Using Tracers to Calibrate / Verify Produced Water Flow Rates

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1. Abstract

Ongoing concerns for offshore discharge and tightening environmental legislation in most parts of the world requires oil and gas producers to more accurately report volumetric flow rates of discharge water along with hydrocarbon concentrations. In many cases existing flow metering systems do not meet measurement requirements due to a number of reasons including;

- fundamental design not meeting current accuracy demands
- location in variable and hostile environments
- age
- lack of maintenance

In many cases there is a need to use onshore calibration facilities leading to delays between removal and re-installation offshore. In addition there is a safety concern during the removal and reinstallation of a meter as well as a cost implication related to the actual calibration process and potential lost production whilst the meter is out of service.

To counter some of these issues, methods have been developed using tracer technologies and radioisotope scanning that allow produced water flow rates to be measured to less than 1% uncertainty. The use of this technology at various produced water flow rates provides a calibration option to oil and gas producers eliminating the need to shutdown and transport to an onshore facility.

This paper gives a brief overview of the technologies developed specifically for produced water flow rate measurement and offers project design considerations needed to reach the accuracy levels required.

2. Introduction

The measurement and record keeping of water discharge flow rates to an uncertainty of +/- 10% forms part of OSPAR rules which is the current organization guiding international cooperation on the protection of the marine environment in the North-East Atlantic. To help achieve this there are many types of installed flow meters. Many have been operational for a number of years with others retrofitted by operators to ensure that they stay in compliance with legislation.

This paper describes how the application of different tracer techniques can be used to verify flow rates in produced water systems. It will also provide an overview of other technologies based upon the application of radioisotopes that can be used to identify problems that occur within produced water discharge systems including solids build up leading to a reduction in bore size upstream of a flow meter thus giving inaccurate flow measurements and gas entrainment that can lead to difficulties in obtaining reliable measurement.

3. Measuring Flows Using Tracer Techniques

General Discussion

Accurate measurement of produced water flow through a piping system can be achieved using one of two tracer methods. The first is known as the constant rate method. This is based on a dilution principle whereby a tracer solution of known concentration is injected into the water flowing within the pipe. Samples are taken downstream after adequate mixing has been achieved and the tracer concentration counted. The ratio of tracer concentrations within the injected and sampled water together with the injection rate of the tracer into the line allows the main water flow to be determined (figure 1).

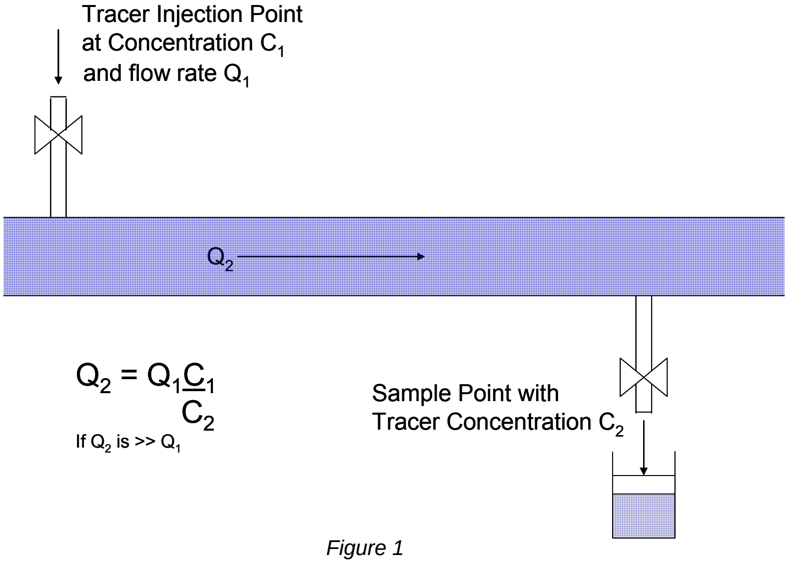

Figure 1

The second method of measurement is known as the mean transit time. In this instance several radiation detectors are positioned at known distances apart along the flow line. A short half-life radiotracer is injected into the pipeline and the time taken by the tracer to travel a specified length is measured by the rise and fall in radiation signal (figure 2).

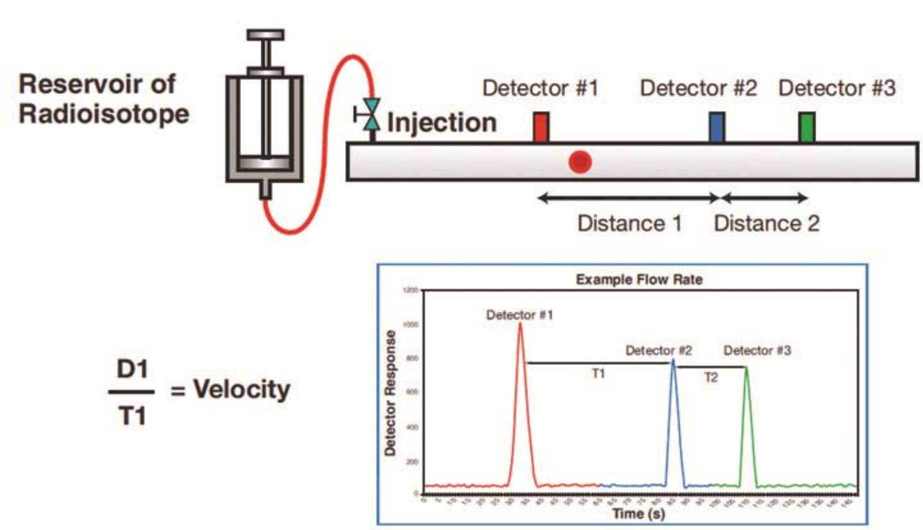

Figure 2

In both of these methods, the advantages and disadvantages of which are considered later, the distance between injection and measuring sections must be large enough to achieve adequate mixing of the tracer with the water flowing through the pipe. In the case of the constant rate method a large number of different tracers may be used, such as radioactive or non-radioactive, mineral or organic materials. The mean transit time method tends to use radioisotope tracers that emit gamma energies as it is necessary to detect the tracer pulse flowing through the line on its external wall.

4. Choice of Tracer Method

With the dilution and mean transit time techniques to choose from several operational criteria determine which is best suited for a particular system. In the case of the dilution method advantages include;

- It is not necessary to know the geometrical characteristics of the pipe
- Dimensional tolerances are not relevant with error propagation only with measurement of tracer concentrations in dilute and concentrated forms making this the most accurate method of measurement
- It can be carried out in a partially filled pipe (although not relevant to this particular application)
- If carried out over an extended period of time it allows for system flow rate fluctuation to be averaged

Disadvantages of the dilution method include;

- Samples must be taken with the sample point located at a minimum distance from the injection point to ensure that adequate mixing occurs
- Sample safety - worker exposure to fluids within the water discharge line
- The necessity to analyze the samples individually can take some time. With some tracers this can be achieved at the work site, but with others, samples have to be sent to a laboratory

Using the mean transit time method advantages include;

- It is not necessary to measure the concentration of tracer material used
- It can be carried out without the need to take samples from the line
- Measurements can be carried out faster than the dilution method as instantaneous data is generated

However, there are several disadvantages when using this method including;

- Handling of a radioisotope is necessary in order that the tracer can be detected through the pipe wall.
- Uncertainty regarding the cross sectional area of the pipe due to wall thickness tolerance or solids build-up within the pipe leading to inaccurate flow rate calculations
- Uncertainty in flow rate measurement due to inaccurate measurement of distance between detectors and time of flight between detector responses during data analysis
- Uncertainty that full bore dispersion occurs across the flowing area from injection point to detection locations.

5. Choice of tracer

The basic principle of tracer investigation is to “tag” a substance or phase and then follow it through a system. Looking at tracer studies from a problem solving point of view, if problems of fluid transport can be described in terms of ‘When?’ ‘Where to?’ and ‘How Much?’ then they can be solved by means of tracer techniques.

The basic requirements of a tracer include:

- It should behave in the same way as the material under investigation
- It should be easily detectable at low concentrations
- Detection should be unambiguous
- Injection and detection should be performed without disturbing the system under investigation
- The residual tracer concentration in the media must be minimal.

The criteria can be met by the use of either chemical or radioisotope tracers and by careful selection of the most appropriate tracer for a particular application. When planning to use a radiotracer, factors that are important in the selection of the isotope include:

- Half life
- Specific activity
- Type of radiation
- Energy of radiation
- Physical and chemical form.

The main advantage of using a radiotracer is that its’ emissions can be detected on the outside of a pipe using a sensitive radiation detector. Measurement of a radiotracer is also not affected by the matrix if used during dilution flow methodology as it is not affected by problems such as the turbidity of the water. One other benefit to radioisotope use is the fact that only short lived radiotracers are used and as such they decay to background very quickly not remaining within the discharge water causing permanent pollution. Finally, the cost of a radiotracer is not proportional to the rate of flow to be measured. Disadvantages of radiotracer use include licensing requirements, source of supply limitations and perception by offshore staff that it may be dangerous.

Benefits of using chemical tracers include the fact that there are fewer legislative and safety related licensing requirements to deal with. In addition it is not necessary for the service provider’s crew to be specially trained and classified as radiation handlers and there is no time limit on performing the project due to radioactive half-life decay. However, chemical tracers can not be used if the mean transit time method is to be applied due to their inability to be detected on the external walls of a pipe.

A large number of tracers have successfully been used depending upon project requirements and possible limitations regarding sampling or the handling and use of radioisotopes. Most common tracers used include low concentration UV/VIS dyes, inorganic salts such as nitrate, iodide or thiocyanate, bromine-82 radiotracer in the form of ammonium bromide produced in a research nuclear reactor or isotope generators such as Tin-113/In-113m and Cs-137 / Ba-137m.

6. Choice of measuring length and adequate mixing distance

When a tracer is used to measure the flow of water in a pipeline, there should be sufficient distance between the point at which the tracer is injected and the point(s) where the sample or transit time measurements are made. The distance, which is required in order to allow the tracer to mix with the water in the pipeline, is known as the mixing distance. Tracer use in flow rate measurement only works if turbulent flow exists in order to disperse the tracer across the whole pipe cross sectional area as it flows. To ensure turbulent flow the Reynold's Number ($N_{Re}=U\partial D/\mu$) must be greater than 3500. Where ∂ is the density, U is the velocity, D is the pipe diameter and μ is the viscosity. It is generally believed that an ideal distance between injection point and sampling or detection location is equal to or greater than 50 pipe diameters to achieve full bore mixing. This length can be reduced based upon operating parameters of the actual flow and equipment located in between the injection point and sampling / measurement position. Several techniques can be used to reduce the mixing distance.

Multi-orifice injectors
When the tracer is injected equally through a number of orifices spaced across the pipeline, a reduction in mixing distance can be achieved compared with the mixing distance associated with a central injector.

High velocity jets
If the tracer is injected against the flow with a velocity which far exceeds the mean velocity of the water in the pipeline, impact mixing occurs at the termination of the jet. The reduction in mixing distance depends on the number and the momentum of the jets and their inclination to the direction of flow. Care must be taken using this method to not significantly increase the overall flow within the line under investigation.

Pumps and turbines
A considerable reduction in mixing distance may be effected by injecting the tracer upstream of a pump or turbine. Information on mixed-flow pumps indicates that this type of pump reduces the mixing distance by about 100 pipe diameters. However, care must be taken to not mix the tracer more than necessary if using the mean transit time method leading to errors on pulse to pulse time measurement due to pulse shape distortion.

Bends, valves and other obstructions
Obstructions in the pipeline introduce additional turbulence and thus tend to reduce the mixing distance. Quantitative information on these types of mixing enhancers is not available but measuring sections that include these features are preferred. In the transit time method, however, the length of pipeline between detectors should be straight and free of obstruction if the highest accuracy is required due to physical distance measurement concerns.

7. Principle of Dilution Technique

Flow rate measurement by constant rate injection is based on a comparison between the concentration C_1 of a tracer, continuously introduced into a stream flowing at Q with a known volume rate of flow q, and the concentration of samples C_2 taken at some place beyond the mixing distance.

$$q\,C_1 = (Q + q)\,C_2$$

Generally Q is much greater than q which leads to a simplification as follows:

$$Q = q\left(\frac{C_1}{C_2}\right)$$

Flow rate *Q* can thus be determined by comparing the concentration of the injected solution with the concentration of samples taken from the pipe.

In order to increase the accuracy it is recommended that a standard solution be prepared to a given dilution ratio which shall be approximately equivalent to the dilution ratio which is expected in the sample taken from the measuring cross-section.

An example is shown below. A 250 ppm solution of fluorescent dye was used with an air driven metering pump delivering a 1ml per second tracer injection rate. Samples were taken over a 7 minute time interval every 15 seconds at a point downstream. The flow rate was adjusted prior to each of the three tests. Tracer concentration within the produced water samples was analyzed using a UV/VIUS spectrometer at a specific wavelength (figure 3).

Figure 3

Results were plotted over time. A graphical representation is shown in figure 4 of the data. Sample data on each plateau was averaged and input into the formula giving flow rate measurements of 2736 +/- 28, 5450 +/- 65 and 18170 +/- 345 bbl per day.

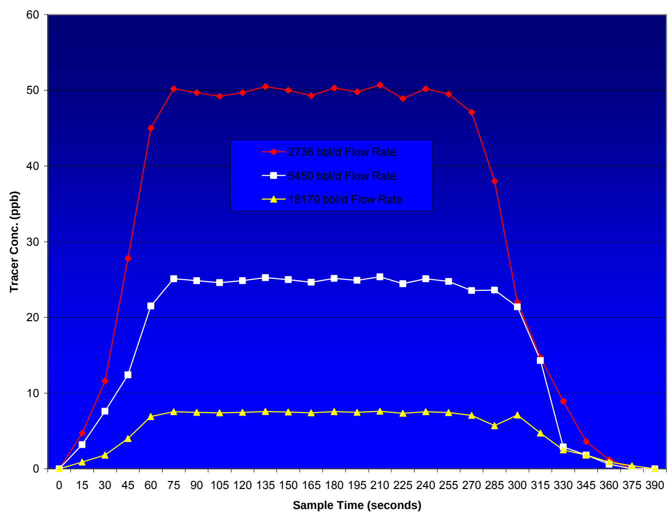

Figure 4

8. **Principle of Transit Time Technique**

Flow-rate measurement by the transit time method is based on measuring the transit time of "tagged" fluid particles between two cross-sections of a pipe a known distance apart. Tagging of the fluid particles is achieved by injecting a tracer into the flow upstream of the two measurement cross-sections (i.e. detector positions) and the transit time is determined from the difference in the arrival times of the tracer at each of the detector positions. Under certain conditions, the flow rate q_v is given by

$$q_v = \frac{V}{t}$$

where V is the volume of the pipe between the detector positions and t is the mean transit time of the tagged fluid particles between detection locations.

In general, the theoretical condition for the validity of the formula is that the measuring section be "closed to diffusion": i.e. that the ratio of the local velocity to the longitudinal dispersion coefficient be equal at both ends of the measuring section.

The signal from the detectors shall be proportional to the tracer concentration. The value of the proportionality coefficient and hence the absolute concentration value need not, however, be known exactly.

An example of a mean transit time project is shown below. Four detectors were positioned at known locations downstream of the injection point. There were several pipe bends and an acceptable distance between the injection point and the first detection location. A small amount of bromine-82 radiotracer in the form of ammonium bromide was injected into the line and the responses measured using a real time data acquisition system. A total of ten injections were carried out at each of several flow rates across the range of a downstream meter.

Figure 5 shows one of the detectors positioned externally on the flow line. Figure 6 shows the tracer responses and set up with various permutations of distance and transit times.

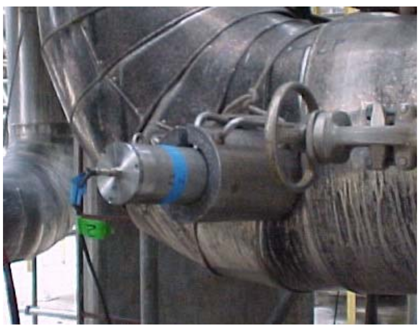

Figure 5

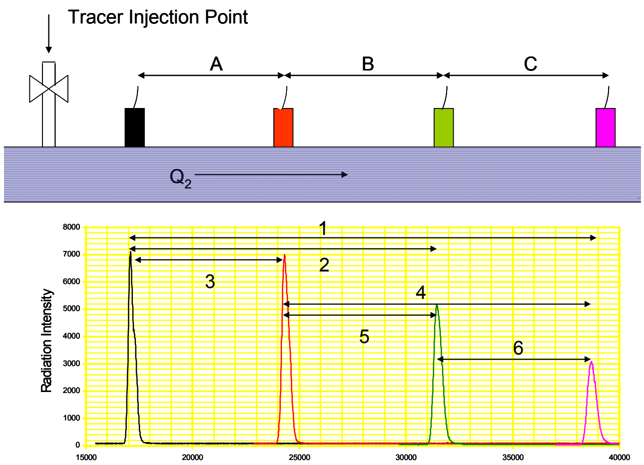

Figure 6

Table 1 shows how each of the permutations can be used to determine the average flow rate from one tracer injection at one of the targeted flow rates.

Distance (meters)	Time (seconds)	Velocity (m/sec)	Volume Flow in 8” pipe
A+B+C = 16.2	(1) = 21.06	0.77	2157 m^3/day
A+B = 10.0	(2) = 13.62	0.74	2073 m^3/day
A = 5.4	(3) = 7.24	0.75	2101 m^3/day
B+C = 10.8	(4) = 15.08	0.72	2017 m^3/day
B = 4.6	(5) = 6.06	0.76	2129 m^3/day
C = 6.2	(6) = 8.60	0.72	2017 m^3/day
		Mean	**2082 +/- 58 m^3/day**

Table 1

9. Peripheral Measurements that can be Used to Assist Flow rate Measurements

Solid Deposits in the Flow Line

Produced water contains a significant amount of salts. As the produced water flows to the surface, salts that are initally dissolved in the water in the resevoir may precipitate from solution and deposit as scale as conditions change.

If there is a suspicion of solids build up on the walls of the produced water flow line then the dilution method is the preferred technology to use as it is unaffacted by geometrical uncertainties within the pipe. However, it may not be possible to find a suitable sample point following complete mixing where fluid can be collected requiring the mean transit time method having to be used.

If the mean transit method is to be used it is prudent to carry out some investigatative work to ensure that the flow line is free from solids. This can be achieved using a gamma scanning technique.

The theory of gamma scanning is summarised in the equation shown in figure 7, essentially defining how gamma radiation interacts and is affected by matter.

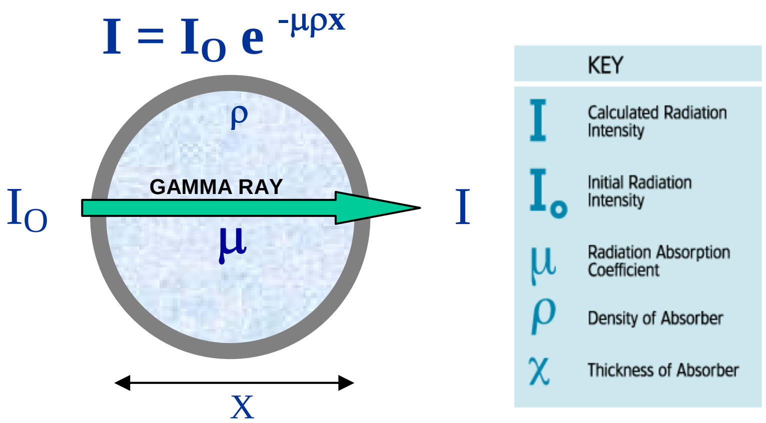

Figure 7 - The Gamma Ray Transmission Equation

Using the equation as a reference, a gamma scanning study on produced water flow lines will require:

- The initial radiation intensity
- The radiation absortion coefficient of the pipework material and the produced water
- The density of the pipework material and the produced water
- The thickness of the pipework material and the internal diameter of the pipework which gives the total produced water path length within the pipe.

Based upon expected radiation transmission through the pipe and taking a typical density of scale, the measurements will show if there is any solids within the pipe. Each section of pipe can be assessed for scale presence and a picture built throughout the whole system as is shown in figure 8.

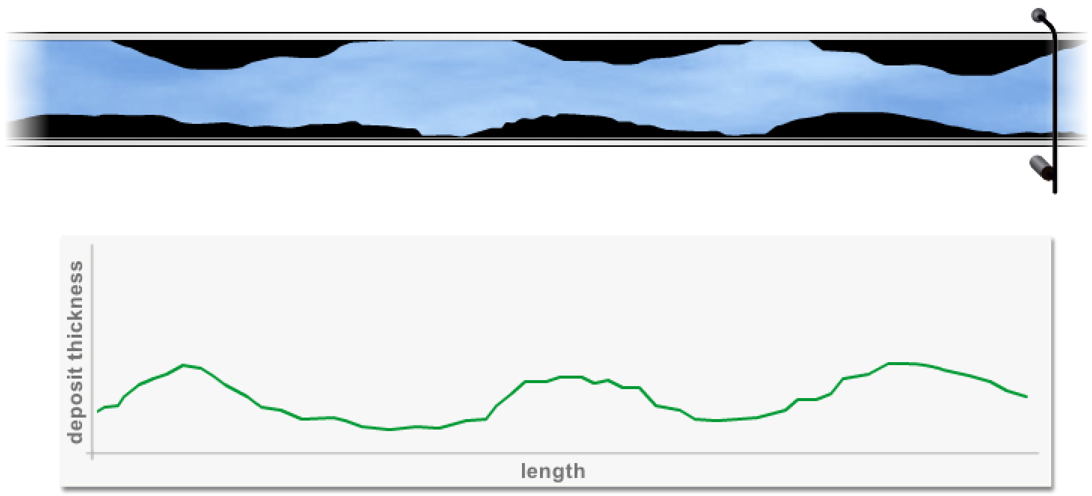

Figure 8 Scanning of Pipeline

This technology can also be used to measure the bulk density of the water flowing through the line to ensure that there is no vapor present within the produced water. If this was the case the calculated flow rate using the mean transit time method would not be accurate due to the decreased volume of the pipe through which the produced water will be able to flow.

The gamma scanning technology can also be applied to offer a much more detailed picture of density within a specific cross sectional area of a pipe by gathering many readings at a number of different orientations around its circumference. Using the data gathered and computer alogrithms it is possible to develop a tomography picture through the cross section of the pipe. Figure 9 shows how a gamma tomography measurement is taken. Figures 10 and 11 show typical tomography data from a pipe where there is an even deposition of scale around the walls and solids deposited in the bottom section respectively.

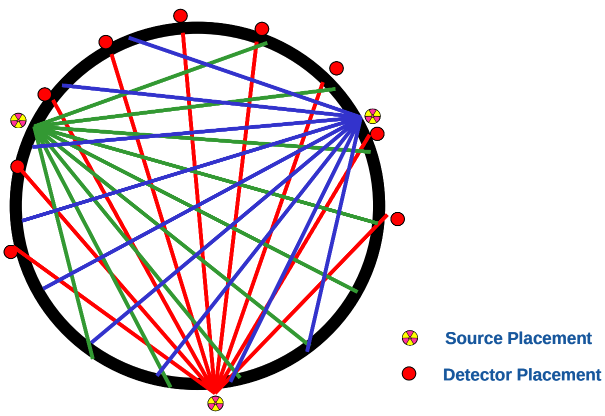

Figure 9 – Tomography Scan Lines

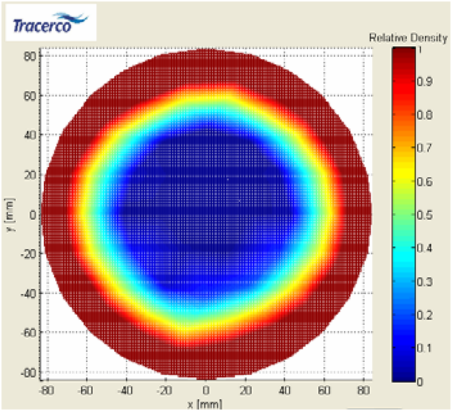

Figure 10

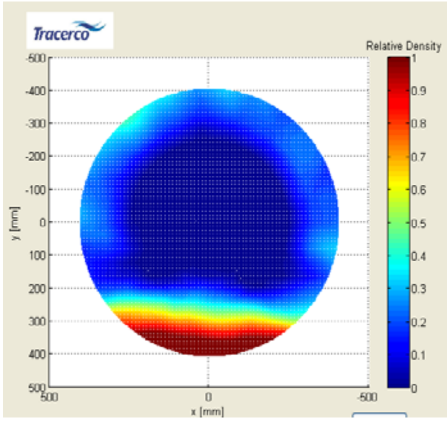

Figure 11

10. Summary

Tracers have been proven as an extremely flexible and cost effective means of calibrating flow meters without the need to shut down and send the meter to an onshore facility for calibration. The technology is accurate enough to allow an operator to prove compliance to required uncertainties, does not take a significant time period to carry out and has the flexibility to cover all turbulent flow rates across the calibration range of any meter. The selection of a specific tracer flow rate technique allows uncertainties such as pipe solids deposits and gas carry through to be discounted.

In addition to water flow rate measurement the technology is commonly used to verify gas, oil and multiphase flows thus proving compliance with other operator and legislative requirements.