Index

North Sea FLOW Measurement Workshop

nel oil & gas services

Paper 8.1

The Expanding Use of LNG From Natural Gas To Satisfy World Energy Demand Can Use Technologically Superior Ultrasonic Cryogenic Liquid Flow Metering, and Ultrasonic Gas Metering for Process and Custody Transfer Operations

Jacob Freeke, James Matson and Michael Scelzo
GE Sensing

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1 INTRODUCTION

Transit-time Ultrasonic Flowmeters are now firmly established as an acceptable technology for gas and liquid flow measurement in the global Oil & Gas Industry. The technology has not only proven to be extremely accurate, exceeding legal metrology requirements, but also able to yield considerable savings for operators due to the effective absence of both pressure drop and maintenance requirements.

This paper discusses how two advanced flowmeter designs, one for liquid LNG, and one for Natural Gas can help financially offset the impact of the anticipated increase in flowmeter numbers within the industry.

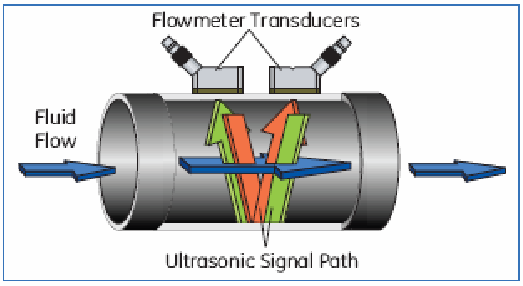
A patented Bundle Waveguide Technology (BWT) system, using a unique design of a thermal buffer enables ultrasonic transducers, and hence flow meters, to be employed, complete with possible removal without affecting line integrity or safety, for liquid cryogenic LNG flow measurement. The paper will cite numerous installations on cryogenic LNG flow measurement applications that have been operating successfully for several years at LNG liquefaction and regasification facilities. Transit-time ultrasonic technology can accommodate the largest LNG pipeline encountered so far, significantly in excess of the largest pipe size accommodated by alternate technologies, without pressure loss and with lower capital outlay. BWT technology theory, design and a case study are discussed.

As the number of LNG terminals rises, and regasified natural gas of varying composition and quality flows into increasingly complex distribution grids, the need for affordable custody transfer standard flowmeters will increase. Such flowmeters have evolved into complex multi-path designs configured to minimise or eliminate the impact of velocity profile distortion. This paper describes the development, testing and deployment of a simplified natural gas flowmeter design employing only two diametric paths and an integral flow conditioning plate, to deliver custody transfer performance. In addition to an in depth discussion of the theory and implementation of the design, improved reliability over more complicated designs and functional test results at three well known calibration facilities are presented. The paper describes applications of the meter for gas allocation at liquefaction and regasification facilities as well as custody transfer for gas transmission pipelines. Finally, a case study of the first commercial installation at a gas fired electric power generating station is presented.

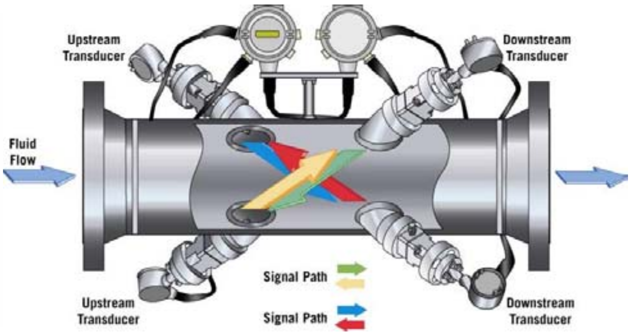
2 TRANSIT TIME ULTRASONIC FLOW METER

Although ultrasonic flowmeters are considered a relatively new technology, they have been used for liquid flow measurement for over 40 years and for natural gas measurement for more than 25 years. The transit-time technique is the preferred method today for the ultrasonic flowmeter and is well understood and documented. The technology was primarily used for liquid flow metering using both wetted and clamp-on installation methods. Ultrasonic systems for gases were more difficult due to issues involved with the transfer of ultrasonic energy into the gas with the acoustic impedance mismatch between the ultrasonic transducers and the gas.

After development of a successful way of acoustically coupling ultrasonic transducers to gases, the transit time technique has become a standard of ultrasonic flow measurement for gases, as well as liquids.



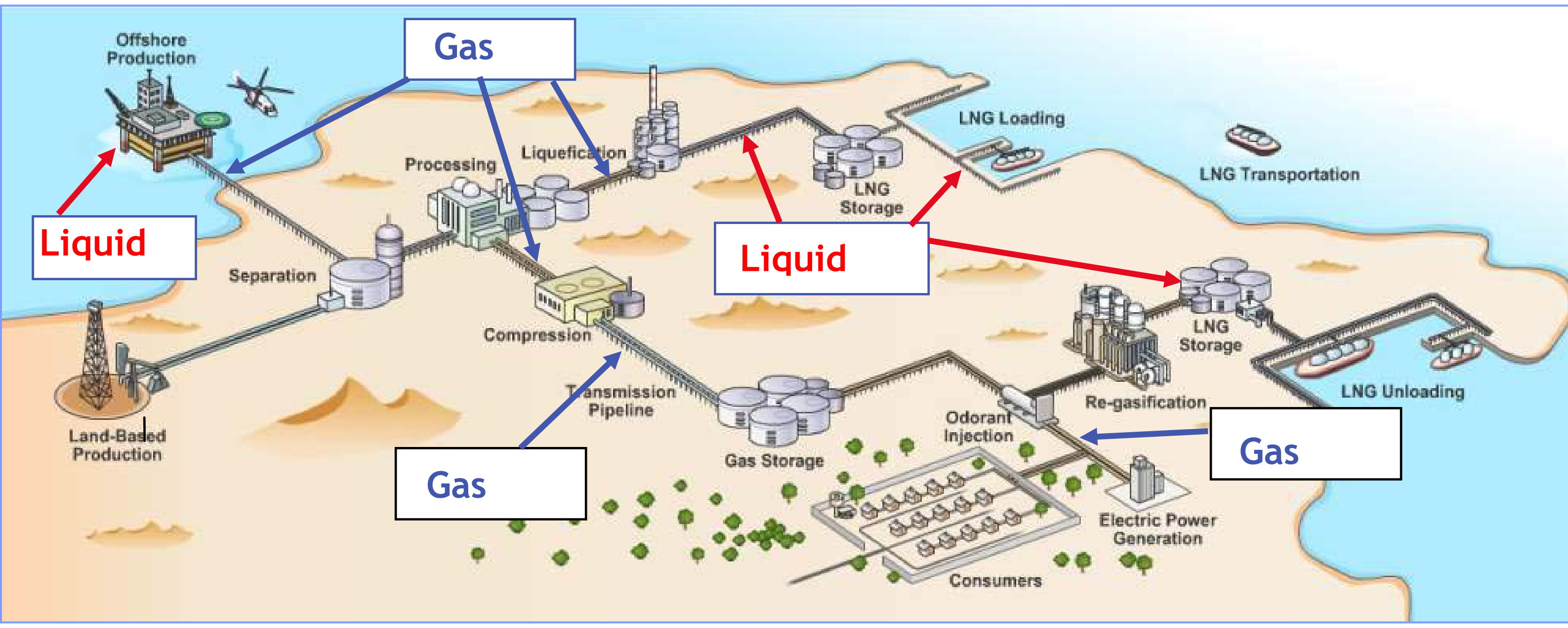
Transit-time flow measurement technique



Today, transit-time ultrasonic flowmeters offer several advantages to users and operators. They create little pressure drop, have low maintenance requirements, and can easily handle large pipe sizes. Because ultrasonic meters create little pressure drop and do not wear, their operating costs and cost of ownership are low. Transit-time ultrasonic meters are used on pipes of 48 inches diameter and larger, and on pipes as small as 2" diameter. In addition, because of their wide turndown ratio, typically greater than 100-to-one, a single ultrasonic meter can handle all the flow through a single pipe.

3 USING ULTRASONIC FLOWMETERS IN LNG PROCESSES

The process of making, distributing and using Liquefied Natural Gas (LNG) presents some unique technological and economic challenges for flow measurement. Extremes of temperature in the liquid cryogenic state, and the requirement for high accuracy for the transfer of ownership or process control in the gaseous state, are the primary concern. High reliability along with low cost of ownership are additional concerns that flow measurement must overcome. There are numerous points in the process where flow measurement is essential.



Major Points in the LNG Process

3.1 Natural Gas Flow Measurement before Liquefaction

In the first phase of LNG production, natural gas liquids, sulphur, and water vapour are removed from the natural gas to improve gas quality and prevent problems, including hydrate formation and pipeline blockage from occurring. After processing, natural gas will be liquefied in liquefaction trains.

3.2 LNG Flow Measurement during Liquefaction

During the liquefaction process the natural gas goes through a multistage process with intermediate temperatures of –53C (-60F). Liquid flowmeters will be for sizes 6 to 16" and process streams can still contain some gas phase.

3.3 LNG Flow Measurement after Liquefaction

After liquefaction flow measurement to storage and loading can be at cryogenic temperatures (-161 C/-258 F) in pipes from 6 inches to 42 inches in diameter. The flowmeter must not be susceptible to, or cause, flashing. It is designed to withstand extreme cryogenic conditions.

3.4 LNG Flow Measurement Offloading and Boil Off Gas Flow Measurement

LNG can again be at cryogenic temperatures (-161 C/-258 F) in pipes from 6 inches to 42 inches in diameter when offloading from ships into storage tanks at receiving terminals. In addition, gas ultrasonic flowmeters equipped with low temperature transducers are suited to measure natural gas vapour recovery flow during the LNG unloading process, the so-called Boil Off Gas. (BOG)

3.5 After Gasification back into the Distribution Grid

When the LNG is re-gasified and sold to local transmission or distribution companies, an ultrasonic flowmeter provides accurate measurement for custody transfer of the natural gas to the local buyer.

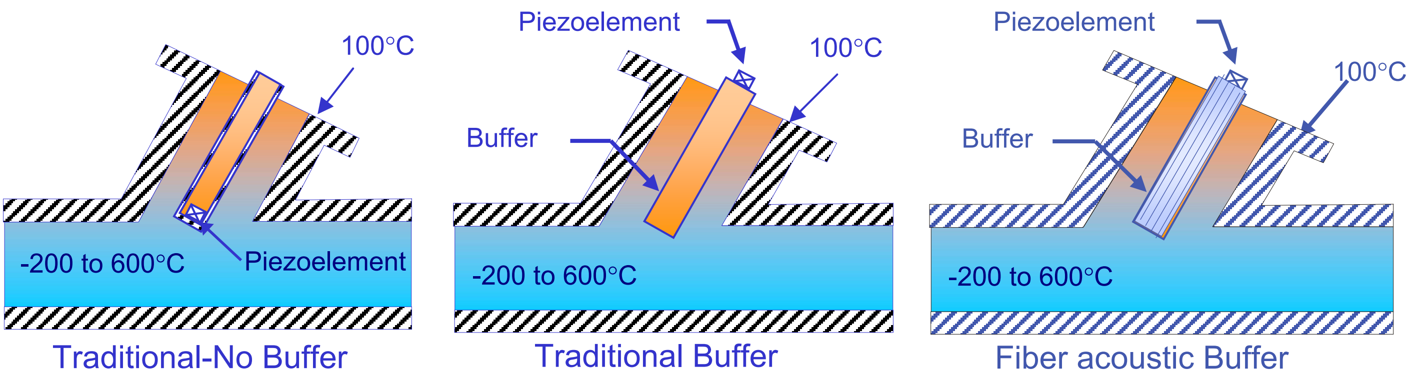
4 ULTRASONIC FLOWMETER FOR CRYOGENIC LIQUIDS

Operating a flowmeter at cryogenic temperatures requires the elements of the flow meter be able to withstand the temperatures involved, and the cycling of the system from cryogenic to normal temperatures as well. The Transit Time ultrasonic flowmeter meets these requirements by means of a "buffer", whereby the elements are removed from exposure to the extreme temperature and the temperature cycling.

4.1 Thermal Buffer

GE Sensing provides a unique solution in ultrasonic technology for cryogenic LNG flow measurement in the Panametrics Bundle Wave-guide Technology (BWT) system. Whilst keeping the sensing element (crystal) at ambient temperature the BWT system ensures signal transmission virtually without loss of energy and quality through its buffer into the cryogenic liquid.

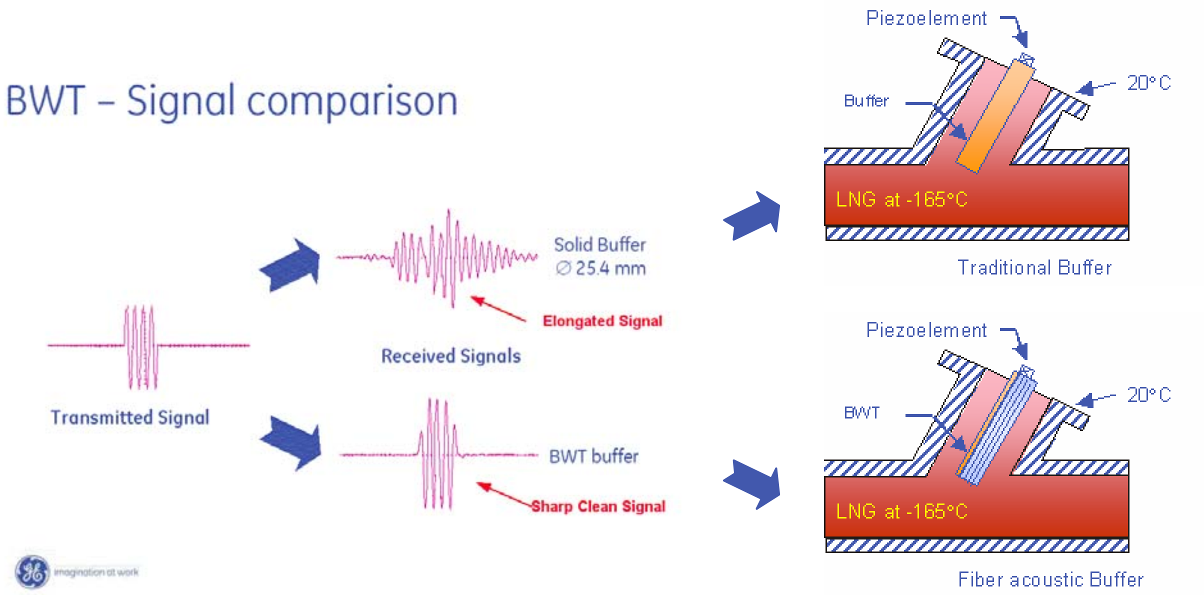
The BWT system is a collection of bundled cylindrical elements that provide a path for the ultrasonic signal to travel from the transducer to its wetted tip. This design provides three major advantages. First, keeping the piezoelectric element of the transducer away from the process keeps the element at a safe near ambient temperature, thus preventing any potential for temperature damage. Second, bundling the elements allows transmission of a highly collimated beam of ultrasound into the fluid producing a high signal-to-noise ratio for robust, stable measurement. Third, the possible removal without affecting line integrity or safety. The transducer is installed at the end of the outer buffer (outside the pressure boundary) so; it can be replaced under operating conditions.



4.2 Bundle Waveguide Technology

The BWT system was developed in 1995 to measure flow in petrochemical processes that require accurate measurement under extreme conditions, such as high (<600 C) or low (>-200C) temperatures. The BWT system has been used successfully since 2001 for cryogenic LNG flow measurement in Spain, Malaysia, Trinidad and Tobago, Egypt, and Russia.

The key to reliable and accurate operation of an ultrasonic flowmeter is the quality and strength of the signals. A strong and clean signal allows measuring even the smallest fractions of time difference in the transit times. These time differences (delta-T) are proportional to the flow rate and are the meter's base parameter for measuring the flow. The waveguide capability of the BWT system ensures very strong, coherent signals as illustrated below. This results in a very high repeatability of the meter allowing an overall meter accuracy of better than 0.15% of reading.



4.3 Cryogenic Effects & Compensation

Ultrasonic flowmeters are based on the well-known linear transit time operating principle. Therefore the effects of operation at cryogenic temperatures are limited, well understood and easy to compensate for:

- Mechanical Dimensions
  - The change in the internal diameter, and hence area, due to contraction
  - The change in the acoustic path and its axial projection due to contraction of the meter body
- Ultrasonic Signals

- Negligible effect on signal quality or strength due to use of BWT technology
- Change in delay time (sound speed and length) in buffer (measured, calculated and compensated)
- Fluid Dynamics
  - Change in viscosity from water calibration to LNG for flow profile correction
  - Or viscosity immune configuration (mid-radius)

GE Sensing has developed a calculation model to correct for the above effects.

4.4 Design Considerations

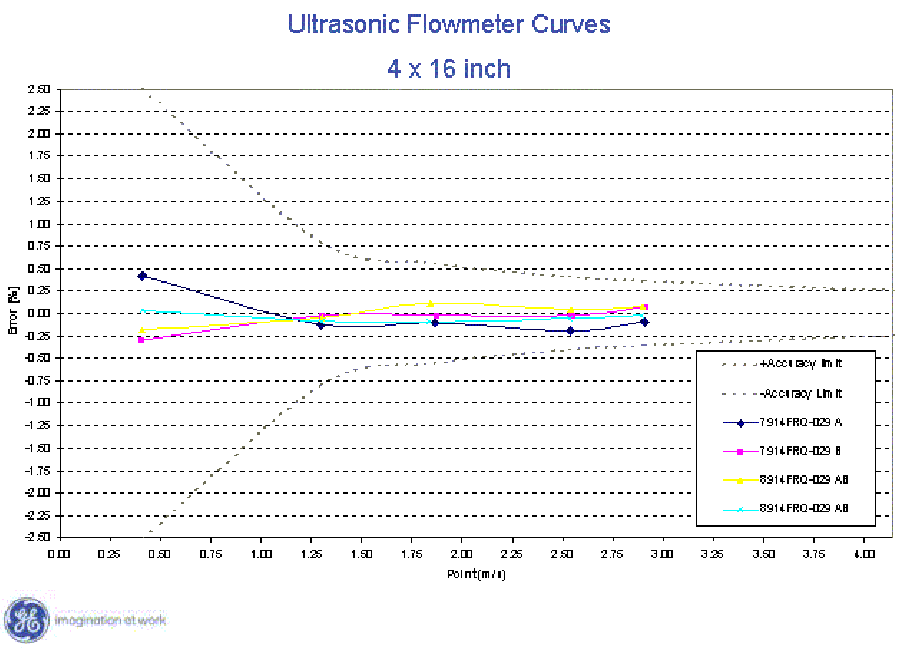
An additional benefit of the BWT based ultrasonic meter for cryogen ice is that there is virtually no pressure loss, and this avoids flashing. Flashing will affect accuracy and has to be avoided at all times. Low pressure drop will also reduce possible Boil Off Gas (BOG) when the LNG is settling in tanks.

Also important for the LNG meters is adequate insulation. The entire meter runs will be insulated except for the outer parts of the BWT buffers and transducers. The sensing element (piezo electric crystal) and flowmeter electronics will be kept near ambient temperature. However, even if the buffer is fully covered with ice, the ultrasonic signal quality, signal strength or signal reliability will not be affected.

4.5 System Calibration

Calibration of virtually any size flowmeter, but especially medium to large size, in LNG is not practical today, so calibration in water is used with the above corrections applied before actual service. LNG meters are calibrated at high accuracy calibration facilities, such as WLDelft Hydraulics in Delft, The Netherlands. This world-class facility has a traceable uncertainty of 0.05%.

The flowmeter and any available upstream piping are best calibrated together in the exact same configuration, as it will be installed for usage. This will reduce uncertainties caused by installation effects



and piping components.

4.6 Field Validation

Like other ultrasonic flowmeter applications, field validation by means of comparison of sound speed from the flowmeter to sound speed from known reference sources is possible with LNG. The temperature and pressure at flowing conditions at the flowmeter must be known well.

4.7 Field Experience

Panametrics experience with ultrasonic flowmeters at cryogenic services started many years ago. The first successes were accomplished with liquefied oxygen and nitrogen in the late 1980's. Starting in 1996 the BWT technology was introduced and found to be well suitable for challenging applications and temperature extremes. The temperature range is: -200ºC to +600ºC. Methanol and glycol at temperatures below zero degrees Celsius as well as LNG applications were successfully done and showed highly reliable operation.

Table 1-Current Liquid LNG Flowmeter Installations

Year	Meter Size	Company	Country
2001	2 x 24" LNG 2 x 18" LNG 2 x 16" LNG	MLNG TIGA	Malaysia
2003	1 x 42" LNG 1 x 30" BOG	Bahia De Bizkaia	Spain
2004	3 x 12" LNG 1 x 16" LNG 1 x 30"	ALNG	Trinidad
2005	2 x 14" LNG 2 x 8" LNG	ELNG	Egypt
2005	1 x 24" LNG 1 x 16" LNG	Sahkalin Energy	Russia
2006 to 2007		Qatar Gas	Qatar
		Free Port	USA
		CASCO	UAE
		CNOOC	China

5 AN LNG PLANT'S EXPERIENCE

At the Bay at Bizkaia Gas LNG plant in Spain, there are multiple points of measurement using ultrasonic meters. Among such measurements are: the seawater volumetric flow to the vaporizer, the measurement of LNG during the discharge from a ship, the Boil-Off gas that returns to the ship, the loss and emissions through the flare, and the LNG flow from the storage tanks to the vaporization systems. It was decided on the part of the engineering teams, that ultrasonic flowmeters were to be installed to get rid of pressure drop, maintenance and interruptions; in addition these flowmeters do not present drift of the measurement with the passage of time (maximum repeatability in the measurements) and have the capacity to measure the different systems in all operations (wide rangebility).

The ultrasonic meters are used at 10 points of measure, primarily for lines of larger dimensions, i.e. > 12"

For this group of measurements, the following characteristics of the principal measurements are listed:

5.1 Discharge of the liquefied Natural Gas from the Ship (LNG)

(Temperature Minimum: –200ºC, operation to –165ºC) Flow range: -2.000 to +15.000 Nm3/h, (with a possibility to operate far above the 15.000Nm3/h rate), (the negative flows are possible for the case when it's required to send LNG originating in the onshore tanks down the line, to provide for the cooling off of the ship). During the process of cooling off of a ship, operational flow rates of 100m3/h can occur; as it can be seen, this is an extremely wide range of flow rate for a single line.

These measurements are utilized to verify the values of discharge delivered on the part of the ship and compared against the values of discharge obtained according to the increment in the levels of the plant storage tanks. This then is a reference value for the subsequent discharge value arbitration.

5.2 Return of Cryogenic Gas to Ship (Boil-Off)

(-190ºC to +100ºC) cold Gas. During normal operation the discharge temperature goes below –100ºC, whereas during idle time the temperature in the line becomes the temperature of the environment. This line is 32" in Stainless Steel, with flow of -10.000 to +13.000 Am3/h (negative flow is possible during the normal operating discharge of ships or during the ships cooling off operations). It is important to measurement negative flows, positive flows, zero flow, due to the variation in the interior of the tanks of the ship during the discharge operation; even the evaporation of the gas in the tanks inside the ship can cause flow be positive or negative, according to the gradients of temperature.

With this equipment the quantity of gas delivered to the ship can be counted during the process of discharge, with negative and positive values, having a way to balance the payment of the gas delivered.

Another important contribution is the security in the operating of discharge or charges of ships, to include a clear indication of the velocity of evaporation of the LNG in the tanks of the ship.

5.3 Amount of Gas to the Flare

(-170ºC to +150ºC), Line of 36" in Stainless Steel. 0 to >200000 Nm3/h (a safety mechanism for very exceptional conditions in the plant).

The range of normal operation goes from 0 to 12000 Nm3/h, with values of emission normally under the 500 m3/h. Here a single installation must be capable of measuring a wide range of flow rate, pressure and very variable temperature.

There needs to be control of gas emission due to environmental reasons and administrative reasons. In the same way there is control of gas evaporation due to the possible inefficiency of the refrigeration system of the plant. Exceptional control of discharges required in exceptional situations as a result of the high production of Boil-Off gas in the tanks or in the process.

Since the start of the operation of the equipment, no failure has been recorded in any of the ultrasonic meters. Maintenance required for the ultrasonic equipment is basically none; just small changes in the range or parameters, and these are very simple and easy to carry out. The electronics and sensors do not present any problem due to function or maintenance. Globally the down time of production due to these points of measure can be called zero. The availability has been 100%.

6 ULTRASONIC FLOWMETER FOR NATURAL GAS

6.1 Gas Flow Measurements

For the Natural Gas inlet to a liquefaction plant or for delivering Natural Gas into a distribution grid, a high accuracy ultrasonic flowmeter is used. Such flowmeters have evolved into complex multi-path designs configured to minimise or eliminate the impact of velocity profile distortion. However, the effectiveness of these designs remains a function of available upstream straight pipe length and the sources of disturbance present. In most situations a flow conditioner is still required despite the number and configuration of paths. A simplified metering system, such as the Sentinel custody transfer gas flowmeter shown below, can meet the accuracy requirements while reducing costs in both initial capital expenditure and longer term cost of ownership.

6.2 Simplified System Description

The sentinel system is a complete ultrasonic flowmeter system for natural gas flow applications fully compliant to AGA report no. 9 and has NMI type approval based on evaluation against new OIML CD5 Draft. This flowmeter system consists of the ultrasonic meter, a flow conditioner, a 10 diameter upstream section, and, optionally, downstream piping. This departure in design from a complex multi-path system is based on a truly redundant, 2 path configuration which ensures reliable and accurate gas metering with a simpler system. This configuration removes the uncertainty associated with the installation effects (distorted flow profiles caused by valves, elbows and other piping components) on the overall meter performance.

6.3 Path Configuration & Design

Multipath ultrasonic flowmeters may be defined as ultrasonic flowmeters employing *n* paths, where *n* is at least two. At present, commercial multipath flowmeters are available with *n* as large as eighteen. The following questions arise: Are more paths better? Do more paths mean higher accuracy? What are the optimum number, placement and weighting of each of the *n* paths *for any particular situation?*

In order to achieve high accuracy, the purely mathematical approach tends to favour a large *n.* But large *n* means many ports, welds, transducers, and many localized disturbances to the pressure boundary. As in many situations, ultimately one is led to consider the cost/benefit ratio for alternative approaches.

Over the past fifteen years or so the use of multipath ultrasonic flowmeters has found wide acceptance among individuals responsible for purchasing, using or selling natural gas.

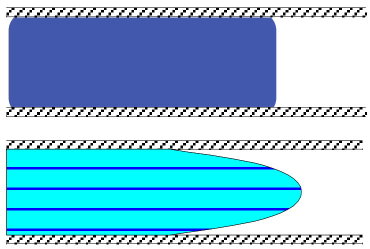
Among the reasons for this acceptance are: high accuracy; measurements are non-intrusive and therefore cause negligible excess pressure drop; cover a wide turndown ratio. Inaccuracy of 0.5% of reading or better has been achieved. Multipaths are typically quadrature paths or combinations of midradius and diameter paths.

The “best” locations and weights for the multiple paths are often specified by quadrature integration formulas due to Gauss, Chebyshev or others. The suggestion to use a Gaussian quadrature integration method to achieve relative immunity to unknown aspects of the flow profile appeared in 1964. Subsequently, various quadrature solutions appeared, e.g. [Malone and Whirlow, 1971, Wyler 1976, Pedersen 1982, O’Hair and Nolan 1987]. A comparison of quadrature vs. alternative numerical integration methods, with application to accurate flow metering, is discussed in [Tereshchenko and Rychagov 2004].

Quadrature integration is one way of finding the average value of a function, or finding the average value of flow velocity in a pipe. If the profile is simple, then few samples are needed for an accurate value for the average. The higher the degree of the polynomial representing the function, the more samples are needed. More samples means more paths.

If the function is a constant (corresponding to plug flow) then one sample suffices, and it doesn’t matter where in the pipe the function is sampled. If the function is a low-order polynomial, e.g. a parabola, again one sample suffices to determine the average value, but now the location of the sample is important. If the sample is taken at the centre of a round pipe, the value observed is exactly twice the average value. The ratio of the local sample to the average over the pipe is compensated by a meter factor *K,* which in this instance would equal 0.500. If a parabolic profile is sampled along the diameter, the average along the diameter equals 1.333 times the average, and is convertible to the average using a meter factor *K* = 0.7500. If that parabola is sampled along the midradius chord, then the chordal average exactly equals the average over the round pipe and *K* = 1.000. The reason for presenting these simple examples is to make the point, that if the flow profile is sufficiently well known and of sufficiently low order, one sample suffices: *n* = 1.

Function/Profile	Samples	Location	K-Factor
Constant (plug)	1	don't care	1.000
Parabolic	1	center point	0.500
		diameter path	0.750
		mid-radius path	1.000



Suppose the polynomial’s degree increases. In order to retain a given accuracy according to quadrature theory, the number of samples (paths) must be increased. Manufacturers have used three path Chebyshev solutions, as well as other quadrature solutions employing five or more paths. If profile complications are minimal, the classical quadrature paths and weights, as well as diametrical plus midradius combinations, all yield 0.5% or better inaccuracy, with appropriate caveats attached to the specifications.

In the field it is common to use flow conditioners together with multipath systems in order to achieve the 0.5% inaccuracy in metering natural gas. There are some flow disturbances encountered in the field that cause sufficient uncertainty in the profile, so that four- or five-path quadrature or other multipath flowmeters cannot achieve the sought accuracy without increasing the number of paths to an impractical large value. Alternatively, the multipath meter designer may need to find a way to reduce the degree of the polynomial describing the flow profile, until it becomes comparable to that intended for the designer’s standard number of paths.

Additionally it can be necessary to supplement an *n*-path quadrature flowmeter with paths in the *x* and *y* directions in the *xy* plane perpendicular to the pipe axis (*z* direction) for measuring the cross-flow components. See figure 1.

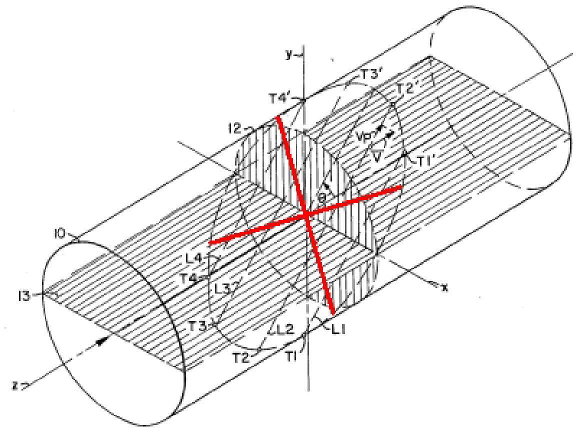


Figure 1. On a plane inclined to the pipe axis, *n* paths may be utilized. This schematic compares the present work's use of two paths that are orthogonal, to four parallel chordal paths (in this illustration, adapted from Wyler, 1976) where each of the four chordal paths are positioned and weighted according to a quadrature formula. © 2005 Lynnworth Technical Services,

Figure 2. Circulation –sensing paths

Furthermore one might add a circulation-sensing path, such as an inscribed equilateral triangle interrogated clockwise and counter clockwise. Such paths are illustrated in Figure 2. and http://www.gesensing.com/products/resources/whitepapers/ur274_5.pdf and were investigated in laboratory studies in the mid-1990s, e.g. [Lynnworth 1994, 1996], based in part on circulation studies at WPI (Worcester Polytechnic Institute) dating back to the 1980s and summarized in [Johari and Durgin 1998].

6.4 Flow Conditioning and Two-Path Location

A flow conditioner, with low pressure drop, conditions the flow profile to be so simple and reproducible, that one or two tilted-diameter paths, weighted by a meter factor *K,* achieve the sought AGA 9 accuracy. The flow conditioning typically requires upstream straight piping of length 10*D* and downstream 5*D* where *D* = pipe diameter. The flowmeter forming the subject of this article uses a CPA 50E ™ flow conditioner. Details on this conditioner are available online at http://www.cpacl.com/products/flowc.htm.

To achieve 0.5% or better inaccuracy despite non-ideal steady flow conditions, the paths are combined with a flow conditioner and straight runs. Calibration data demonstrate performance that meets or exceeds AGA 9 Recommended Practise or OIML Recommendations in situations containing various standard nonideal flow conditions. This alternative to choosing *n* large is to condition the flow so that the degree of the flow profile's polynomial is small. This requires eliminating almost entirely, cross flow and swirl. If these goals can be achieved at reasonable cost, where cost includes pressure drop, then an ultrasonic solution suffices where *n* is as small as one or two. This is the approach taken by the Sentinel flowmeter and is shown schematically in a figure above, with practical implementations illustrated in the figure below.

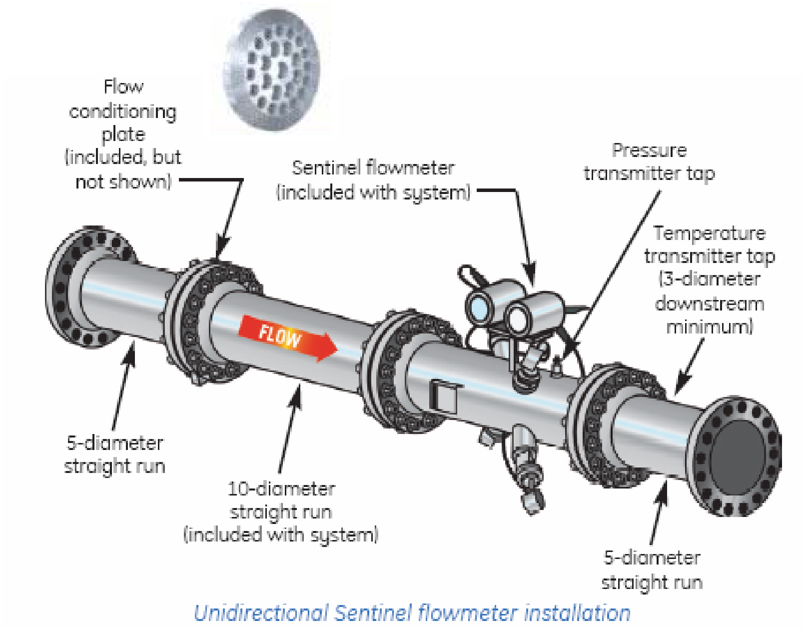


Figure 3. Unidirectional arrangement for a *Sentinel* flow metering system. The flow conditioning plate is typically a CPA (Canada Pipeline Accessories) 50E™ multi-hole plate. The inset shows the CPA E50™ flow conditioner.

The question of optimizing the flowmeter under the above situation of well-conditioned flow can be stated as follows: if only two paths are to be used, where should they be placed?
One of the simplest multipath configurations for this placement in the ultrasonic transit time flowmeter is one that consists of two tilted diameter paths in an $n = 2$ solution. In the present work we emphasize intersecting paths.

6.5 Crossed Paths, Crossed Planes, and Two Diameter Paths

For various reasons, early ultrasonic flowmeters for liquids often employed two paths. Paths were crossed in a side view in a 1966 arrangement due to [Yamamoto 1966]. Paths may be crossed in the end view in order to average in two orthogonal planes and thereby be less sensitive to flow asymmetry, e.g. page 275 in [Lynnworth 1989]. In [O'Hair & Nolan 1987] two paths were used in each of two crossed planes.

Other two-path arrangements include: two chords each near a midradius chord position [Baker and Thompson 1978] or precisely at a midradius position [Lynnworth 1978]. A combination of diameters plus midradius chords was introduced by [Drenthen 1996]. Other special chord locations are found in the work of [Brown 1978], [Kim et al. 1996], [Hammond 2002], and in the helical path used in Siemens' Sitrans® ultrasonic flowmeter [pp. 410-412 in Lynnworth and Mágori 1999].

Referring to the simple schematic in Figure 1. flow, indicated by the arrow, is presumed to be steady and can be from the left or right, and has been conditioned to eliminate upstream or downstream flow disturbances. The flow is a reproducible function of the Reynolds number *Re*. Accordingly, the average of the velocities measured along the two tilted diameter paths (red lines), each of which involves only a single traverse, can be converted to average flow in the pipe using a meter factor K which depends only on *Re.* The two paths provide some averaging, reducing the influence of random errors. Also, two paths inherently include a backup in case one path fails. As seen in the calibration in Figure 4, accuracy of the meter is maintained, even if one path should not be available.

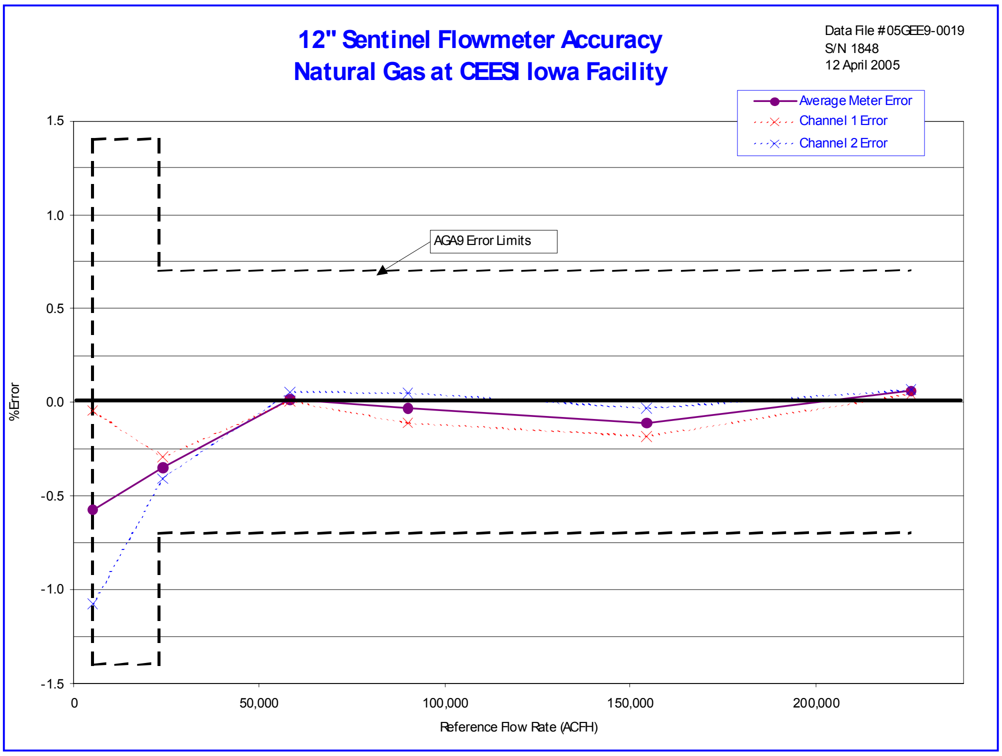


Figure 4. Calibration with plot of each path and the average of those paths.

Still referring to Figure 1, since two intersecting lines determine a plane, the two paths lie in *one* plane. That one plane, tilted with respect to the pipe axis, *could* contain the traditional multiple paths of a quadrature or other combination of tilted diameter and/or chordal paths. However, the present approach places *only tilted diameters* in the measuring plane. The nozzles are oriented so that any disturbance introduced by one does not flow directly past another nozzle.

The profile is now presumably a function only of the Reynolds number *Re* and the condition (e.g. relative roughness) of the walls on the straight runs adjacent the measuring section and within that measuring section. If the geometry remains constant (including details down to the wall surfaces), then an empirical meter factor *K* can be determined as a function of *Re*. As long as *Re* can be determined to within a small factor e.g. factor of two, *K* would be known and accurate results for the average flow in the pipe can be expected.

6.6 Reliability

The number of paths (n) in an ultrasonic flow meter system will also affect reliability. For example, the 2-path, redundant diametrical configuration of Sentinel renders it more reliable than alternative meters that use a higher number of paths. This reliability can be quantified by examining the meter's probability of requiring a service call and its probability of reporting and erroneous reading.

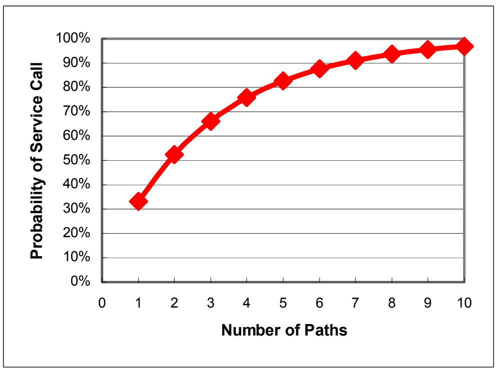


Figure 5: Meter's Probability of Requiring a Service Call vs. Number of Paths. Because all electrical connections, cables, transducer and circuit boards have a finite probability of failure, the probability of a meter reporting and erroneous reading will increase with the number of paths.

Many may believe that extra paths help to ensure accurate measurement if one path becomes inactive. However, this is only true for redundant measurement paths, and many multi-path metering systems use data from a combination of independent path configurations to calculate flow rates.

This redundancy significantly reduces the effect on accuracy when a measurement path becomes inactive.

The probability of a flowmeter reporting an erroneous result is a function of total number of paths, number of independent paths used to calibrate the system and a given failure rate for a path. The calculations used to generate the following results assume that each individual path fails at the same rate.

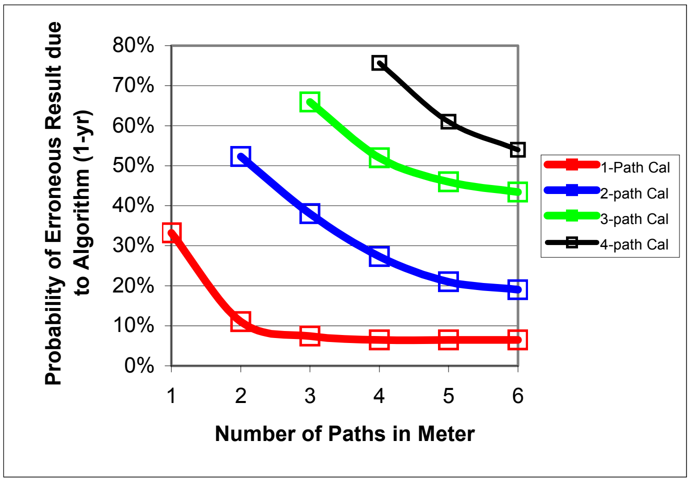


Figure 6: Probability of Erroneous Result due to Algorithm vs. Number of Paths. Adding non-redundant paths to a measurement system will increase the probability of an erroneous result rather than decrease it. If a meter using a 2-path redundant diametrical system is used in conjunction with a flow conditioning plate to ensure axi-symmetric flow profile, it is calibrated with a 1-path calibration. In other words, the 2 separate diametrical measurement paths are redundant and are supplying similar data sets to be used in the flow rate calculations. When a flow metering system comprised of independent measurements paths loses a path, a unique set of data is no longer included in the flow rate calculation and the overall accuracy of the meter will be significantly affected.

As shown in Figure 6 above, a 4-path measurement system with 4 independent paths is about 7 times more likely to report an erroneous reading than a redundant system using a total of 2 paths with 1 independent path. These calculations were performed assuming an exponential distribution per MIL-STD-217, which is a common approach to analyze failure rates of electronics and electromechanical devices.

It is also important to note that a metering system using Chebyshev mathematics with n=4 does not become a Chebyshev system with n=3 when a path is lost because the paths would not have the proper n=3 orientation. Such a path loss would cause the meter's flow profile calculation to be affected, and therefore affect the meter's overall accuracy.

6.7 Calibration Data

The Sentinel two-path ultrasonic flowmeter has been proven to exceed AGA 9 accuracy requirements at various 3rd party test facilities under both normal and extreme operating conditions. These extreme conditions include varying pressure, varying fluid composition, severely disturbed flow profile, and disabling one measurement path as shown above. Legal metrology approval was obtained April 2006. NMi Certin evaluated 2 Sentinel systems (12" and 6") based on the new OIML CD5 Draft standard which is expected to come into force end of 2006 or early 2007. The outcome of the evaluation is Type Approval (B37 dispensation) for the Netherlands based on fulfilling the OIML requirements for all performed tests. The same OIML standard will be used for legislation around the world, as well as MID (EU directive).

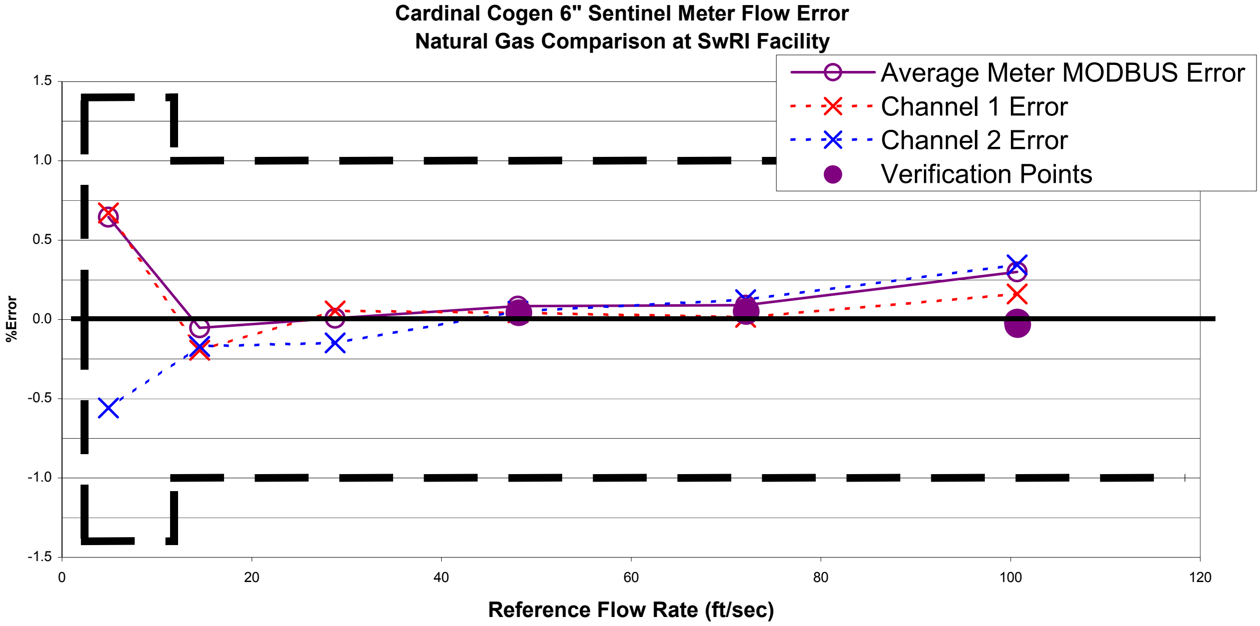


Figure 7. Calibration of a 6" Sentinel flowmeter in natural gas

7 NATURAL GAS FLOWMETER AT CARDINAL COGEN

A 6" Sentinel, Figure 8, custody transfer meter was installed and commissioned at Cardinal Cogen to monitor the accuracy of the Pacific Gas & Electric orifice plate (billing) meter. Ten diameters upstream, a flow conditioner, five diameters upstream and five diameters down stream were installed to create a fully developed axis symmetric flow profile. Temperature and pressure transducers were also installed to provide inputs for standard volumetric and mass flow calculations.

Fig 8. Commissioned Sentinel Flowmeter

Ultrasonic flowmeters have an extremely high turndown ratio relative to other metering technologies. Sentinel's 50:1 turndown ratio allows Cardinal Cogen to measure natural gas usage both during seasons of peak demand and base demand with a single meter. A typical turndown ratio for an orifice plate meter is about 4:1, so plants often require multiple orifice plates in order to measure their entire range of gas usage. This need for multiple meters further increases the maintenance cost of the plant. The above chart, Figure 7, shows the third party calibration results for a 6" Cardinal Cogen Sentinel system completed at South West Research Institute. The as-found results for each channel were within 0.33% of the reference meter, and the as-left results were within 0.125% of the reference meter.

8 CONCLUSIONS

LNG production will require the use of many flowmeters for all the different parts of the process of production of LNG from Natural Gas. Flow meters for the liquid state and for the gaseous state need to be reliable, accurate and inexpensive. The ultrasonic transit time flowmeter offers these solutions for both the cryogenic liquid state with a BWT based sensor, and for the high accuracy gas state with a simplified two-path design. The lower cost of measurement and ownership will allow the process of LNG to be efficient and provide both users and producers more product for less cost.

9 ACKNOWLEDGMENT

GE Sensing contributors include: Shirley Ao, Daryl Belock, Ted Furlong, Nick Mollo, Toan H. Nguyen, Jeff Tilden and John A. Umina. Larry Lynnworth of Lynnworth Technical Services also contributed to this article.

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