MEASUREMENT ACCURACY AND SOURCES OF ERROR IN TANK GAUGING

Class # 2270.1

C. Stewart Ash, P.E.
Measurement Engineer
BP Pipelines (North America), Inc.
1250 Crane View Road
Salisbury, NC 28146

Introduction

Tank gauging is the means used to determine the quantity of oil contained in a storage tank. How the volume is to be used often determines the degree of desired accuracy. If the volume is to be used to quantify a custody transfer movement and money will change hands based on the result, a high degree of accuracy is required; but if the volume is to be used only as an operational tool (i.e., is the tank nearly full or nearly empty), a high degree of accuracy is usually not required. If the volume is to be used for inventory control and/or stock accounting, the desired accuracy would be less than for custody transfer but greater than for normal operations.

The volume contained in a tank can be determined either by manually gauging the tank or by using an automatic gauging system installed on the tank. Hand gauging of tanks has normally been considered a very accurate method to determine the quantity of oil transferred into or out of a tank. In the United States, most automatic gauging systems have been considered to be less accurate than hand gauging, but there are automatic tank gauging systems available that meet the requirements for custody transfer.

When discussing the accuracy of a custody transfer movement by tank gauge there are several factors that must be considered:

(1) The tank
  a. Age of the tank and calibration
  b. Bottom movement
  c. Structural changes
  d. Sediment build-up
  e. Stilling wells
(2) Gauging methods
  a. Manual vs. Automatic
  b. Innage or Outage
(3) Gauging Errors
  a. Temperature measurement
  b. Sampling techniques
  c. Sample analysis
  d. Human error
(4) Calculations
  a. Correction to standard temperature
  b. Deduction for free water
  c. Floating roof correction
  d. Thermal expansion of the tank shell and/or tape
  e. Correction for suspended sediment & water
(5) Uncertainty
  a. Random and systematic errors
  b. Statistical analysis

The Tank

The volume measured in a tank is usually based on the calibration or strapping of the tank. If a tank is to be used for custody transfer, the calibration is normally done by an independent third party. When examining the calibration table for a tank, the date of the calibration should be checked. If the tank is old and has not been calibrated since 1965, the effect of liquid head was not included in the calibration, and could cause discrepancies of up to 0.25%. If the tank did not have an adequate foundation when it was built, the bottom of the tank could sag and result in a change in volume. This change in volume is not accounted for in the tank calibration tables. Bottom movement occurs when the tank is being filled or emptied. If the bottom deflection is permanent or if the bottom moves uniformly, the error is minimal. Depending on the magnitude of the movement, the error could be significant if the center sinks more than the outside or if the bottom movement varies with each filling or emptying of the tank. In these cases, the error can be as much as 0.10%, which would understate gauged receipts and overstate deliveries. Bottom movement is normally only a problem in fixed roof tanks, or when floating roofs are touching the bottom. Studies have shown that bottom movement in floating roof tanks normally occurs before the roof totally floats. Since most locations operate their tanks at levels above the critical zone (i.e., above the point where the roof is floating freely in the product), problems from tank bottom movement should be minimized for receipts into or deliveries from floating roof tanks.

Physical damage to a tank, such as dents in the side that change the volume, can also cause errors. Other physical changes that could affect the accuracy of the calibration include changing the type of floating roof on a tank or the addition of secondary seals. These changes affect the displacement weight of the roof that is included in the calculation of the calibration table. Movement of the reference gauging point or the datum plate can also affect accuracy of the measurements. Hydrostatic forces on improperly supported stilling wells and/or datum plates cause this movement and can result in movement of more than one inch. All tank gauging is no better than the stability of the measurement reference point. If a tank gauge is accurate to 1/16-inch but the datum plate moves two inches, the overall gauge accuracy is 1/16-inch ± 2 inches.

Build up of sediment on the bottom of a tank is another area of concern that can result in errors in gauging. When sediment/sludge and/or water are detected at the gauging point, it is assumed that it is evenly distributed on the bottom of the tank. Often irregular flow patterns in the tank result in uneven distribution of sediment on the bottom. When unusually large levels are detected it is often necessary to gauge the tank from several different points on the roof of the tank to determine the true profile of the sediment. During the gauging of a tank for the sale of a facility, a large crude oil tank was found with over eighteen inches of sediment at the gauging point. From the capacity table, this equated to over 25,000 barrels. Gauging from eight additional points on the roof determined that the sediment build up was limited to the area around the gauging point, and the total sediment was determined to be less than fifty barrels. Problems are also often encountered with free water on the bottom of a tank. It is usually assumed that the water is level across the bottom, but in reality it is often found to collect in puddles on the bottom.

In an effort to reduce emissions from the tank, some floating roof tanks have stilling wells that are not slotted. This will result in gauging and sampling errors. Unslotted stilling wells cause a slight overstatement of the gauged liquid level and therefore the volume. While the liquid level may be close to correct, the temperature of the oil in the stilling well is usually not at the same temperature as the oil in the rest of the tank. A sample of the oil from the stilling well also will not be representative of the oil in the rest of the tank. If a tank has a stilling well that is not slotted, it is recommended to find an alternative point to gauge and sample the tank.

For these reasons, it is recommended in the American Petroleum Institute's Manual of Petroleum Measurement Standards (MPMS) Chapter 2 that verification of the bottom diameter, plate thickness, and tank tilt be carried out every five years for tanks in custody transfer service. To reassure good measurement accuracy, tanks should be recalibrated at least every fifteen years even if the five-year verifications do not indicate any problems. For tanks not in custody transfer service, the verifications should be done every five to ten years and total recalibration at fifteen to twenty year intervals.

Gauging Methods

The first consideration in gauging is whether to manually gauge the tank or to use the automatic tank gauge. In the United States, custody transfer is usually based on manual tank gauging, since most automatic tank gauging systems do not have the desired reliability. There are, however, automatic gauging systems on the market that are as reliable as manual gauging. In other parts of the world, some of these systems are accepted by the government authorities (customs, etc.) for custody transfer.

All physical gauging of the tank should be done in strict accordance with the procedures listed in MPMS Chapter 3. Determining the volume in a tank consists of five different steps: measuring the level in the tank, measuring the temperature of the contents, sampling the contents, analyzing the sample, and calculating the volume in the tank at the observed temperature and then correcting it to a standard reference temperature (usually 60°F or 15°C).

There are two basic types of procedures for obtaining the gauges: Innage and Outage methods. An innage gauge, or bottom gauge, is the depth of liquid in a tank, measured from the surface of the liquid to the tank bottom or to a fixed datum plate. An outage, or ullage gauge, is the distance from a reference point on the top of the gauge hatch down to the surface of the liquid in the tank. Different equipment is used for each method. The tank calibration table also needs to agree with the gauging method utilized. The gauging method chosen often depends on the product in the tank. Innage is usually used for tanks with clean products, while outage is often used for heavier, heated products like fuel oil. Outage is also often used to measure product on marine vessels.

Gauging Errors

It is important that the gauges be repeated until duplicate gauges are determined. Often this step is ignored, and thus the first gauge could be in error. All gauges should be reported at least to the nearest 1/8-inch. As a cross check when innage gauges are taken, the total height of the tank must be checked against the reference height reported in the strapping tables. Direct innage gauges tend to be less accurate than outage, because the bob may tilt, or it may rest on a broken sample bottle or other surface irregularity.

Obtaining a truly representative temperature for the material in a tank is very difficult, and often impossible. Often the material in a tank is stratified and/or has temperature gradients throughout the tank. With electronic equipment it is possible to obtain accurate vertical temperature profiles of the tank; however, horizontal temperature gradients may also be present in the tank, contributing to the difficulty of obtaining an accurate average temperature of the product in the tank. If the tank is equipped with mixers, these problems can be reduced. However, many tanks do not have mixers, and thus the uncertainty associated with these problems must be accepted. The accepted procedures for measuring the temperature of a tank are discussed in MPMS Chapter 7. The preferred method is to average the upper (middle of the upper third of the tank), middle, and lower (middle of the lower third of the tank) temperatures; however, only the middle temperature is often used, resulting in an error in the temperature reported for the tank.

Electronic thermometers (thermoprobes) will equilibrate more rapidly (usually in seconds) in the tank and thus can be used to quickly obtain multiple temperatures to be averaged. The thermoprobe must be used properly, be checked regularly, and calibrated on a routine basis. Liquid-in-glass cup-case thermometers still tend to be widely used in the industry to determine temperature. In many cases it may take up to 15 minutes for a liquid-in-glass cup-case thermometer to reach equilibrium temperature, depending on the gravity of the material in the tank. Thus to get three temperatures, it can take over 45 minutes on top of the tank. The greater the difference in temperature between the oil temperature and ambient temperature, the greater the chance of an error in temperature tending towards the ambient temperature. The indicating fluid column may also separate in cup-case thermometers, resulting in a higher reading than is correct. The indicating fluid in liquid-in-glass thermometers has traditionally been mercury. Environmental concerns are making mercury less desirable for use in field thermometers.

Accurate temperature measurement is the single most difficult measurement to obtain from a storage tank and is generally the source of the largest volumetric error. The effect of temperature errors is dependent on the density of the product, i.e., the lighter the product, the greater the impact. The volume of gasoline changes 0.06%/^{o}F, while fuel oil changes only 0.03%/^{o}F. An error of 2.5 degrees Fahrenheit will result in an error of $\pm$ 0.1 percent for crude oil. For a typical storage tank, this is equivalent to an error of more than a half-inch on the gauge. An example of the effect of gauging and temperature errors is shown in Table 1.

Many of the problems associated with measuring the temperature also affect the obtaining of a representative sample from a tank. Since all gauging, temperature measurement, and sampling is done from a single location on top of the tank (the gauge hatch), it is often impossible to obtain a truly representative sample of the material in the tank. The oil in a tank may be a mix of different density materials that will remain stratified unless the tank is well mixed. Following the procedures in MPMS Chapter 8 will result in the best possible sample, but its limitations must be recognized.

After the sample is obtained, it has to be analyzed to determine compliance with the various product specifications. The gravity of the material is needed for the calculation of the actual volume in the tank. The accuracy of the gravity depends on the equipment used, the precision of the tester, and adherence to the test procedures in MPMS Chapter

9. The two most common errors associated with gravity determination are (1) failing to allow the temperature to stabilize before reading the hydrometer, and (2) misreading the hydrometer either by not looking at it level or by misinterpreting the meniscus. If an electronic densitometer is used, care must be given to eliminating air bubbles in the measurement tube.

The largest potential error in gauging is simply human error. This includes the failure to follow the proper procedures, use of improper equipment, allowing the bob to tilt, misreading the gauge tape, or not allowing the thermometer to reach equilibrium. Errors often result from the taking of "short cuts" in an effort to save time. The financial impact of these errors can far exceed the value of the time that is saved.

Calculations

The level gauge of the tank and the tank calibration table are used to determine the volume at the temperature of the tank. Before two volumes can be compared, they must be adjusted to the same temperature. MPMS Chapter 11.1 is used, along with the tank temperature and the gravity at standard temperature, to determine the Liquid Temperature Correction Factor (CTL), also known as the Volume Correction Factor (VCF), to correct the observed volume to the volume at the reference temperature of 60^{o}F. The current API volume correction tables, introduced in 1980 and revised in 2003, have been generally accepted. However, in some parts of the world, other correction tables and reference temperatures are used, and thus this must be considered when comparing data on foreign cargoes that are discharged in the U.S.

If the tank has a floating roof, the calibration table must be checked to determine the gravity of oil at which the roof correction was calculated. If the gravity of the oil in the tank (at tank temperature) is different from the roof correction gravity, an additional correction needs to be made. In many cases the roof correction is ignored resulting in an error. The extent of the error depends on the difference between the actual tank gravity and the gravity used to calculate the calibration table.

If the oil in the tank is very hot, other problems may be encountered in addition to the increased difficulty of determining the average temperature or obtaining a representative sample. Thermal expansion of the gauge tape can produce errors if corrections are not made. This can be reduced by gauging hot oils by outage (ullage). If the tank was strapped and the calibration table calculated at a different temperature, thermal expansion of the tank shell will have an effect on the measured volume, and the appropriate corrections should be made. The temperature could also cause the vertical movement of the stilling well and the reference gauge point. MPMS Chapter 12.1.1 provides additional information on calculating the volume of oil in a tank and on applying the appropriate corrections.

Uncertainty

Even if all of the measurements discussed above are taken in strict accordance with the API Standards, there is no guarantee that the results will be within acceptable tolerance. Custody transfer is normally based on the difference between two gauges - one before the start of the movement and another at the conclusion of the movement. The overall uncertainty of the measurement of a movement is as dependent on the quantity of oil in the tank and the amount transferred as it is on the accuracy of the individual measurements. Small movements out of large tanks that are nearly full tend to have the highest degree of uncertainty, while movements that take most of the tank volume tend to have the lowest degree of uncertainty. To illustrate this, consider two movements of 23,500 barrels from a 172,000-barrel tank. In the first, the tank has 171,000 barrels initially; while in the second, the tank has only 26,600 barrels. By variance analysis, the uncertainty of each transaction is reported as the standard deviation, which is the 95% confidence limit for the transaction (i.e., if the exact movement was repeated 100 times, 95 of the results would fall within a band around the current value equal to plus or minus the standard deviation amount). For the movement from the nearly full tank, the uncertainty is ± 313 barrels, or ± 1.33%; while from the nearly empty tank, it is ± 113 barrels, or ± 0.48%. As seen from this example, the uncertainty of a transaction based on tank gauges can vary widely. If all of the measurements were not made in strict accordance with the standards, the uncertainty would increase.

The overall uncertainty associated with a movement can be determined by considering the uncertainty (error) associated with each individual phase of the movement. The individual uncertainties can be combined statistically by taking the square root of the sum of the squares of the individual uncertainties. Table 2 illustrates some typical manual gauging errors and uncertainties and their impact on the volume in a 100,000-barrel tank.

Conclusion

The accuracy of an oil movement into or out of a tank is dependent on many varied factors. Depending on the precision of the individual measurements, adherence to accepted standards, and the particular circumstances of the movement, the uncertainty can vary from as low as ± 0.25% to over ± 1.5%. However, with attention to the procedures and the amount of oil transferred, the uncertainty should be in the ± 0.3% to ± 0.5% range.

TABLE 1

EFFECT OF GAUGING & TEMPERATURE ERRORS

ASSUME:	Product	=	Crude Oil
	Gravity	=	36° API
	Gauge	=	41' – 0"
	Temperature	=	85.0° F
	Volume	=	145,820 BBLS

GAUGING ERROR	GAUGING BBLS	TEMPERATURE ERROR	TEMPERATURE BBLS
¼"	66	1°F	73
½"	131	2°F	146
¾"	197	3°F	219
1"	263	4°F	277
		5°F	365

TABLE 2

IMPACT OF TYPICAL MANUAL INNAGE GAUGE ERRORS ON A 100,000-BARREL TANK

Error		Inches	Barrels	Percent
Tank Table Errors		±0.6 in.	±150 bbl.	±0.15%
Bottom Movement		+0.25 in.	+ 60 bbl.	+0.06%
Shell Diameter Thermal Expansion		+0.25 in.	+ 60 bbl.	+0.06%
Datum Plate Upward Movement		+1.5 in.	+350 bbl.	+0.35%
Error in Temperature Reading, 3^{o}F		±0.5 in.	±120 bbl.	±0.12%
Tape Calibration		±0.12 in.	± 30 bbl.	±0.03%
Tape Thermal Expansion		±0.15 in.	± 40 bbl.	±0.04%
Human Errors - Level Reading		±0.12 in.	± 30 bbl.	±0.03%
Total (if all errors positive)		+3.5 in.	+840 bbl.	+0.84%
Statistical Error Range:	High	+2.68 in.	+670 bbl.	+0.67%
	Low	+1.08 in.	+270 bbl.	+0.27%