

The Engineer's Guide to Tank Gauging

2021 EDITION



What is tank gauging?

Tank gauging technologies

Engineering standards and approvals

Volume and mass assessment

Accuracies and uncertainties

Temperature measurement

Liquefied gases

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System architecture

Overfill prevention

Appendix: Typical tank gauging configurations

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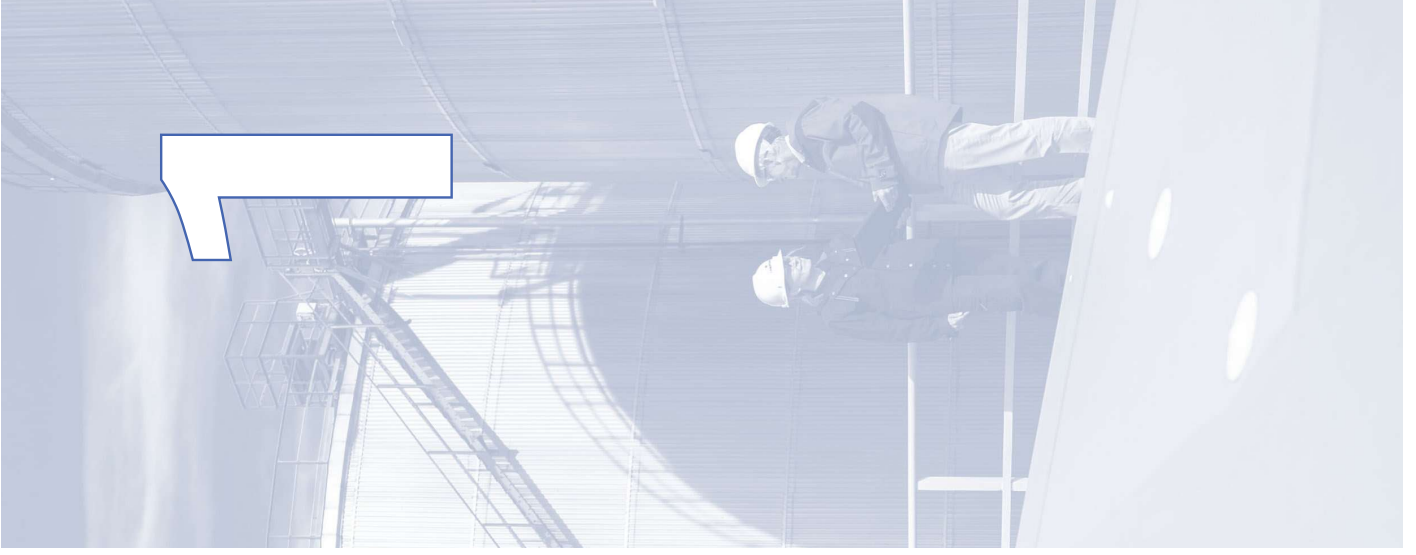
Abbreviations

AOPS	Automatic Overfill Prevention System	MPMS	Manual of Petroleum Measurement Standards
API	American Petroleum Institute	MTBF	Mean Time Between Failures
ATG	Automatic Tank Gauge	NIST	National Institute of Standards and Technology
ATT	Automatic Tank Thermometer	NMI	Nederlands Meetinstituut
BEV	Bundesamt für Eich- und Vermessungswesen	NSV	Net Standard Volume
BS&W	Base Sediment & Water	OIML	International Organization of Legal Metrology
DCS	Distributed Control System	OPS	Overfill Prevention System
EMC	Electromagnetic Compatibility	PLC	Programmable Logic Controller
EODR	Electro-Optical Distance Ranging	PTB	Physikalisch-Technische Bundesinstitut
FMCW	Frequency Modulated Continuous Wave	R 85	Recommendation 85, a special procedure for testing of tank gauging equipment defined by OIML.
FWL	Free Water Level	RRF	Risk Reduction Factor
FWV	Free Water Volume	RTD	Resistance Temperature Detector
GOV	Gross Observed Volume	SAT	Site Acceptance Testing
GSV	Gross Standard Volume	SIF	Safety Instrumented Functions
HTG	Hydrostatic Tank Gauging	SIL	Safety Integrity Level
IEC	International Electrotechnical Commission	SP	Technical Research Institute of Sweden
ISO	International Organization for Standardization	TCT	Tank Capacity Table
LNE	Laboratoire national de métrologie et d'essais	TOV	Total Observed Volume
LNG	Liquefied Natural Gas	VCF	Volume Correction Factor
LPG	Liquefied Petroleum Gas	WIA	Weight in Air
LTD	Level Temperature Density	WIV	Weight in Vacuum
MOPS	Manual Overfill Prevention System		
MIPE	Maximum Permissible Error		

1

What is tank gauging?

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1 - What is tank gauging?

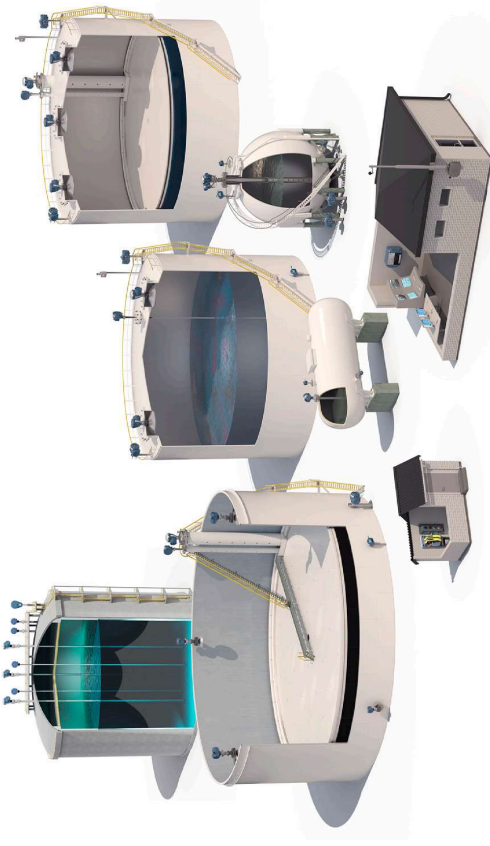
1. What is tank gauging?

Tank gauging is the measurement of liquids in large storage tanks with the purpose of quantifying the volume and mass of the product in the tanks.

The oil and gas industry generally uses static volumetric assessments of the tank content. This involves level, temperature and pressure measurements. There are different ways of measuring the liquid level and other properties of the liquid. The measurement method depends on the type of tank, the type of liquid and the way the tank is used.

Besides precision level gauging, temperature measurements are essential in assessing tank contents accurately. All liquids have a thermal expansion coefficient and proper volume compensation needs to be applied when transferring volumes at different temperature conditions. A pressure measurement of the liquid head is often added to provide a current assessment of the average observed density and to calculate the product mass.

Modern tank gauging systems digitize the tank measurement and digitally transmit the tank information to a control room where the liquid volume and mass information is distributed to users of the inventory data.



Storage tanks can contain large volumes of liquid product representing a significant value. The accuracy performance of a tank gauging system is of high importance when assessing the tank content at any given time.

Tank gauging is used on large storage tanks in refineries, fuel depots, pipelines, airports, and storage terminals. Storage tanks usually come in four basic designs: Cylindrical fixed roof tanks, cylindrical floating roof tanks and pressurized tanks of either spherical or horizontal cylinder design. There are tank gauges available for all these tank types.

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1 - What is tank gauging?

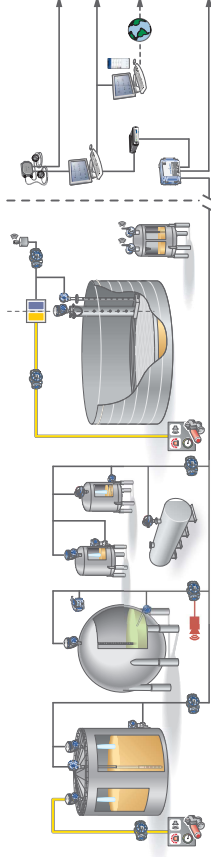


Figure 1.1 : Tank gauging involves a substantial number of interdependent devices and functions.

many different functions spanning from operator interface, batch handling, reporting, alarm functions, connectivity to host systems and much more. It is a system engineering science across many areas of technology.

Storage tanks are often placed in clusters or tank farms. The tanks are atmospheric, pressurized or cryogenic.

Atmospheric tanks are vertical cylinders with various roof designs. Most common are:

1.2 Where is tank gauging used?

Tank gauging is needed wherever liquids are stored in large tanks. Such storage tanks are found in:

- Refineries
- Petrochemical industry
- Distribution terminals
- Pipeline terminals
- Fuel depots
- Air fueling storage at airports
- Chemical storage

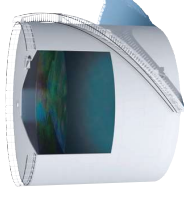


Figure 1.2: Fixed roof and floating roof tanks.



In a fixed roof tank there is a vapor space between the liquid surface and the external roof.

In a floating roof tank the liquid surface is covered by either an internal or an external floating roof. There are many different designs of floating roofs depending on the service, the liquid and the size of the tank. It is common that floating roof tanks have one or more still-pipes that go from the bottom of the tank, through an opening in the floating roof to the top of the tank. This still-pipe is used to access the liquid for sampling, hand level gauging, hand temperature measurement and automatic tank gauging. With a good Automatic Tank Gauge (ATG) design, all these things can be performed in one still-pipe.



3

1 - What is tank gauging?

Pressurized tanks are often of spherical or horizontal cylinder design.

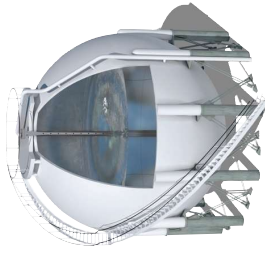


Figure 1.3: Pressurized tanks normally require automatic tank gauging in a still-pipe.

Hand gauging cannot be performed on pressurized tanks. For high accuracy automatic tank gauging a still-pipe inside the tank is normally required.

In cryogenic tanks, automatic tank gauges are often of the same design as for pressurized tanks.

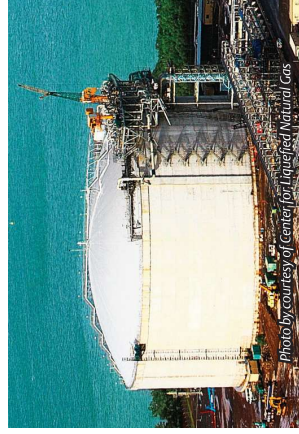


Photo by courtesy of General Ion, liquefied Natural Gas
1.4: Cryogenic tank storing LNG at -162°C.

The methods for proper automatic tank gauging are described in various engineering standards. The most commonly applied standards are the [Manual of Petroleum Measurement Standards \(MPM5\)](#) issued by the American Petroleum Institute (API).

1.3 The purpose of tank gauging

The information from a tank gauging system is used for many different purposes. The most common are:

- Oil movement and operations
- Inventory control
- Custody transfer
- Loss control and mass balance
- Volume reconciliation
- Overfill prevention
- Leak detection

1.3.1 Oil movement and operations

The operation of a tank farm relies heavily on information regarding the situation in the tank farm. To operate the tank farm safely and efficiently it is important to know exactly what is going on inside the tanks. The tank gauging system must at any given time provide instant information about:

- How much liquid is in the tank
- How much available room is left in the tank
- At what level rate the tank is being filled/discharged
- When the tank will reach a dangerously high level
- When the tank will become empty at a given pump rate
- How long a given batch transfer will take

The operation will also require that the tank gauging system gives alerts and alarms before any preset level or dangerous high tank level is reached.

Oil movement and operations depend on reliable and readily available tank information. A loss of tank gauging data will seriously interrupt time critical operations and product transfers which may lead to unplanned shut downs.

1 - What is tank gauging?

1.3.2 Inventory control

A tank farm stores valuable assets, and owners of the assets will require very accurate assessments of their value.

The tank gauging system should be able to provide high accuracy inventory reports at given intervals or instantly if so required. Automatic measurement of free water at the bottom of the tank may also be required for accurate inventory assessment. The tank inventory figures are essential for financial accounting purposes and are often used for fiscal and customs reporting. The system should be able to calculate net volumes and mass according to the rules set forth by industry standards organizations such as API and others.



Figure 1.5: Inventory management calculations.

1.3.3 Custody transfer

When buying and selling large volumes of liquids, tank gauging data serves as the main input for establishing correct invoicing and taxation. Certified tank gauging can provide more accurate transfer assessments compared with metering when performing large transfers such as from a tanker ship to a shore tank. With a certified tank gauging system manual tank surveying can often be omitted.

For legal or fiscal custody transfer, the tank gauging system must be certified by international authorities, mainly the International Organization of Legal Metrology (OIML). The system may also be required to have approvals from local metrology entities such as PTB, NMI, LINE or other national institutes.

Custody transfer requires the highest possible accuracy of the tank gauging system. The OIML standard R 85:2008 defines the requirements for tank gauges used for custody transfer.

1.3.4 Loss control and mass balance

The financial impact of refinery losses is of great importance. Achieving a high quality mass balance of a refinery is the method by which losses are estimated. It is important to distinguish between real losses and apparent losses stemming from measurement errors.

The refinery loss is defined as:

$$\text{Loss} = \text{inputs} - \text{outputs} - \text{current inventory} + \text{previous inventory} - \text{fuel}$$

For loss control purposes the highest possible accuracy of inventory measurement is required. Hence the quality and performance of the tank gauging system is of utmost importance in the area of loss control and mass balance.

1.3.5 Overfill prevention

A tank overfill can have disastrous consequences. A spill can cause explosions and fire that can spread to all tanks in the tank farm and to the surrounding area. Since the tanks contain huge amounts of stored energy, a fire can have far-reaching consequences.

Fires caused by overfill have rendered legal damages exceeding \$1 billion. From this, and many other perspectives, preventing tank overfill is extremely important.

A spill can happen when the tank operators are unaware of what's going on in the tank farm. This could take place if an undetected fault occurs in the tank gauging components. High level switches could, if not maintained and tested properly, also fail.

Tank gauging devices provide the basic process control layer in the tank farm. Independent high level indicators or level-switches form the next layer of protection. Any undetected failure of these two protection layers can cause a serious accident.

1 - What is tank gauging?



Figure 1.6: Puerto Rico accident in 2009.

This is why the reliability of the tank gauging system and the high level alarm system has to meet the requirements stated by the standards for Functional Safety. More about this subject is explained in Chapter 10.

1.3.6 Leak detection

If the tank gauging system is accurate and stable enough it can be used for tank leak detection. When a tank is settled and closed, the tank gauging system can be set to detect small liquid movements. It is recommended that leak detection is based on Net Standard Volume (NSV) rather than just level. By monitoring the NSV, level movements caused by temperature changes can be canceled out. Custody transfer grade accuracy performance of the tank gauging system is required for proper leak detection.

1.3.7 Volume reconciliation

Tank farm operations need to accurately manage transactions and reconcile transfers versus physical inventory. Every company is accountable; reconciliation and error reporting provide the auditing and traceability that is often required. The tank gauging system will allow the immediate data acquisition and response required for accurate daily accounting and reconciliation.

The performance of flow meters can be monitored when transfer data from the meters are compared with batch reports from the tank gauging system.

1.3.8 Floating Roof Monitoring

Floating roofs can create operational and safety issues, with significant mechanical damage, overfills, and release of explosive hydrocarbon vapor. Tank content may also become contaminated. Reasons for tank malfunction may be that the roof is stuck due to damaged or incorrectly mounted rim seals. Leaking pontoons, overfills, strong winds, and inadequate draining during heavy rain or snowfall can also dangerously affect buoyancy and roof position.

A floating roof monitoring function detects whether a roof in a storage tank is stuck, sinking, tilted, floating higher or lower than normal, or if it is covered by water or product.

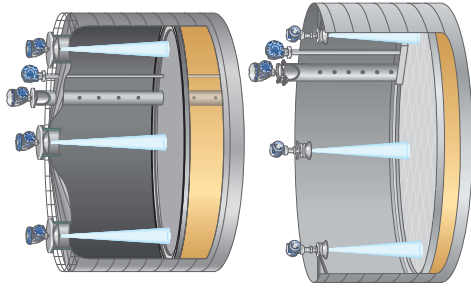


Figure 1.7: Up to six non-contacting level instruments are placed either at the tank shell or on top of the outer roof. Roof tilt is tracked by comparing the distance between each device and the floating roof.

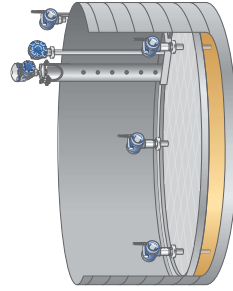


Figure 1.8: Up to six guided wave level transmitters can be installed directly on the floating roof, with rigid probes penetrating through the roof and into the liquid below. Roof tilt is tracked by comparing the distance from the floating roof down to the product surface. With one or two extra transmitters one can also detect if the roof drain gets plugged or if there is any hydrocarbon on the tank roof.

2

Tank gauging technologies

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2 - Tank gauging technologies

The servo gauge generally performs better than a float gauge. A newly calibrated servo gauge can meet custody transfer accuracy requirements. However, the servo gauge has many moving parts and the displacer and the wire are in contact with the tank liquid. Hence servo gauges need attention in the form of calibration, routine maintenance and repair.

Servo gauges used for density and water measurement

Some servo manufacturers claim that the unit may be used for purposes other than level gauging. The servo can be used to measure liquid density and water bottom levels, but in both cases the level gauging is inhibited while the servo gauge performs a displacer dip into the product. By measuring the wire tension it is possible to measure the liquid density at various levels in the tank. When water bottom detection is carried out, the displacer is lowered until it hits the free water level at the tank bottom. Both these actions can create dirt build up on the wire, the displacer and the wire drum, creating a maintenance problem over time. The most significant drawback is the lack of level gauging during these dipping exercises. It should also be noted that density measurement with a servo gauge is not recognized by any engineering/gauging standard.

Today, both float gauges and servo gauges are being replaced by modern tank gauges based on radar technology.

2.4 Radar gauges

The first radar tank gauges were developed in the mid 1970's (radar is also referred to as microwaves). The early versions were made for installations on seagoing tankers. Radar technology quickly gained popularity and has since then basically been the only level gauging technology of choice for any large tanker ship.



Figure 2.8: Radar level measurement was introduced for marine applications by Saab in 1976.

In the early 1980's, radar tank gauges were further developed to fit shore based storage tanks. Radar technology rapidly gained market share and is today generally the first choice in any tank gauging project. Since the 1980's, many different radar gauges have been marketed for tank gauging and other level applications. Today, there is a large supply of radar instruments on the market effectively replacing mechanical, ultra sound and capacitance level sensors due to their inherent user benefits.

A radar level gauge has no moving parts and requires no regular maintenance. Radar devices require no direct contact with the liquid. This makes it possible to use a radar gauge on a wide variety of liquids from heated heavy asphalt to cryogenic liquefied gases like Liquefied Natural Gas (LNG).

A good radar tank gauge can easily provide reliable gauging for over thirty years.



Figure 2.9: First high precision radar gauge installed in 1985 on a refinery tank.

If the radar is designed correctly it requires no recalibration after the first adjustment on the tank.

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Figure 2.10: Modern radar level gauge on a fixed roof tank.

2.5 Different types of radar gauges

There are many radar level gauges on the market. Several are made for process applications where high accuracy and stability are not the primary requirements. Unit cost and other considerations related to these applications are more important.

2.5.1 Process radar level gauges

Process radar devices are made for many different applications in the process industry. High pressure and high temperature combined with strong tank agitation are common challenges for process radar installations. Under these conditions, high level accuracy is not the primary focus. Other qualities such as high reliability and low maintenance are more important. Pulse radar is the dominant technology in most process radar transmitters. Pulse radar provides low cost, low power and reliable gauging under tough conditions. Process radar transmitters are in general 2-wire units driven by a 4-20 mA loop bus powered, or battery powered wireless. They are either of free space propagation type or guided wave. The free space radar transmitters have a horn, a lens or parabolic antenna. The guided wave type has a solid or flexible antenna protruding into the tank.

There is a wide spectrum of process radar devices, and manufacturers in the market serve different market segments such as the chemical industry, oil and gas and the food and beverage industry.

Currently, pulse technology based radar transmitters are less accurate than FMCW based transmitters used for tank gauging applications.



Figure 2.11: Non-contacting radar level transmitter and guided wave radar level transmitter for process applications.

2.5.2 Tank gauging radar gauges

To meet the high performance requirements of custody transfer accuracy in tank gauging applications, radar devices typically use the Frequency Modulated Continuous Wave (FMCW) signal processing method. The FMCW method sometimes goes under the name "Synthesized Pulse".

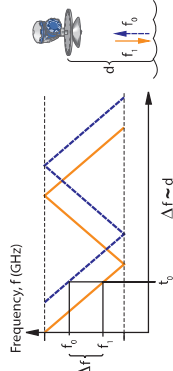


Figure 2.12: The FMCW method.

FMCW is capable of delivering an instrument level gauging accuracy of better than a millimeter over a 50+ meter range.

Since its birth in the 1970's, the FMCW based radar tank gauge has developed rapidly. Several generations of radar tank gauges have been released. The latest design has been miniaturized to the extent that two radar units can share the same small enclosure and deliver reliability and accuracy never seen before. At the same time, power requirements have been reduced to the point that radar tank gauges can be made totally intrinsically safe and require only a 2 wire bus for power and communication.

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FMCW is required to make a radar tank gauge accurate, but this is not enough on its own. Precision radar gauges must also have specially designed microwave antennas to be able to deliver both the instrument accuracy and installed accuracy required by custody transfer standards.

One important property of radar antennas is that they should be designed in such a way that any condensation will quickly drip off. Therefore, antennas inside tanks require sloping surfaces to avoid accumulation of condensate liquids.



Figure 2.13: Antenna design with no horizontal surfaces, according to the American Petroleum Institute Standard (API ch. 3.1b, ed. 1)

There are three main types of applications for radar tank gauges:

- Fixed roof tank installation
- Floating roof tank installation on a still pipe
- Installation on tanks with liquefied gases, pressurized or cryogenic

A radar tank gauge should be able to deliver highest accuracy when mounted on existing tank openings. On a fixed roof tank, the openings suitable for tank gauging are normally found on the roof close to the tank wall.



Figure 2.14: Fixed roof tank openings.

This position is ideal due to stability provided by the tank wall and a minimum of roof flexing as a result. A radar tank gauge must be able to deliver highest accuracy even when placed close to the tank wall. Antennas with a narrow microwave beam are most suitable for such tank locations in close proximity to the wall. The larger the antenna, the narrower the microwave beam becomes.

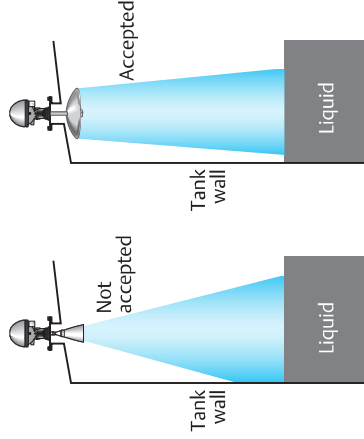


Figure 2.15: Radar gauges with wide beam (small antenna) and narrow beam (large antenna).

On a floating roof tank, the still-pipe is located where any liquid level gauging takes place since the rest of the liquid surface is covered by the floating roof. A radar tank gauge antenna for still-pipes must be designed so that existing still-pipes of various sizes and designs can be used. The still-pipe must have slots or holes to allow good liquid mixing between the inside and the outside of the pipe. If no holes or slots are present it is likely that the liquid level inside the pipe will be different from the rest of the tank. If the pipe is filled from the bottom, heavier product will then accumulate in the pipe. The slots or holes prevent this.

A radar tank gauge for still-pipe applications must have the ability to cope with a still pipe with large slots/holes and yet deliver high accuracy. It must also perform with the highest accuracy even if the pipe has rust and dirt build-up on the inside.

In addition, a still-pipe antenna must be made so that the still-pipe can be accessed for other tasks like sampling and hand gauging.

2 - Tank gauging technologies



Figure 2.16: Low loss mode radar measurement can be used to virtually eliminate measurement degradation in old still-pipes.

Using a still-pipe as a waveguide

Tubular shaped waveguides supporting the so called H01 mode are capable of providing an attenuation of just a few decibels per kilometer. Such pipe shaped waveguides have been tested to act as telecommunication channels across nations. The same low loss H01 propagation mode has successfully been utilized in radar tank gauging applications for many years.

Still-pipes in normal storage tanks are tubular, often in sizes between 5 to 12 in. or 125 to 300 mm in diameter. These pipes can work as wave guides for radar tank gauging in the 10-11 GHz frequency range. A waveguide with holes and slots in combination with dirt build-up and weld residue between pipe sections will generate microwave losses and make the still pipe unsuitable for tank gauging. However, using the low loss mode of the H01 propagation, these slot/hole related problems are virtually eliminated. It is proven that still-pipes with more than 30 years of crude oil service will work perfectly as a waveguide for accurate radar tank gauging provided that the low loss H01 is used.



Figure 2.18: Hand dip access in a still-pipe.

2.6 Radar frequency selection

For tank gauging applications, the reliability of the gauging and the accuracy performance are the primary qualities. To meet the requirements it is

important to select the optimal antenna design and the right microwave frequency. When using still-pipes as waveguides it turns out that frequencies in the X-band are optimal. Fixed roof storage tanks without still-pipes often have tank apertures in sizes 200 to 600 mm (8 to 24 in.) in diameter. Suitable antennas for such openings are those that can handle heavy water condensation and dirt build-up. Under these conditions horn, cone or parabolic antenna design has proven to work very well, especially since they can be designed with drip-off surfaces. Such antennas at this size range have an excellent track record when used in frequency ranges between 9-10 GHz (X-band).

Higher frequencies are used in process radar gauges to be able to fit smaller antennas in narrow tank gauge openings. However small antennas and higher frequencies tend to increase sensitivity to condensation and dirt build-up.

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2.7 Pressurized tanks

Special properties are required for a microwave antenna used for tank gauging in pressurized tanks:

- The antenna arrangement must be able to withstand the tank pressure.
- It should have a shut-off valve for protection and to meet safety requirements.
- It should have the ability to compensate for high-density tank atmospheres and any effect this has on the microwave propagation speed.
- It should be possible to verify the performance of the gauge during normal tank operations.

There are solutions to meet all these criteria with a good gauge and antenna design. See [chapter 7](#) for more about radar gauging on pressurized tanks.

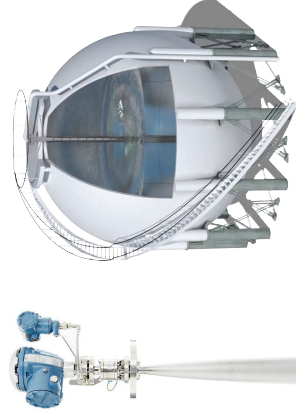


Figure 2.19: Radar gauge sensor including heavy atmosphere compensation in an LPG tank.

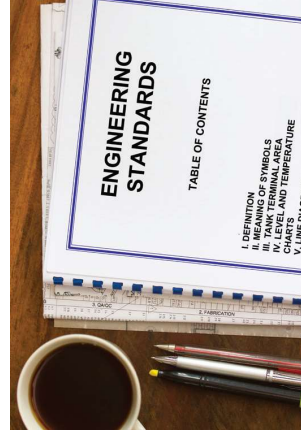
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Engineering standards and approvals

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3. Engineering standards and approvals

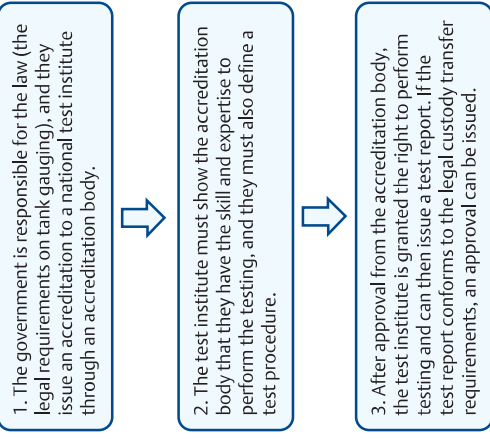


There are a number of international standards that are relevant for tank gauging. The main purpose of these standards is to serve as guidelines for both users and manufacturers of tank gauging equipment. The members of the working groups behind the development of these documents are in most cases experienced users from the petroleum industry or manufacturers with considerable tank gauging knowledge. It is important that the working groups have a good balance between users and manufacturers, to avoid standards becoming biased in any direction. The present trend is to avoid technology specific standards as much as possible, and specify the requirements on equipment for a certain application. This leaves the door open for any technology to conform, if it can be proved that it fulfils the requirements.

To prove compliance to a standard is however not always easy, since there must be an independent authority/body available that has the knowledge and resources to test a tank gauging system. ISO (International Organization for Standardization) and API (American Petroleum Institute) are responsible for the most important standards within tank gauging, but do not have their own test organization and are not organized as typical test institutes.

Instead it is the national metrological authorities in a country who should have this expertise. Depending on how custody transfer based on tank gauging equipment has been implemented in their country,

they have (to a varying degree) the necessary experience, skills and resources. Therefore, in countries where there are legal requirements for tank gauging equipment, there should also be a department within a metrological organization which handles the legal aspects of tank gauging equipment. Typically it works like this:



Fortunately, the different national institutes in the world that perform testing are cooperating within an organization named OIML (International Organization of Legal Metrology). In this organization a number of test procedures are defined, and there is a special procedure defined for tank gauging equipment called [R 85 \(Recommendation 85\)](#).

Since most countries that have defined requirements for legal custody transfer are members of OIML, the test procedure for having national approval is basically the same in each OIML country, and complies with R 85. There may be some minor differences in the requirements from one country to another, but in principle a country that is a member of OIML should not adopt any other requirements than those prescribed by R 85.

A tank gauging system that has been tested by an accredited OIML R 85 institute in one country, will therefore not need to repeat the same test in another. However, it cannot be assumed that there

will be an automatic approval in each new country, since the original R 85 test report will often be subject to a thorough examination to check that the R 85 procedure has been followed as intended.

Since many requirements on level gauges for tank gauging in OIML R 85 have been harmonized with the requirements defined in both the ISO and API standards, it will in most cases mean that a level gauge that fulfils the testing criteria according to OIML R 85 also fulfils the requirements according to ISO and API. It should be noted however, that the OIML R 85 only covers the testing of the level gauge functions. Product temperature measurements or density measurements are not covered by OIML so far, see [section 3.3](#).



Figure 3.1: Still-pipe in an open floating roof crude oil tank.

Another aspect of the standards should also be noted. If an accident such as an overflow of a tank (or in the worst case a fire with casualties) occurs at a petroleum plant, it will probably result in a lawsuit and/or criminal prosecution. In such legal proceedings the status of the whole installation of the level gauge system is likely to be scrutinized. One question then becomes very important: "Is the level gauge system installed and operable to best engineering practice?"

If not, and the level gauge system or installation is in a bad condition, it is probable that the owner of the plant could receive serious fines, have to pay huge damages, or even face imprisonment. If the owner, on the other hand, can show that the equipment or installation conforms to a standard with good

reputation like the API or ISO standards, it may be difficult to prove that the status of the equipment is not according to "good engineering practice". In particular, the guidelines in API Manual of Petroleum Measurement Standards (MPMS) chapter 3.1A and chapter 3.1B are important in this respect, since they include several guidelines which could be said to define "good engineering practice", see following example:

Example 3.1: Good engineering practice
 API MPMS chapter 3.1 A recommends how a still-pipe in a floating roof tank should be designed, and especially what minimum hole size is needed to ensure proper product flow from outside the pipe to the inside. It is obvious that holes that are too small, (or no holes at all) could cause an overflow since the level gauge mounted on the still-pipe in this case would indicate a level that is too low, because the level outside the pipe will be higher. On the other hand, the user does not want to have an excessive hole size since this would increase product evaporation which could conflict with environmental regulations. By complying with the recommendation in API MPMS chapter 3.1A, the owner would be following recommendations issued by the most knowledgeable people in the petroleum industry.

3.1 American Petroleum Institute (API) standards

The API standards are well known by most people in the petroleum industry. One important characteristic of the API standards is that they provide very useful experience based facts about daily tank gauging problems and how to solve them. They also summarize know-how from practical investigations which have been performed by research departments at major oil companies. Specifically for tank gauging there are some important API standards in MPMS such as:

- **Chapter 3.1A** Standard Practice for the Manual Gauging of Petroleum and Petroleum Products
- **Chapter 3.1B** Standard Practice for Level Measurement of Liquid Hydrocarbons in Stationary Tanks by Automatic Tank Gauging

3 – Engineering standards and approvals

The American Petroleum Institute (API) was established in New York City 1919, following a momentum build towards forming a national association to represent the oil and gas industry in the postwar years.

API

Today, API is based in Washington D. C. and it is the largest U.S. trade association for the oil and natural gas industry. It represents approximately 650 petroleum industry corporations involved in production, refinement and distribution among other areas.

The main function of the API is speaking for the oil and natural gas industry in order to influence public policy in support of the industry. Its functions include advocacy, negotiation, lobbying, research, education and certification of industry standards.

- Chapter 3.3 Standard Practice for Level Measurement of Liquid Hydrocarbons in Stationary Pressurized Storage Tanks by Automatic Tank Gauging
- Chapter 3.6 Measurement of Liquid Hydrocarbons by Hybrid Tank Measurement Systems
- Chapter 7 Temperature Determination
- Chapter 7.3 Temperature Determination – Fixed Automatic Tank Temperature Systems
- API 2350 Overfill Protection for Storage Tanks in Petroleum Facilities

These standards are briefly described below.

3.1.1 Chapter 3.1A and 3.1B

The API MPMS chapter 3.1A is related to how to perform manual measurements according to best engineering practice. Since the manual measurement on the tank is the reference for automatic measurement with level gauges, it is of utmost importance that manual gauging is performed correctly. Chapter 3.1A includes detailed information on how a manual measurement should be performed and also how it should not be performed. This procedure may seem very simple at first glance, but it

is surprising how often a discrepancy between a value taken by hand dip and a value from an automatic level gauge is caused by an inaccurate hand dip. The reason may be that poor equipment such as inaccurate/non-calibrated hand dip tapes were used, temperature corrections of the tape were not made, the hand dip was carried out on a moving/turbulent surface, or the person performing the hand dip was careless etc.

Another common reason for hand dipping discrepancy is the mechanical properties and instability of the tank. The influence of mechanical instability can be explained as follows: The level gauge measures the distance from its reference point down to the liquid surface, and calculates the level by subtracting the measured distance (ullage) from the reference height (the distance from the gauge hatch reference down to the datum plate, see [chapter 2, figure 2.1](#)).

The person who performs the hand dip measures the distance from the datum plate up to the mark the product makes on the tape, i.e. if the reference height varies due to mechanical or thermal stress there will be a discrepancy. How much the reference height varies depends on the actual tank type and the design of the tank. In API MPMS chapter 3.1A (and also in chapter 3.1B) there is valuable information on how to design tanks with a minimum variation of the reference height. Some important basic guidelines can be mentioned:

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Tank with still-pipe:

- If the tank has a still-pipe it is important that it is attached to the tank bottom correctly and that it is guided only at the top, see figure 3.2.

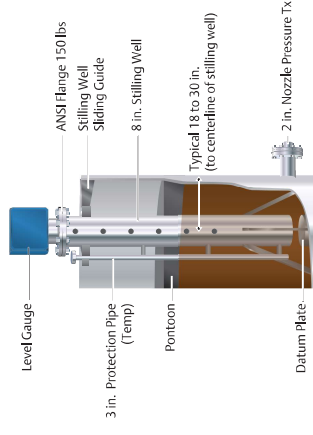


Figure 3.2: Still-pipe attached to the tank bottom.

- When attached to the wall, the bulging effect of the tank wall due to heavy static pressure from the liquid should not cause the still-pipe to move vertically. A hinge design as in figure 3.3 should prevent this.

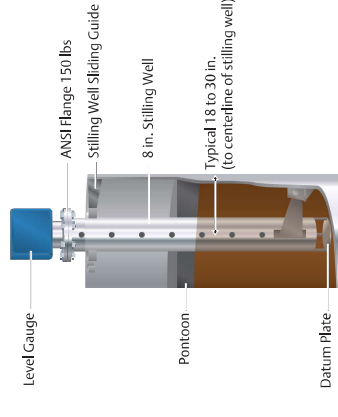


Figure 3.3: Still-pipe attached to the tank wall.

- The datum plate (the hand dip reference plate) should be attached to the still-pipe and not installed on the bottom of the tank unless the still-pipe stands directly on the tank bottom.

Tank with fixed roof, no still-pipe:

- To avoid movements between the level gauge reference point and the gauge hatch, the level gauge should be installed close to the gauge hatch.
- When the level gauge is installed on a manway on the roof, flexing of the roof where the level gauge is located should be minimized. Best practice is to install the level gauge “fairly” close to the tank wall where the roof is most stable. (The meaning of “fairly” depends on the level gauge type, see relevant level gauge installation information.)

Some of the reference height variations can also be compensated for in a modern level gauge. The criteria for using this option is that the variation is predictable. Bulging of the tank wall is one example, since it is related only to the static pressure on the tank wall and therefore predictable. If the reference height is measured at a number of different product levels, it is possible to program the change into the level gauge and compensate the level value for the reference height variation. Another predictable variation is the thermal influence on the tank wall or still-pipe. By using the temperature information from a multi-spot temperature sensor, the level gauge can compensate for the expansion/contraction caused by temperature changes. For a fixed roof tank, this compensation calculation depends on both the ambient temperature and liquid temperature. Chapter 3.1A describes how this should be taken into account.



Figure 3.4: Manways are normally located near the tank wall which provides mechanical stability.

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Chapter 3.1A lacks a more exact description regarding how to handle the hand dip tape and how to make tape corrections. Some users measure ullage (the distance from a reference in the dip hatch to the liquid surface) instead of level. This is common for heavy products in order to avoid the whole tape being coated with product. Hand dipping a full bitumen tank in cold winter weather by lowering the tape all the way down to the bottom will make the tape unusable for the future.

When making a hand dip in heated tanks it is very important to make a temperature correction of the tape. An example:

- A hand dip tape typically has a thermal expansion coefficient of 12 ppm / °C, and is calibrated at 20°C.
- In a bitumen tank with temperature 220 °C and at 20 m distance the tape will be: $(220-20) \times 12 \times 10^{-6} \times 20000 = 48$ mm longer.
- The tape will consequently show an error of 48 mm at 20 m distance.

It is clear that in the case above temperature correction is necessary. This is also the case in heated tanks with lower temperatures like fuel oil etc. where temperature correction is necessary to get a reference accuracy in the range of a few millimeters.

Another method of hand dipping used by some is to attach a metal bar at the hand dip tape and position the tape by placing the bar on top of the hand dip hatch and only dip the lowest end of the tape into the liquid. After subtracting the liquid cut on the tape from the value on the tape to which the bar was attached, it is possible to get a very exact reading. This is an ullage measuring method, and reference height changes will not influence the reading except for any variation in the level gauge reference position compared to the position of the gauge hatch.

API MPMS chapter 3.1A and also 3.1B strongly recommends that the user measures the reference height at the same time as the liquid level hand dip is made. This is a very straightforward method, and it will immediately tell the user if any discrepancy is related to the level gauge or to the mechanical instability of the tank.

In API MPMS chapter 3.1B, the focus is on automatic tank gauging equipment. The chapter does not specify any particular preference for any technology, but it is very clear that there are very few technologies that can meet the custody transfer requirements of 1 mm (0.04 in.) accuracy under laboratory conditions over the whole temperature range.

Chapter 3.1B also specifies a very relaxed accuracy requirement when the level gauge system is used for inventory purposes only. The requirement is defined as low as 25 mm (1 in.). It is unlikely that a user would purchase a level gauge system with such a low performance, so it is probable that this figure is set to allow old systems to fall in the category of “best engineering practice” in a legal dispute, and they would therefore not be in immediate need for exchange to more modern equipment.

The level gauge system is generally not only used for operations, custody transfer and inventory purposes, but also for mass balance, loss control and in some cases leak alarm purposes. Chapter 3.1B does not address the requirements of these latter purposes at all, however in modern tank gauging it could be noted that many users have similar requirements for these as for custody transfer purposes. The requirements do however become more complicated since the requirements for mass balance and loss control are based on mass precision, and level accuracy is in these cases only one parameter in the equation.

3.1.2 Chapter 3.3: Level measurement in pressurized tanks

The standards in Chapter 3.3 deal with level measurement in pressurized tanks. It describes the special safety precautions required for pressurized LPG tanks and how an installation according to best practice may be achieved.

A special circumstance with a pressurized tank is that the normal reference measurement with a manual hand dip cannot be used. Instead the standard describes some indirect reference methods; one for servo based, and one for radar based level gauges. This means that in this case, the rule of avoiding technology specific solutions has not been followed.

Both the described reference methods may be questionable from a theoretical metrological point of view, since the traceability to a national standard is not entirely straightforward. However, there are no better verification methods for this application, and the metrological authorities have in general accepted the limitations of the reference methods.

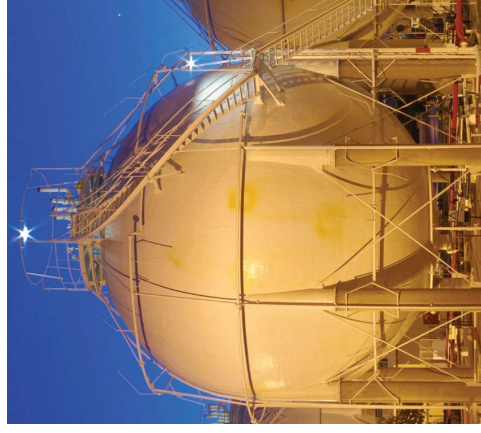


Figure 3.5: Level measurement in pressurized tanks cannot be done by hand gauging, leading to technology-specific recommendations for servo based and radar based level gauging.

Since LPG usually has a lower economic value compared to refined oil products, user requirements are generally not that strict. Often the accuracy achieved by mass flow measurements is regarded as sufficient. Transactions of LPG based products based on legal custody transfer are therefore not very common.

Much of chapter 3.3 instead focuses on performance requirements to obtain a safe and reliable measurement in LPG tanks, and the accuracy figures mentioned are very much based on the metrological uncertainty in the reference measurement, where hand dip not is an alternative. Despite this, chapter 3.3 provides valuable information on best practices for installing and putting a level gauge system for LPG in operation.

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3.1.3 Chapter 3.6: Hybrid tank gauging system

The name “hybrid tank gauging system” comes from the fact that it is a combination of a traditional tank gauging system and a Hydrostatic Tank Gauging (HTG) system. There are two main use cases for a hybrid system where the user is interested in either mass or density (or both).

Most hybrid system users in the petroleum industry are interested in measuring density online since the calculation of transferred volume (Standard Volume) requires measurement of level, temperature and density. The hybrid system makes it possible to avoid manual density measurement on tanks, which is a labor intensive task and is often related to serious measurement errors if not done properly. To be able to calculate density, a hybrid system therefore has one pressure sensor if the tank has atmospheric pressure, and two pressure sensors if the tank is not freely ventilated.

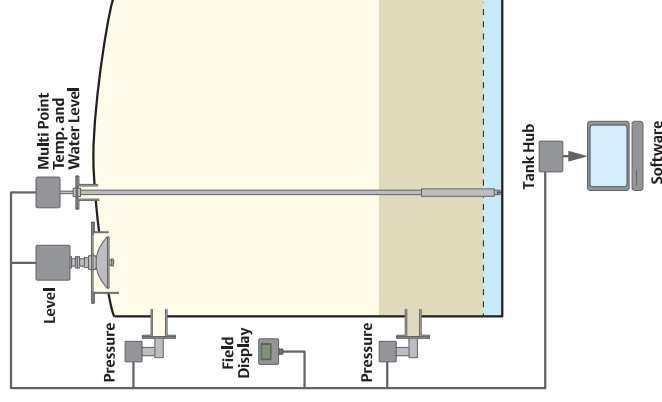


Figure 3.6: Hybrid tank gauging is a combination of a traditional tank gauging system and an HTG system.

In a traditional Hydrostatic Tank Gauging (HTG) system there is one additional pressure sensor and no level gauge system. The product density in the HTG system is calculated from the density between the P1 and P2 sensors only. The density in this range is not representative of the density of the whole tank and the value is therefore normally not usable for custody transfer.

With a hybrid system, the density is calculated by using the liquid column height above the P1 sensor given by the level gauge. In this case a much more accurate density value is received, representing the overall density of the product.

Since most petroleum products are by tradition traded based on standard volume and not mass, the use of a hybrid system (or HTG system) for mass measurement is of very limited use worldwide. There are however some exceptions, for example China, which has for many years used mass based custody transfer. Some installations, mainly for storage of special chemical petroleum products are another exception, but they are in general rare.

Chapter 3.6 is unique in that it not only gives information on best practice for installation of a hybrid system, but it also shows what accuracies can be expected on density and mass. All calculations in a hybrid system and the expected performance will be discussed in chapter 8.

3.1.4 Chapter 7: Temperature Determination

API MPMS chapter 7 is now being revised and one important new approach is to divide the different use cases into four subchapters. The previous edition of chapter 7 included many different temperature measuring cases in the same section which was somewhat confusing, so the new approach is an improvement.

Only part 7.3 is finalized today. It describes temperature measurements in tanks for inventory and custody transfer purposes. Section 7.3 gives a lot of important guidance on how a proper installation should be made, how many sensors are required for custody transfer use, and what accuracy on individual temperature elements, electronic conversion units, etc. is required.

Since the accuracy of a modern level gauge today is very high, it is in many cases the temperature

accuracy that is the most critical measurement in order to get a high accuracy of the quantity assessment. The importance of temperature measurement accuracy is described more in chapter 6.

3.2 ISO standards

The International Organization for Standardization (ISO) has also developed a number of standards for tank gauging. In the past these standards could be quite different compared to API standards, but during the last 15 years, considerable harmonization between API and ISO has taken place.

This has resulted in standards which have very similar content. As a consequence it was decided to have more direct cooperation between API and ISO, which would reduce the costs for the standards development.

Today ISO issues no new standards in the tank gauging area. Instead ISO takes an active part in the API work of standard revisions and development of new ones. There are however some API standards not yet ready (one example is the remaining sub chapters under API chapter 7) and therefore some ISO standards are still relevant.

The ISO standards are not discussed in detail in this guide, but the list below shows the relevant ISO standards for tank gauging purposes:

- ISO 4266-1:2002 Petroleum and liquid petroleum products -- Measurement of level and temperature in storage tanks by automatic methods -- Part 1: Measurement of level in atmospheric tanks
- ISO 4266-2:2002 Petroleum and liquid petroleum products -- Measurement of level and temperature in storage tanks by automatic methods -- Part 2: Measurement of level in marine vessels
- ISO 4266-3:2002 Petroleum and liquid petroleum products -- Measurement of level and temperature in storage tanks by automatic methods -- Part 3: Measurement of level in pressurized storage tanks (non-refrigerated)

- **ISO 4266-4:2002** Petroleum and liquid petroleum products -- Measurement of level and temperature in storage tanks by automatic methods -- Part 4: Measurement of temperature in atmospheric tanks

- **ISO 4266-5:2002** Petroleum and liquid petroleum products -- Measurement of level and temperature in storage tanks by automatic methods -- Part 5: Measurement of temperature in marine vessels

- **ISO 4266-6:2002** Petroleum and liquid petroleum products -- Measurement of level and temperature in storage tanks by automatic methods -- Part 6: Measurement of temperature in pressurized storage tanks (non-refrigerated)

- **ISO 15169:2003** Petroleum and liquid petroleum products -- Determination of volume, density and mass of the hydrocarbon content of vertical cylindrical tanks by hybrid tank measurement systems

3.3 OIML

The most important document from OIML which concerns level gauges is the R 85 recommendation. This document specifies the requirements of a level gauge that should be used for legal custody transfer, how it should be tested for a pattern approval, and what procedures should be followed to put the level gauge in operation on a tank. In addition it describes a suitable procedure for verifying that the level gauge is in proper condition.

The requirements of the level gauge when used for legal custody transfer are quite high, and today there are very few products that can live up to them. The reason for the high demands is that a level gauge in legal use acts as a third party between a buyer and a seller of large volumes of bulk liquids with high economic value. The measurement device is neutral in this transaction, and there are many corresponding transactions in our daily life which are similar. Some examples which we take for granted are the result from a weighing machine or a gasoline pump, where we don't question the result if we know that it is approved by a metrological office.

Also, the result from the level gauge can often be used for determination of import tax where the government has an interest in the measurement having highest possible precision.

The accuracy requirements in OIML R 85 for having pattern approval is: Maximum Permissible Error (MPE) which may not be larger than ± 1 mm (0.04 in.) over the intended operating range. In addition this requirement must be fulfilled over the intended temperature range which may be the most severe requirement, since it puts high requirements on the temperature stability of both mechanical components and electronics. The installed accuracy requirement is: MPE may not be larger than ± 4 mm (0.16 in.), and this figure includes not only errors from the level gauge but also all errors from tank mechanics, thermal stress of the tank etc.



The International Organization of Legal Metrology (OIML) is an intergovernmental organization founded in 1955 and based in Paris. It promotes global harmonization of legal metrology procedures that are the base of and facilitate international trade. Harmonizing legal metrology ensures that certification of measuring devices in one country is compatible with certification in another.

OIML has developed guidelines to assist its members in creating appropriate legislation and guidelines on certification concerning metrology. They work closely with other international organizations to ensure compatibility between certifications. OIML does not have the authority to impose solutions on its members, but its recommendations are often used as part of domestic laws.

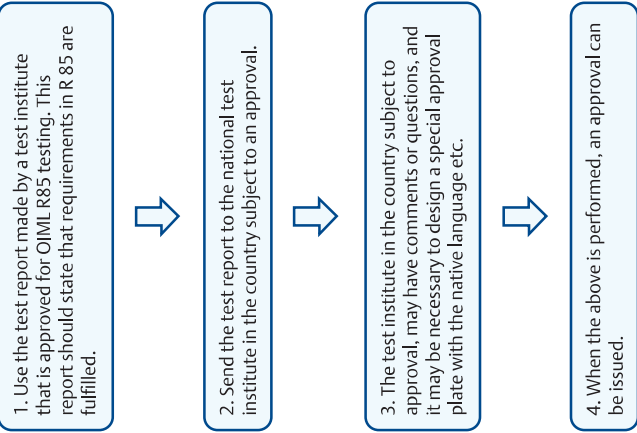
The procedure when testing a level gauge against R 85 also includes a number of influence factor tests, like EMC, short power interrupts, stability in communication links, provisions to allow metrological sealing etc. Consequently, a level gauge that passes a pattern approval test according to R 85 will have shown that it has potential to work with high precision on a tank. However it is not sufficient to just pass the pattern approval tests, since the level gauge also needs to conform to the installed accuracy requirements, i.e. the whole mechanical arrangement on the tank must be in good condition. The latter is normally the responsibility of the owner of the tank, but in practice the level gauge manufacturer is often involved by giving guidance and recommendations to the tank owner.

So far OIML has not issued any recommendation on how to measure temperature or density for legal tank gauging purposes. Corresponding ISO and API standards are therefore at present the most important documents in this area. Also the requirements on total volume accuracy is not defined in any OIML recommendation, even though working group activity has been discussed.

3.4 National metrological institutes

As mentioned earlier, neither ISO nor API are organized as test laboratories, and therefore they do not have the capability to test a tank gauging system against the requirements in a standard. Since the test procedure is not described in detail in most standards, it will be up to the test institute, who is often the expert in this area, to define the procedure. OIML has for their guidance developed a detailed test procedure for OIML R 85, and it is expected that this procedure will be followed by all institutes. This is a big improvement compared to how it was some 20 years ago, when each country had their own test procedure, which made tested equipment more expensive in each country, and also reduced the number of available models of level gauges.

The procedure to get an approval in a country is much easier today:



This procedure assumes that the actual country has accepted OIML R 85 as the base for their national requirements. Not all countries have yet become members of OIML, but it is very rare that they will not accept OIML R 85, or have requirements that are not in line with R 85.

Some OIML member countries have been approved for making tests of level gauges according to the R 85 recommendation. Some of the most important are mentioned below (in alphabetical order):

3.4.1 Netherlands Meetinstituut (NMI)

NMI has a long experience in testing level gauge systems used for custody transfer, especially servo based level gauges. They chaired the secretariat for R 85 for many years, and there is a long history of using metrological sealed level gauges in the Netherlands.

3.4.2 Physikalisch-Technische Bundesanstalt (PTB)

Germany also has a long history of using level gauge systems under legal metrological control, and the approval of equipment has been made by PTB. Some time ago Germany had their own requirement for level gauge systems, but have now adopted R 85 as their national requirement. Germany has also for many years had national requirements on the temperature measuring system in a tank gauging system. Surprisingly, they are alone on this despite the fact that temperature is a very important parameter in the assessment of a transferred quantity. See chapter 6 and [example 6.1](#) for the influence of temperature on volume and mass assessment.

3.4.3 Technical Research Institute of Sweden (SP)

SP has also been accredited for the testing of level gauge systems according to OIML R 85. They have a very good reputation for testing advanced radar based level gauge systems, and they use very advanced equipment for testing this type of technology. The total uncertainty in the test equipment they use is less than 0.17 mm (0.0067 in.) over a 30 m (98 ft) measuring range.

3.4.4 Other national institutes

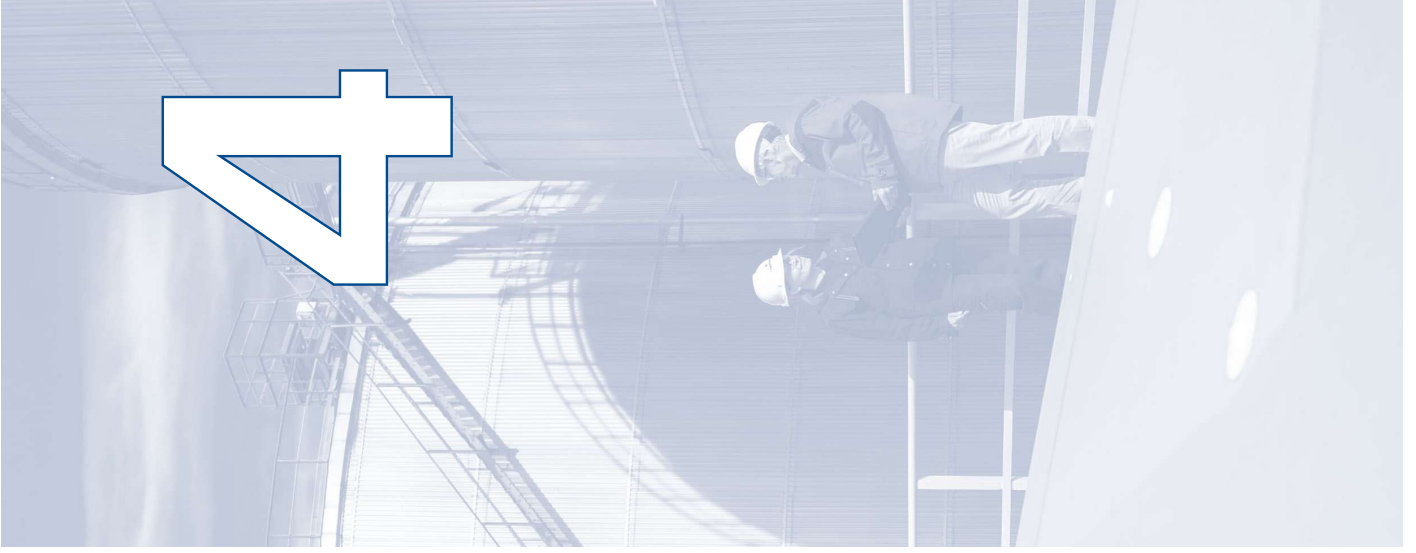
Bundesamt für Eich- und Vermessungswesen (BEV) in Austria chaired the secretariat for R 85 for a number of years in the past, and have also carried out some testing against OIML R 85 requirements.

National Institute of Standards and Technology (NIST) in the USA has recently taken over the secretariat for R 85. Custody transfer under legal metrological control is not well known in the USA currently, however with the presence of API and many major oil companies there is a lot of know-how in the country. The fact that the institutes mentioned above are experts on metrological issues and often have limited knowledge of the practical life for a tank gauging system, has sometimes raised criticism against documents like R 85. With NIST as chairman (and maybe with API involved) this could probably be overcome.

4

Volume and mass assessment

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4. Volume and mass assessment

Measurement data from a tank gauging system plays an important role for the operation of both refineries and terminals in the petroleum industry. Depending on the type of operation, various calculations are performed which to a high degree have been standardized within the industry.

4.1 Volume assessment

Calculation of volumes is central, and this procedure is described in figure 4.1 below. For a more detailed view, see figure 4.4.

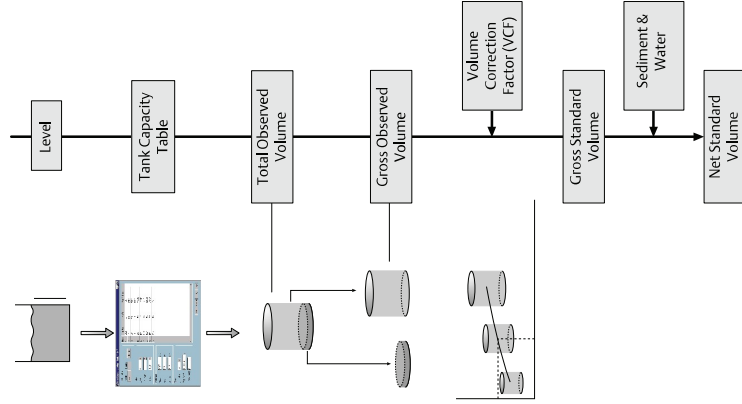


Figure 4.1: Volume calculation flowchart.

4.1.1 Total Observed Volume (TOV)

The measurement value from the level gauge is a value that is calculated within the level gauge. When calculating the value, corrections both for reference height changes due to static mechanical stress and temperature expansion/contraction may have been applied. This corrected level value is entered in what is referred to as a Tank Capacity Table (TCT), also called a Strapping Table. The TCT converts the level value to a volume value normally called Total Observed Volume (TOV). Since the TCT is only valid for certain temperatures, a correction also needs to be applied to allow for tank wall expansion/contraction due to the influence of product temperature and ambient temperature. API has stated that the tank wall temperature for non-insulated tanks should be calculated as:

$$T_{\text{tankwall}} = \frac{7}{8} T_{\text{product}} + \frac{1}{8} T_{\text{ambient}}$$

Measuring the ambient temperature on a tank may however require an expensive ambient meteorological station on each tank, so in many cases this figure is manually entered as a fixed value, since it does not affect the final result very much. The temperature effect from the liquid can however be quite large on the TCT, especially on heated products, or tanks which have ambient temperatures which differ considerably from the calibration temperature of the TCT.

The correction for a TCT due to temperature on a cylindrical carbon steel tank is:

$$\text{Volume TCT}_{\text{corrected}} = \text{Volume TCT} \times (1 + \Delta T \times 0.000022)$$

$$\text{where } \Delta T = T_{\text{TCT calibration temp}} - T_{\text{tankwall}}$$

Some TCTs also state that a correction due to density should be applied, i.e. this means that the TCT is only valid for a certain product density, and a different density will, due to more or less mechanical stress,

Dip [mm]	Volume [litres]	Incr. [l/mm]	Dip [mm]	Volume [litres]	Incr. [l/mm]
100	12,062	81.8	200	19,811	87.2
110	12,813	75.1	210	20,705	89.4
120	13,488	67.4	220	21,619	91.4
130	14,190	70.3	230	22,554	93.5
140	14,920	73.0	240	23,508	95.4
150	15,675	75.5	250	24,482	97.4
160	16,456	78.0	260	25,474	99.2
170	17,260	80.5	270	26,409	93.5
180	18,088	82.8	280	27,360	95.1

Figure 4.2: Example of a Tank Capacity Table.

change the values in the TCT. It is unusual to see this correction today, but in case it is required, a modern tank gauging system should have this possibility.

Another correction that should be made applies to floating roof tanks with still-pipes. In a floating roof tank, the roof will occupy a certain volume of the product and it should therefore be subtracted from the value given by the TCT. This correction depends on the weight of the roof and the observed density of the product, where the observed density is the actual density of the product at the temperature when the correction is made.

4.1.2 Gross Observed Volume (GOV)

The next calculation step is Gross Observed Volume, which includes subtraction of any Free Water Volume (FWV) from the bottom of the tank. The free water level is either measured manually by hand dipping or automatically with a Free Water Level (FWL) measurement probe connected to the level gauge system. The value from this probe or the manually entered free water level value is entered into the TCT, and the FWV value is subtracted from the TOV.

4.1.3 Gross Standard Volume (GSV)

All hydrocarbon liquids change their physical volume in relation to their temperature. When stating a volume value, this would be of no value without stating at what temperature the figure applies to. In the petroleum industry, this temperature value is usually standardized to 15°C or 60°F, where the Celsius value is commonly used in Europe, Asia, Australia and South America. The Fahrenheit scale is

used in North America and often also for crude oil in the Middle East. The conversion of Observed Volume into a temperature Standardized Volume is carried out using the API tables, where a conversion factor is defined.

Since hydrocarbon liquids in the petroleum industry may consist of many hundreds of different individual liquid components, it will be difficult or impractical to determine the volumetric expansion of a product like crude or gasoline based on the individual volumetric expansion of the incorporated liquid components. Instead a simplified approach has become an accepted standard. It is based on the fact that there is a correlation between volumetric expansion and density. Instead of complex investigations of all individual hydrocarbon components in a product, only the density of the product is considered and from that an estimation of the volumetric expansion due to temperature is made. This method is not 100 percent accurate, but as long as all parties in the petroleum business use the same method and base the price on a product on this estimation, it could be argued that the precision of this estimate is acceptable.

This is the essence of the API tables, which were first issued in 1952. In the first issue there was no differentiation between any petroleum products; crude was handled in the same way as gasoline, kerosene or fuel oil. In 1980, a new revision was released which made a differentiation between crude and refined products, where the refined products were also divided into four different subgroups depending on their density range. The 1952 tables were based on printed tables, and the underlying algorithms were not presented. There were even some printing errors in these first tables and some

4 - Volume and mass assessment

values were adjusted by hand before printing. These tables would be quite difficult to implement in a computer today.

The 1980 table presented an algorithm which was possible to implement effectively in a computer, but the table had limitations in resolution. This limitation was mainly a consequence of the fact that the intention with the printed table was for the user to have a look-up table and enter values rounded off to the resolution in the table. The tables could be entered into a computer, as long as the software rounded the input values to the same resolution as in the printed table.

With the introduction of computers which simplified all these calculations, and new measurement technologies which had a precision above the resolution in the printed 1980 tables, the request came up to have "tables" that were based on algorithms only and where no rounding of measured values were made. These tables were published in 2004, and are often referred to as "the year 2K tables". They use the same algorithms which were the base for the printed 1980 tables but do not require the rounding of the input values. With improved measuring devices, they will therefore give different results compared to the 1980 tables, and with better precision.

Today all the tables described above are still in use, and for different reasons. Some users have the 1952 tables as their standard since it appears that oil exporting countries get some benefit from these tables. Many use the 1980 tables, often because they have not yet made any investment in new software to be able to use the new 2004 tables. Buyers of new tank gauging systems often request the new 2004 tables. A supplier of tank gauging equipment must therefore be prepared to have both the new and all the old API tables implemented in the tank gauging calculation software, even though the old 1952 tables may be somewhat awkward to implement.

To change from one revision to another is more complicated than it seems. On a refinery it might mean that there will be a substantial change to the inventory value of products, which could be difficult to handle from an accounting point of view. Also all transfer contracts and pricing to external customers may have to be adjusted to the new revision.

The input values for the API tables are average product temperature and density or thermal

expansion coefficient. The density value used in the API tables must be the density at the same temperature as the reference temperature for the actual table, e.g. the density value for table 54 should be the density at 15°C. In practice this is achieved by taking manual samples of the product on tank, these samples are then measured in a laboratory either with a glass hydrometer or an electronic density meter. The measurement also includes measurement of product temperature, and the corresponding density value is called "observed density" (i.e. the density at the actual temperature during measurement). To be able to use this value in the API table, it should be converted to reference density (using the same temperature that the table refers to). This is made with another API table which is linked to the volume table, i.e. if table 54A is used then there is an API table called 53A which should be used to convert observed density to reference density. The same applies to table 6A, B and C, where there are corresponding API tables called 5A, B and C which give the gravity value for number 6 tables. In modern tank gauging systems all these calculations are normally available, i.e. the user only needs to enter the observed density and related product temperature of the sample, and the tank gauging system will then calculate the value for reference density that should be used for the VCF calculation.

Since engineering units vary globally, the tables are also divided into tables using Celsius temperature and density, Fahrenheit temperature and API gravity, or Celsius temperature and specific gravity (specific weight). Therefore the tables are referred to as:

- Table 6A, crude oil: Conversion using 60°F and API gravity
- Table 6B, refined products: Conversion using 60°F and API gravity
- Table 6C, special products: Conversion using 60°F and thermal expansion coefficient
- Table 54A, crude oil: Conversion using 15°C and density (at 15°C in vacuum)
- Table 54B, refined products: Conversion using 15°C and density (at 15°C in vacuum)
- Table 54C, special products: Conversion using 15°C and thermal expansion coefficient

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4 - Volume and mass assessment

The output from the API tables as above is a value called Volume Correction Factor (VCF).

The Gross Standard Value (GSV) is then given by:

$$GSV = GOV \times VCF$$

It should be noted that the C tables above may be used for special products where the thermal expansion coefficient is known. This is mainly the case where only one or a few single hydrocarbon components are present. There is also some use of API tables, mainly in some South American countries, which are based on specific gravity (specific weight) and temperature corrected to 20°C.

4.1.4 Net Standard Volume (NSV)

The Net Standard Volume (NSV) is the same as GSV unless there is a measurable content of base sediment and suspended water (BS&W) in the product. This is mostly common in crude oil and measured at laboratories in percent. Therefore, the NSV is given by:

$$NSV = GSV - BS\&W \times GSV$$

4.2 Mass assessment

Standardized volumes are vital for a number of operations in the petroleum and terminal industry such as custody transfer, inventory management etc. Sales of petroleum are in most cases based on NSV, but there are a few exceptions where the mass value is used in transactions. China is one example that has practiced mass based custody transfer over a number of years. Also, when selling refined products over a weighing bridge it would be natural to sell the quantity in mass terms. LPC is another example where sales are often based on mass, using mass flow meters for the measurement.

However, loss control is normally the most common use case for mass measurement. If we imagine a refinery which wants to estimate the efficiency or the losses that occur in the process, volume is not an option to use. The reason is that if they measure the product input in volume terms then they cannot compare that to the output volume from the plant.

since the chemical process changes the physical composition of the crude oil. In theory one could actually get more volume out from a refinery than was put in.

It is different with mass, where the output would be the same as the input if no losses occur and no addition of weight is made in the process. Therefore loss control is based on mass, not volume.

The term "mass" also needs an explanation, since by definition it is the Weight in Vacuum (WtV). In practice this unit is rarely used; the term Weight in Air (WtA) is more common. WtA is calculated by subtracting the weight of 1 cubic meter of air from WtV. The weight of 1 cubic meter of air is typically 1.22 kg, which value is used in the calculation. This value should be programmable for the operator since it may vary slightly from country to country.

4.3 Quantity assessment of liquefied petroleum gases

As mentioned in chapter 3, LPG transfers are generally based on mass using mass flow meters. Quantity assessment in volumetric terms is not uncommon however, particularly for inventory purposes, and in rare cases also for transfer. The calculation of LPG volume is however problematic, as the calculation of VCF via the API tables is not supported. The reason for this is that the density range for LPG products is below what modern API tables are defined for. This is true for tables from 1980 and onwards, but the very old API tables from 1952 have a density range which could allow them to be used for LPG products. The input from users has shown that it is a quite common practice to use the old 1952 tables despite the fact that they are only available as printed tables (no defined data algorithm is available), and they also have some printing errors in the tables. This is of course not an ideal situation, but since no other API tables are available this is currently the only option.

There are also some special calculations for LPG products since tanks containing liquefied gases may have a substantial amount of product in the gas phase. To calculate the total product volume, the tank gauging system must be able to accurately assess product volume and mass in both liquid and gas phases. This involves the calculation of Vapor Liquid Volume Ratio (VLR) which requires measurement of the vapor pressure in the tank.

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4 - Volume and mass assessment

For this reason, an LPG level gauge should have a pressure sensor attached (often integrated) for the VLVR measurement.

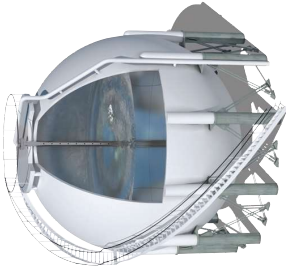


Figure 4.3: A pressurized tank with product in both liquid phase and gas phase.

The VLVR calculation method was published in a preliminary ISO standard which did not receive the status as a final standard. However since the calculation is based on general physics, the method has received acceptance in the industry as the standard method for calculation of VLVR.

An inventory control system as described above can automatically carry out the total volume assessment based on the tank liquid level, the volume tables, the product properties and pressure measurement.

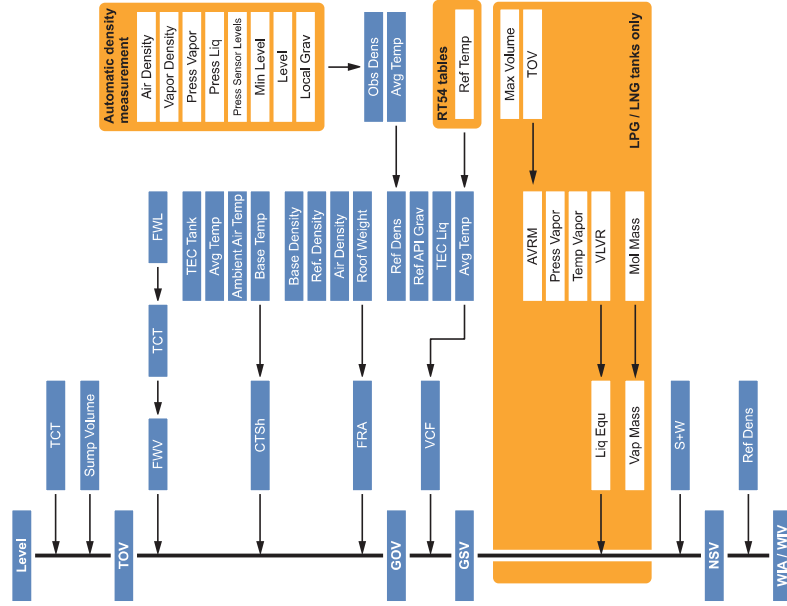


Figure 4.4: Detailed volume calculation flowchart.

Accuracies and uncertainties

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5. Accuracies and uncertainties

The term "accuracy" is used in most level gauge manufacturers' sales documents. The definition of accuracy is however somewhat unclear, unless the manufacturer has actually specified it. It should also be noted that in more precise documents like the OIML R 85 this word is not used or defined.

Customers may ask themselves: does the accuracy figure also apply when the level gauge is installed on a tank? Does it consider all types of parameters (temperature, pressure, EMC, ageing etc.) that may influence the operation of the level gauge, and does the figure mean that all level gauges will never show an error larger than the accuracy statement?

The reason for using the word accuracy is likely to have a historical explanation, and it could be assumed that since the interpretation varies, that is also what some manufacturers want. Going back to the questions above, it is worth considering the following:

Does the accuracy figure also apply when the level gauge is installed on a tank?

A responsible supplier of tank gauging systems will clearly state that the figure applies to what is called *reference conditions* and the supplier should also be prepared to show the customer how these reference conditions are set up. In other words, the user should obtain a document from the supplier which details the conditions in which the accuracy statement was originated. The measuring range and the temperature range should be addressed, and there should be an uncertainty calculation of the precision of the reference measuring system etc.

A responsible supplier will not guarantee the installed accuracy, since that means guaranteeing the skill of the persons making the comparing hand dip, guaranteeing all types of conditions that could occur in the tank, and also guaranteeing the mechanical stability and method of installation for each tank. It is not possible to guarantee all these things without making a time consuming investigation, for which in most situations there is neither time nor resources available. A vendor that gives such guarantees

without knowing anything about the tanks or operation of the tanks should be looked upon with some suspicion by the user.

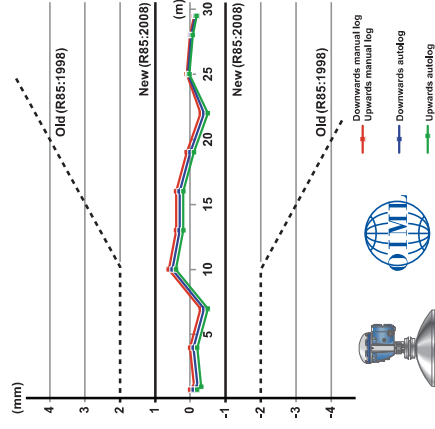


Figure 5.1: Graph showing OIML level accuracy requirements with a high performance radar gauge.

Often when a user buys a tank gauging system there is a certain goal that must be achieved, like: "the system should be used for legal custody transfer". This means that it should not only fulfil the requirements of accuracy under *reference conditions*, but also fulfil the system requirements when installed on a tank. This could mean that the user needs to calculate how much it would cost to make modifications to the tank to be able to fulfil the installed accuracy statement. In this whole process the experience and the help a manufacturer can contribute is of great value to the user. A tank gauging supplier may have experience from more than 100 000 tank installations, and also have a record and a reputation which may be easily checked by the user. In this respect it is a good idea for the customer to check for references from other users who have tank gauging systems installed where the requirements are high.

Does the accuracy figure apply to all types of influences (temperature, pressure, EMC, ageing etc.) that may occur during the operation of the level gauge?

A level gauge which normally has an excellent performance but performs poorly when an operator starts using their walkie-talkie, or during a very warm summer day, is not what a user wants. One easy way for a customer to ensure the tank gauging system is suitable for the intended operation, is to check if it has been OIML R 85 approved. The customer should also check that it is approved according to the latest revision of R 85, which is currently from 2008. A serious supplier should also be prepared to give the customer a copy of the R 85 test report if the customer wants to check the results from the tests. The OIML R 85, 2008 is probably the best guarantee a user can get with regards to these questions, except possibly for the issues related to ageing.

The ageing of a tank gauging system is of great importance, since its lifetime can be some 15-20 years or even more. The environment in a refinery or tank terminal is often harsh, with high salt and sulfur content in the air, solvents that attack rubber or plastics and UV-radiation which breaks down paint and plastics. References from other installations are the best way to ensure that a long lifetime system is selected.

Since the lifetime is long for a tank gauging system, spare part availability is also important. Spare parts from third parties may affect the performance of the system and should be avoided. The supplier should also show their life-cycle policy for spare parts.

Does the accuracy figure mean that all level gauges will never show an error larger than the accuracy statement?

The accuracy figure may also mean *typical accuracy*, meaning that the figure has some statistical distribution (e.g. Gaussian) where some units are within the range of the figure, but a certain distribution may be outside. In this case the word accuracy could be exchanged for *uncertainty* which is a more appropriate term for a statistical method of expressing performance. When statistical means are used for the expression of performance, it is also important to define the confidence interval for the value, i.e. the sigma (σ), where normally 2 sigma or 3 sigma are used.

Manufacturers who test every level gauge individually before delivery can claim that the accuracy figure is the maximum deviation that the unit will show during final testing. The figure is then an approval criteria in the production. OIML R 85, 2008 states requirements for use in legal custody transfer as: Maximum Permissible Error (MPE) shall be ± 1 mm (0.04 in.). If every delivered unit is tested to be within this criteria, then the accuracy figure consequently means all units are within the stated figure.

Also important is the uncertainty in the reference measurement system when establishing the accuracy figure. A metrological rule of thumb is that the reference shall have an uncertainty at least 3 times better than the figure it should verify. For verification of a stated accuracy of 0.5 mm (0.02 in.) this would then require a reference uncertainty in the range of 0.17 mm (0.0067 in.), which implies very high requirements on the reference measuring system, and it typically requires expensive arrangements with tracking laser equipment etc.

5.1 Uncertainties in tank gauging systems

Following section aims to give some understanding of what uncertainties can be achieved in a tank gauging system.

A modern radar level gauge is capable of an intrinsic accuracy (accuracy at reference conditions) of maximum error ± 0.5 mm (0.02 in.) and over the whole temperature range (-40 °C to 85 °C) the maximum error should be within ± 1 mm (0.04 in.). The installed uncertainty on the tank may be estimated to be in the range:

Level uncertainty (installed) = 2 mm

This assumes a high performance custody transfer level gauge with proven performance. The method of installation is important; the installed level gauge must be rigidly mounted to the most mechanically stable point of the tank. This is normally accomplished by installing the level gauge on a still-pipe, which is either mechanically fixed to the tank bottom or the lower corner between tank wall and tank bottom. For further installation guidelines see API Ch. 3.1B. Certain corrections may be necessary to achieve 2 mm installed accuracy like correction of thermal expansion of still-pipe etc. Corrections like this should be available in these types of level gauges.

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One problem could be to verify an uncertainty in this range with hand dip. It would require a very experienced person to make hand dips with an uncertainty in the range of 1 mm (0.02 in.) or less, but some metrological authorities claim that it is possible. It is clear however, that this is not a common day-to-day practice because it can only be done under very well controlled conditions.

Level uncertainties in transfers are affected by the fact that a custody transfer is a difference measurement, i.e. the difference in level at start and at end of transfer is measured. Some types of errors will thereby be cancelled out in a cylindrical tank, e.g. an offset error of the level gauge will be the same before and after transfer, and will subsequently have no (or very little) influence on the transferred batch.

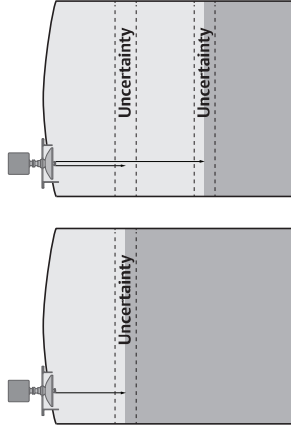


Figure 5.2: Uncertainty when measuring batches could be reduced by offset error elimination.

Uncertainty in average product temperature: 0.3 °C

To achieve 0.3 °C installed accuracy, a multi-spot Resistance Temperature Detector (RTD) with sensor elements at various heights in the product is required in most cases. A stable electronic temperature conversion unit converts the resistance

Density at 15°C (kg/m ³)	739.0	739.4	741.3	742.0	742.8	745.0	745.8	746.5	746.9	747.2
Uncertainty (% reading)	-0.80	-0.75	-0.50	-0.40	-0.30	0.00	0.10	0.20	0.25	0.30
VCF Computed	0.9938	0.9939	0.9939	0.9939	0.9939	0.9939	0.9939	0.9939	0.9939	0.9940

Table 5.1: Density variation does not affect the Volume Correction Factor to a large degree.

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has been used, and the time since the calibration was performed. Old calibration methods often state an uncertainty of 0.10% in the TCT, but recent calibration methods based on EODR (Electro-Optical Distance Ranging) have shown figures as low as 0.01% – 0.02%.

The fact that custody transfer is a difference measurement also affects the uncertainty in the TCT, and errors are to a certain degree cancelled out. Particularly on small transfers this cancellation effect can have a large impact and uncertainty may be better than the figures above. Also, an offset error due to difficulties in estimation of the bottom volume will thereby have no (or very little) influence on the transferred batch, since this part of the tank should not be used for transfers.

So what will the above uncertainties end up as when it comes to standardized volume and mass? To answer this question, all the uncertainties above need to be taken into account for calculation of a figure. This work has been discussed within OIML R 85 for a number of years, but a document has so far not been issued and no working committee has been set up. The figure that has been discussed as a requirement for custody transfer has been in the range of 0.5 % based on mass, and this is also a figure that some metrological authorities use today when they use mass based custody transfer. The future will tell what requirements will be set in forthcoming standards.

5.2 ATG system vs. flow meter system

A tank gauging supplier often gets the question: “How accurate is a tank gauging system compared to a flow meter based system at transfers?” This question may be answered “It depends on the actual transfer”, but one basic fact is illustrated in figure 5.3 below:

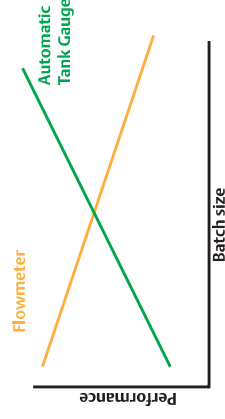


Figure 5.3: ATG systems perform better than flow meter systems when handling large batches, and vice versa.

Figure 5.3 shows that in general an Automatic Tank Gauge (ATG) system is superior for handling large transfer batches, and a flow meter system is superior for smaller batches. Where the intersection of the two curves is located varies between different tanks, and the shape of the tank has certain influence. There is however a lot of other factors that also may influence the performance, and in general it can be said that:

ATG's may not perform well if:

- Batches are small
- Tank Capacity Table is old or badly strapped
- Tanks are deformed or mechanically unstable

Meters may not perform well if:

- Batches are large
- Product contains abrasive material, sand etc. which damages mechanical parts
- Product is viscous (bitumen, lube oil, waxy crude etc.)
- There is a lack of proper meter calibration facilities

The last point above may be considered in particular. Calibration of an ATG system is normally very simple and low cost compared to meters which require complex and expensive equipment.

What should also be considered is that an ATG system is normally also required for other purposes such as:

- Operational control
- Inventory control
- Mass balance and loss control
- One independent layer of overflow prevention and leak alarm

If we assume there always has to be an ATG system installed for the above purposes, the additional cost for using the ATG system for custody transfer can also be estimated. There is a somewhat higher price for a custody transfer class ATG system, compared

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to a system with lesser performance. However, the lifetime of an ATG system is often very long with an average of around 15-20 years. In this time perspective the additional investment in better performing equipment will be negligible. Also, the procedure of supervision of the performance (subsequent verification) when the system has been installed on a tank is limited to some hours per year by an independent resource. The total overall additional cost to have an ATG system with certified custody transfer performance can therefore be considered low.

The status of the Tank Capacity Table should also be considered. It is well worth considering a re-strapping of an old tank according to new modern methods, especially if the strapping was made a long time ago. The cost for re-strapping may not be high considering the measurement error in terms of product volume that can occur during a single emptying or filling operation of a tank.

For product transfers, many operators use both an ATG system and a flow meter based system. They can then compare the result from both technologies and investigate the cause if the difference is too large.

5.3 Process level gauges vs. tank gauging level gauges

It may be tempting for a user to go for a radar based process level gauge in a tank gauging application, since the cost often is lower (see [chapter 2](#)). In this case there is a number of important factors to bear in mind, presented in the following sections.

5.3.1 System architecture

Most process level gauges are designed to produce only level information to a DCS system, and there are no particular ATG functions available. Such a function could be an integrated average temperature measurement which considers the level in the tank, correction algorithms for tank wall expansion, temperature correction of Tank Capacity Tables etc. Also, most process level gauges are using a 4-20 mA current loop which has a resolution that is too low for tank gauging purposes, and the unit may lack communication possibilities for a more efficient or advanced digital bus. Some tank gauging systems also have the possibility to handle existing cabling from old mechanical level gauges, and can often coexist with them by emulating the old level gauges. Software functions for complex standard volume and mass calculations are also required and these are normally not available in standard PLC or DCS systems.

5.3.2 Accuracy statement

A process level gauge is often optimized to handle difficult operating conditions such as turbulent liquids, product foam, high pressure and temperature. In such conditions the focus is not on accuracy. Despite this, accuracy statements like "3 mm accuracy under reference conditions" for a process level gauge may be seen. This may be true under reference conditions, but in a tank gauging application it is necessary to know how big the temperature influence is. Typically there is a very big discrepancy compared with a tank gauging level

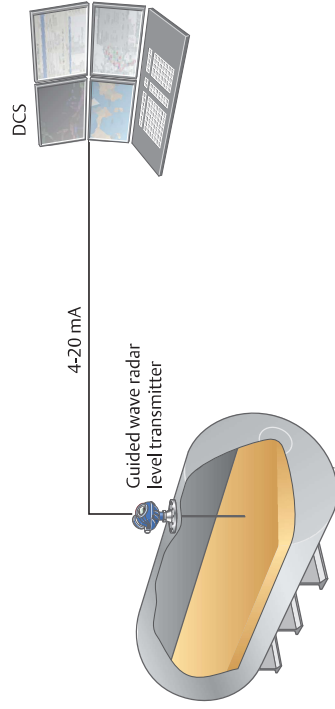


Figure 5.4: Typical process level transmitter architecture.

5 - Accuracies and uncertainties

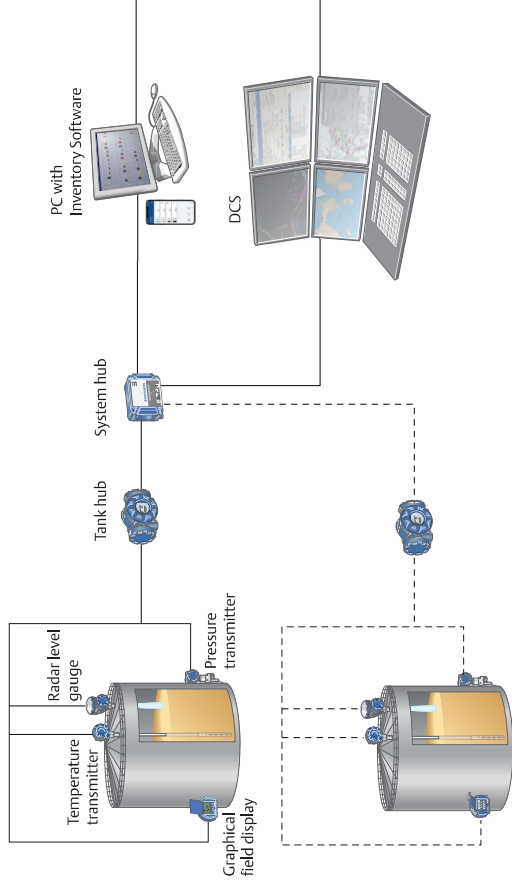


Figure 5.5: Typical tank gauging system architecture.

gauge, which if OIML R 85 approved, is not allowed to vary more than 1 mm (0.02 in.) in the whole ambient temperature span. If the statements on temperature influence on a process level gauge (if stated at all by the manufacturer) are checked, typical figures on accuracy in the range of 20 mm (0.8 in.) or more over the intended ambient temperature range can be seen. This temperature dependency often makes the process level gauge unusable in a tank gauging application. Just a difference in temperature between day and night may be enough to make an operator nervous, since it could look like there is a leakage in a non-active storage tank. Inventory estimations can vary considerably with the weather, and mass balance and loss control may be inaccurate.

The difference in temperature influence between a typical process level gauge and an ATG is due to the technology used. An ATG level gauge is normally based on FMCW technology which is easier to design with little temperature influence, compared to a pulsed (also called time-of-flight) process level gauge, where it is a challenge to get the timing circuitry temperature stable.

5.3.3 Lifetime expectations

The lifetime of a tank gauging system is often in the range of 20 years or even more, which is rarely the case for a process level gauge. During this time period there must be spare parts available to secure maintenance without serious operational disturbances. The lower cost and the simple 4-20 mA connection to a DCS system used by a process level gauge may imply that a change of the complete level gauge unit is all that is required. A check of the manufacturers' life-time policy may be important.

5.3.4 Installation

A process level gauge is often designed for installation on smaller vessels with narrow openings, which often would disqualify a typical ATG level gauge. ATG level gauges based on radar often have larger antenna apertures to allow installation on available manways on storage tanks. These are often located close to the tank wall since this section is regarded as a reasonably stable installation point.

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The larger antenna aperture on an ATC level gauge will allow installation close to the tank wall without degraded performance resulting from interfering radar echoes from the tank wall. An antenna that is too small would in this case have its installed accuracy affected by the interfering echoes. It is possible to increase the frequency of the radar signal to some extent to get higher directivity of the transmitted radar beam and thereby avoid tank wall influence. There are however other disadvantages with higher frequencies and since the size of the tank openings is rarely critical on storage tanks, they offer no benefits in most cases.

5.3.5 Installation on still-pipes

In ATG applications it is common that the level gauge installation is made on a still-pipe. The reason is that a still-pipe, correctly installed at the tank bottom or lower part of the tank wall is a very stable reference point for the level measurement. Another reason may simply be that the tank has a floating roof, and it is necessary to penetrate the roof with a still-pipe to get access to the liquid surface.

The percentage of installations that require installation on still-pipes is approximately 50% in ATG installations and close to 0% for process installations. As a result of this it is very rare to see process level gauges supplied with the special type of radar antenna that is required for high performance installations on still-pipes. To use a standard free-propagation device on a still-pipe would give very poor measuring results since they do not have the special H01 transmission mode which is necessary (see chapter 2). This absence of a suitable antenna solution for still-pipes may therefore be the major difference between a radar based ATC level gauge and a process level gauge.

6

Temperature measurement

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6. Temperature measurement

Measurement of product temperature is vital in a tank gauging system for input to the Standard Volume and Mass calculation, and it has a greater importance than some users may think. In the past (and also to some extent today), storage tanks could be seen with only one temperature sensor mounted on the tank wall near the bottom of the tank. This type of arrangement will not show a representative value of the overall product temperature, since all storage tanks will show a considerable temperature gradient from top to bottom. This can to some extent be minimized by agitation of the product, but agitation is in most cases unwanted since it will increase evaporation in or from the tank. Figures on how much temperature difference can be expected in a normal cylindrical tank that has been settled is in the range of 1–4 °C in a vertical direction. Cold products will have higher density and will therefore end up at the bottom of the tank. The temperature gradient in a horizontal direction has often been debated, but under normal conditions API documents state that the horizontal temperature difference in a storage tank is less than 0.5 °C.



Figure 6.1: Top mounted temperature transmitter for up to 16 spot temperature elements.

Example 6.1: Volume error given by temperature error

The following example illustrates how large volume error will be given by an error in the average product temperature of 1 °C:

In a normal, typical cylindrical shape product tank, with a height of 20 m, a diameter of 36 m, and a total tank volume in the range of 20 000 m³, the error in volume will be:

$$\text{Volume error} = 20\,000 \times 700 \times 10^{-6} = 14 \text{ m}^3$$

where 700×10^{-6} is based on the assumption that the volume of petroleum products is affected by temperature in the range 600–800 ppm per 1 °C.

This may not seem too alarming, but if one considers that the temperature error might be systematic, i.e. if a similar error occurs every time when filling or emptying a tank, it will cause considerable loss to one of the parties involved in the transaction.

In a tank the same size as in example 6.1, a level error will correspond to approximately 1 m³ for each mm. The 1 °C error in temperature will then influence the volume the same as a level gauge error of 14 mm!

The tank gauging system is therefore poorly matched if the level gauge has an installed accuracy in the range of a few millimeters and the temperature measurement has an accuracy of ± 1 °C. To be able to

the value 18.4 °C should be used in the algorithm, not 18.25 °C as with the old tables.

The new API tables open up possibilities for better volume estimation through more precise temperature measurements. The resistance difference possible in a 3-wire Pt100 system is therefore not uncritical anymore, and there is a clear trend to go for 4-wire Pt100 sensors instead. A 4-wire Pt100 sensor will fully compensate for the resistance difference in wires from conversion electronics to the Pt100 element. It requires a resistance to temperature conversion unit that is designed for 4-wire connections, and the conversion electronics should have sufficient accuracy and ambient temperature stability.

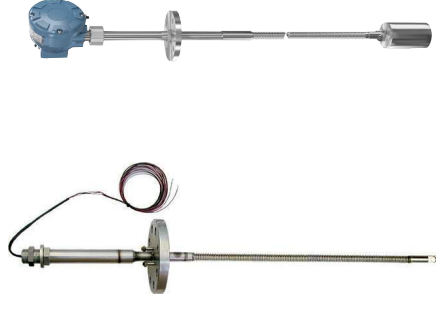


Figure 6.2: Left - Multi-spot temperature sensor with Pt100 elements and corrosion resistant metallic sheath. Right - Complete temperature measuring assembly with transmitter, sensor, optional water level sensor and anchor weight.

The Pt100 sensor elements exist in different accuracy classes, and in general 4-wire elements use the highest accuracy classes. Some manufacturers also issue a calibration sheet together with each element. This calibration sheet could then be used for entering corrections of the sensor element and thereby improving the accuracy even more. To do this automatic calibration, a corresponding function must be available in the temperature measuring system.

end up in the same accuracy class as the level gauge, the temperature measuring system must first of all be able to handle the temperature gradient. That is, it needs to be of the multi-spot type measuring temperature at different heights in the tank and calculating an average from the sensors which are submerged in the liquid. Secondly, the temperature sensor combined with conversion electronics should have an accuracy far better than ± 1 °C.

6.1 Influence of API tables

A limitation in the temperature measurement related to the API tables and the Volume Correction Factor (VCF) calculation should be considered. The API tables before 2004 only had a resolution of 0.25 °C accuracies better than 0.25 °C meaningless. The typical sensor type that is used in this case is 3-wire Pt100 elements, where the error due to different resistance in the three wires in most cases should be possible to get below 0.25 °C.

Still, if the temperature precision is only as good as 0.25 °C, the corresponding level error in the tank example above is in the range of several millimeters, and on large crude tanks the figure can be a lot larger. A modern level gauge has an intrinsic accuracy of 0.5 mm (0.02 in.) and when applying certain tank corrections the installed accuracy could be in the range of 2 mm (0.08 in.) or better. This is why it is important to decrease the error in the temperature measurement, and to arrive at an accuracy in the range of 0.1 °C or better. Since the introduction of the new higher resolution 2004 API tables, using these high accuracies is now highly relevant.

The 2004 tables are different compared to all the earlier tables in that they do not use the tabulated VCF value (the printed value) from the API table. Instead it is the result from the algorithm behind the table that is the correct value. This is a consequence of the fact that that operators today do not use the table value but instead have a computer program which has the algorithm implemented to enable the computer to make the calculation. However, when the computer makes the calculation for the old tables it should round off the temperature value to nearest 0.25 °C to get the same result as in the printed table. This is different in the 2004 table, where the rounding instead should be to the nearest 0.1 °C. This means that if the temperature system has measured and calculated an average liquid temperature of 18.37 °C,

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To summarize, it could be stated that temperature measurement must not be a limiting factor for a proper performance matching with the level gauge in a tank gauging system. However, the aspects above should be considered and they are as important for correct volume estimation as the performance of the level gauge.

6.2 Systematic measurement errors

Measurement errors that can be described as systematic should be avoided as far as possible in a tank gauging system, since they will multiply over time and can create a considerable loss for a buyer or a seller. For level measurement with a radar level gauge, the error is mostly of a random type but for temperature measurement it can often be systematic.

Example 6.2: Temperature measurement using only one sensor

In a common case where only one temperature sensor is installed at the bottom of the tank it is certain that this will not represent the average temperature of the product in a settled tank. If the temperature gradient is 4 °C the temperature sensor can be expected to show an error in the range of 2 °C too low average temperature each time a transfer from a full tank is started. Expressed in Standard Volume it means the volume is overestimated at the start, and in example 6.1, this would for a typical tank correspond to an error of 28 m³. This means that 28 m³ less is delivered than the measurement indicated. The implication is that the error is approximately the same every time a transfer from this tank takes place, since the temperature stratification, due to its physical nature, is systematic. With a turn-over rate of 30 times per year, it will end up in the range of 800 m³ per year or some 40 full tank trucks, for one tank only.

The scenario in this example illustrates the importance of using a multi-spot temperature sensor, but it is still important to take care, since an error in one temperature element could cause a similar systematic error: the faulty temperature

element may only be included in the average temperature measurement at certain liquid levels and excluded at lower levels. The quality of the multi-spot sensor is therefore important, and the performance of each element may be subject for check at certain intervals.

Example 6.3: Volume error caused by temperature error compared to corresponding level gauge error for a 20 m high tank with a diameter of 36 m and a volume of 20 000 m³.

Temperature error (°C)	Resulting Volume error (m ³)	Corresponding Level gauge error (mm)
0.25	3.5	3.5
0.50	7	6.9
0.75	10.5	10.3
1.00	14	13.8
1.25	17.5	17.2
1.50	21	20.6
1.75	24.5	24.1
2.00	28	27.5

6.3 API standard

API MPMS chapter 7.3 "Temperature Determination – Fixed Automatic Tank Temperature Systems" was released in 2011 and describes the methods, equipment and procedures for determining the temperatures of petroleum and petroleum products under static conditions by using an automatic method.

Guidelines for equipment and design requirements are given, among other things recommending Resistance Temperature Detectors (RTD's) and the use of multi-spot averaging sensors for custody transfer applications. It provides installation and accuracy requirements and suggests procedures for the inspection and verification of a complete Automatic Tank Thermometer (ATT) system.

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6.4 Location of spot elements

To achieve a good representation of the average temperature in an upright cylindrical tank, the temperature spots should be evenly positioned with at least 2-3 m intervals.

To avoid possible influence from ground temperature, the lowest spot should be placed around 1 m from the tank bottom. Furthermore, to avoid ambient temperature influence, the sensor should be installed at least 1 m from the tank wall and close to a gauging hatch for verification purposes.

6.5 Additional uses of temperature measurement in tank gauging

In addition to the use for Standard Volume calculation, the temperature measuring system is also used for other purposes, see following example:

6.5.1 Correction of tank height

Most level gauges measure the distance from their mounting position down to the liquid surface (ullage measurement), and calculate the level by subtracting ullage from the reference height (the distance from the level gauge mounting point to the datum plate). This calculation will show an error if this distance is not constant, i.e. the level will vary with the reference height change. One type of change which is easy to compensate for is the thermal expansion/contraction of the tank wall or the still-pipe. With a multi-spot temperature sensor installed from the top of tank down to the bottom, an average temperature value of either the tank wall or the still-pipe can be estimated. In this case all individual temperature elements are used for the average temperature calculation, and a correction can be applied on the reference height based on thermal expansion of carbon steel (10-12 ppm/°C).

For correction of a tank wall, the fact that there is liquid on the inside of the tank and air on the outside, as well as different media involved, should be taken into account. The thermal influence is quite different for air and liquid and API has stated that tank wall temperatures in each measuring point should be calculated as:

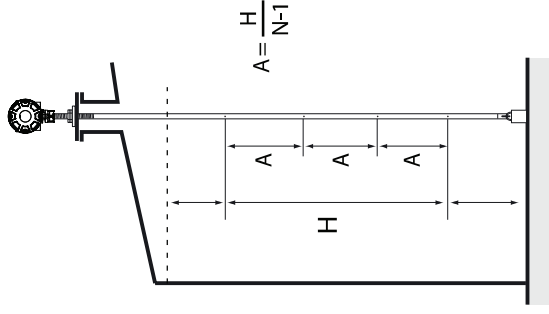


Figure 6.3: Spot temperature elements should be placed with equal distance between each element.

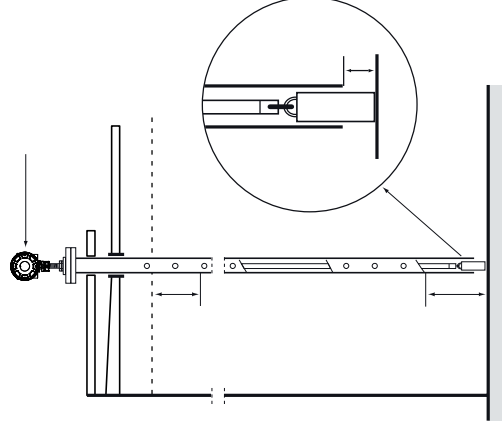


Figure 6.4: On floating roof tanks, a still-pipe is often used for the temperature sensor installation.