboratories in the calibrations were quite satisfactory for both atmospheric tank provers used in the comparison, especially considering that different calibration methods were used for determination of the reference volumes. The normalized errors obtained were between 0.08 and 0.15 for the 20 L tank prover and 0.05 to 0.22 for the 1 000 L tank prover, indicating a very satisfactory comparability between the two calibration methods.

References

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[6] API - MPMS – Chapter 4.9.4 – *Proving Systems*, Section 9 – *Methods of Calibration for Displacement and Volumetric Tank Provers, Part 4 Determination of Volume of Displacement and Tank Provers by the Gravimetric Method of Calibration*.