# Subsea Ultrasonic Flowmeter for Gas, Liquid, and CCS

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## 1 INTRODUCTION

OneSubsea and Sensia, a Rockwell Automation and SLB company, have jointly developed a subsea ultrasonic flowmeter in collaboration with Equinor and Gassco and with support from the Norwegian Research Council under the DEMO2000 program. The primary application is subsea custody transfer metering of natural gas, but the subsea ultrasonic flowmeter may also be used to measure the flow of liquids, dense-phase carbon dioxide for carbon capture and storage (CCS) applications, and gas production including, within certain limitations, wet gas. The subsea ultrasonic flowmeter is a development based on the Sensia Caldon LEFM™ family of ultrasonic flowmeters and is re-using core technology elements like transducers, electronics design, and firmware. The enabling technology is a novel transducer packaging with metal-to-metal sealing to eliminate the risk of degradation of O-rings and other soft materials exposed to process fluids, while maintaining excellent acoustic performance. The subsea ultrasonic flowmeter is a full subsea design complying with applicable industry standards such as API Spec 6A [1] , API Spec 17D [2] and API Std 17F [3].

In this paper, we present the key technical features of this design, together with test results from static testing and flow testing. Flow testing of an 8-path 16-inch meter with natural gas at high pressure in a calibration facility will be discussed in detail.

## 2 KEY TECHNICAL FEATURES OF THE SUBSEA ULTRASONIC FLOWMETER

The subsea ultrasonic meter is based on the Sensia Caldon LEFM™ family of ultrasonic flowmeters. The measurement core, including data acquisition and interpretation algorithms, is reused without modification. Electronics design and software have been slightly modified to conform to subsea standards, in particular API 17F [3], but are otherwise unchanged. The main differences are in the mechanical design, in particular the transducer housings and associated process sealing, and the packaging and connection of the electronics. The latter is based on the design of OneSubsea's Vx Omni multiphase flowmeter and is reusing many of its components.

### 2.1 Specifications

Table 1 summarizes the key specifications of the subsea ultrasonic meter.

Table 1 – Design specifications of the subsea ultrasonic meter.

| Description | Specification |
|---|---|
| Line size [inch] | 5" – 24" (enquire about smaller and larger sizes) |
| Material class | FF or HH trim as per API 6A |
| Number of paths | 2, 4, or 8 |
| Design temperature | Process: -46 to +177 °C<br>Instrumentation: -18 to +70 °C |
| Design pressure | 5 000 psi / 345 bar; 10 000 psi / 690 bar |
| Supply voltage [V] | 24 VDC |
| Power consumption [W] | < 15 W |
| Data output | Modbus TCP/IP / SIIS Level 3 (Ethernet) |

## 2.2 Transducer Design

Transducers are composed of a transducer module encapsulated in a transducer housing. For the topside designs, the transducer housings are generally made of several parts sealed together using O-rings. In addition, the parts of the housing are acoustically decoupled using 'isolating' spacers. Those O-rings and spacers are usually made of elastomer or thermoplastic. All these combined factors allow the transducer to reduce the coherent ultrasonic noise that is 'conducted' through the flowmeter body. As a result, the ultrasonic signals received for flow measurement are not significantly affected by coherent noise.

For subsea applications, elastomer or thermoplastic materials are not recommended when exposed to process fluids and/or wide operating temperature ranges. Metal seals are considered better suited for such use. However, the transducers would then be rigidly coupled to the flowmeter body, creating routes for propagation of coherent noise, which could degrade measurement performance. This necessitated a redesign of the transducer housing.

The main design novelty of the subsea transducer housing is that the conducted coherent noise is reduced by the introduction of ribs on the transducer stem. The ribs are optimized to act as acoustic filters, reducing coherent noise propagation into and through the flowmeter body and minimizing interference with the measurement signal. Owing to this noise reducing feature, metals seals can be used as process seals.

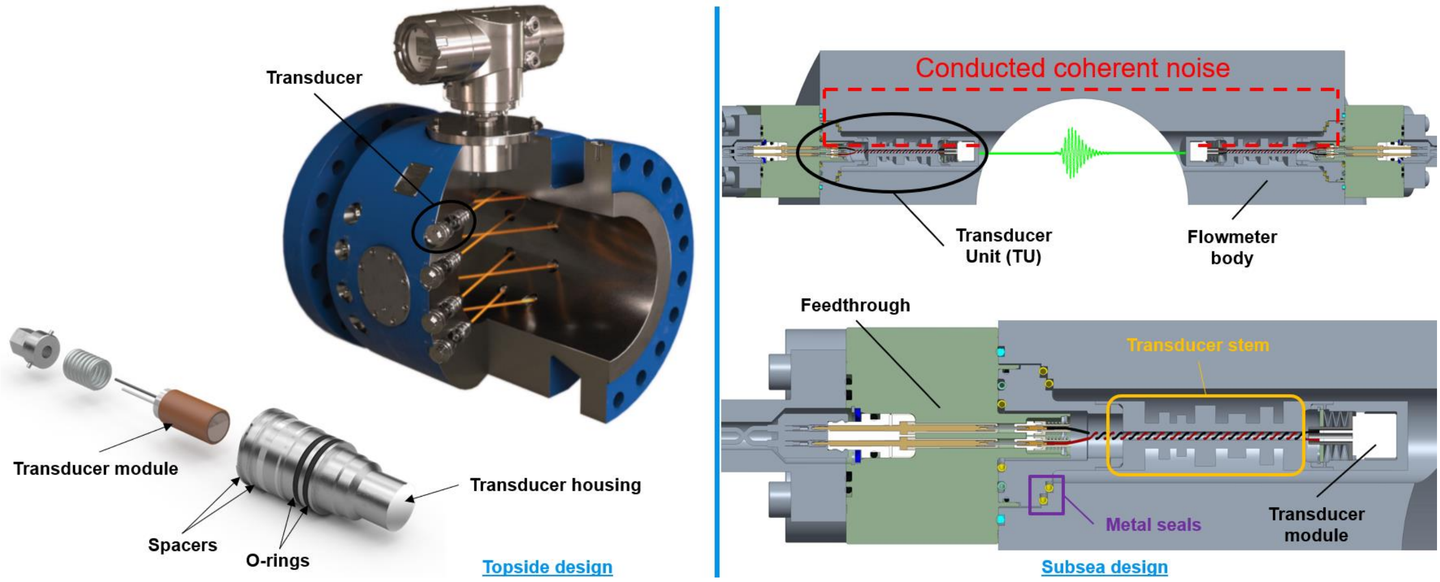


Figure 1 – Comparison of Transducers – Topside design (Left) vs. Subsea design (Right). In the subsea design, the ribbed transducer stem acts as a filter, reducing conducted coherent noise.

## 2.3 Sealing Technology

Gold plated C-ring metal seals are used as process barriers. These seals have many advantages compared to other sealing technologies. They are compact, perfectly hermetic, not prone to rapid gas decompression, do not degrade over time, and can be used over a wide range of temperatures. OneSubsea has been using these seals in subsea applications for more than 20 years with an excellent track record.

The seals employed in the meter are qualified to 20 ksi and -50 to 400 F (1380 bar and -46 to 205°C). The following tests have been performed for qualification:

- API 6A PR2: over 1000 cycles
- Proof test at 50 000 psi (3450 bar)
- Reverse pressure test at 500 bar

An overview of the transducer seal installation and qualification is shown in Figure 2.

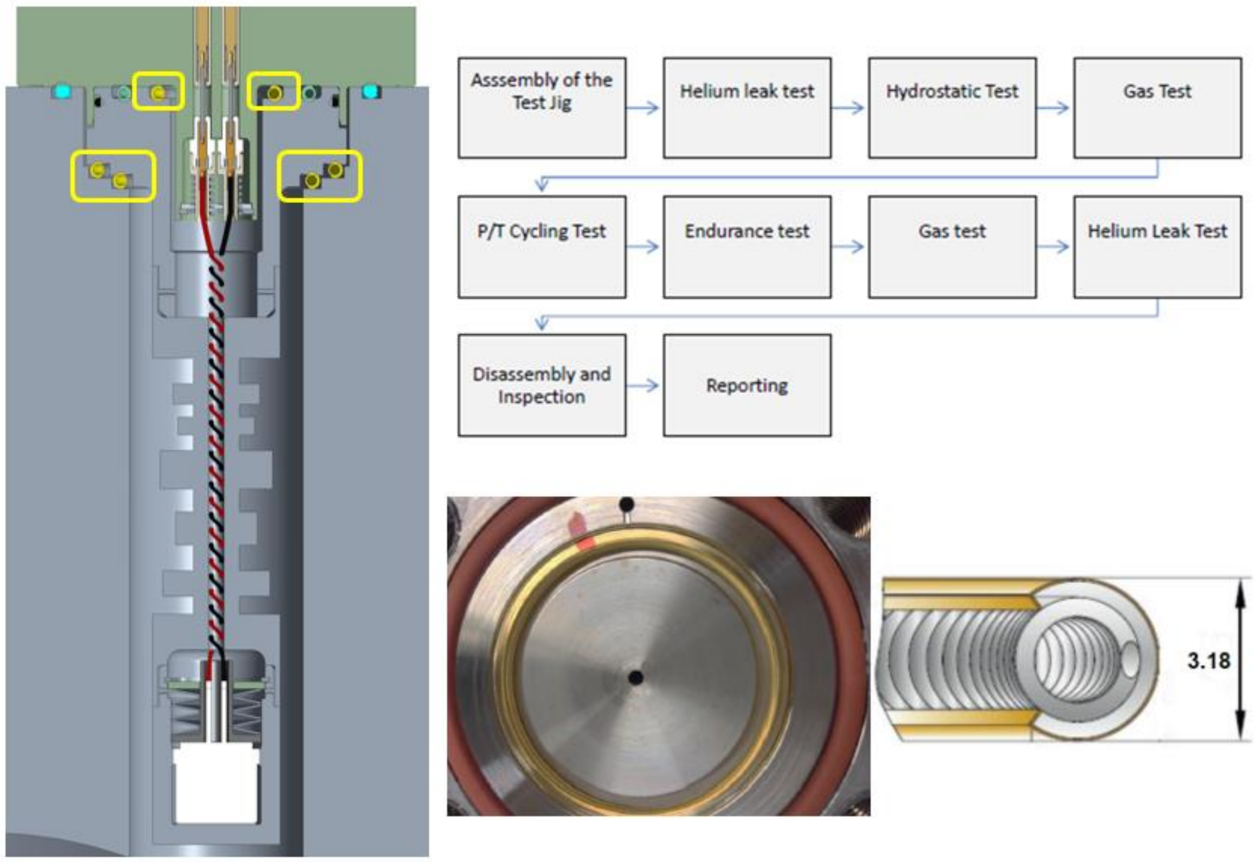


Figure 2 – Overview of transducer seals (left) & qualification test program and test pictures (right).

## 2.4 Redundant Electronics Design

The electronics and electronics housing are designed according to subsea standards, in particular API Std 17F [3] and Equinor TR1233 [4]. Key requirements of the electronics design are summarized in Table 2.

Table 2 – Electronics & electronics housing requirements.

| Parameter | Requirement |
|---|---|
| Seawater depth, max. | Design seawater depth: 4500 m<br>Qualification seawater depth: 3000 m |
| Seawater temperature | -5 to 30°C |
| Ambient temperature | -18°C to +70°C |
| Standard and codes | API 17F and Equinor TR1233 |
| Design life | 25 years |
| Redundancy | • Electronics (each set operating half of the paths)<br>• Communication ports<br>• Power inputs<br>• Subsea connectors |
| Power consumption | < 15W (redundant electronics) |
| Communication ports / protocols | 4 x SIIS Level 3 (Ethernet) |
| Subsea connectors | Compatible with Siemens, Teledyne, and Diamould subsea connectors |

The electronics redundancy is ensured by 2 electronics sets connected via RS-485 serial (see Figure 3). Each set is connected to one half of the acoustic paths (up to four per set). Under normal circumstances both sets of electronics compute the flowrate using all paths. If one set should experience a failure, the other set will continue to operate with its half of the acoustic paths. The calculations in the meter will automatically account for the absence of the other paths, and the measurement uncertainty will increase. In the event of a failure, the impact on the accuracy of the measurement will be dependent on the total number of paths and the installation conditions.

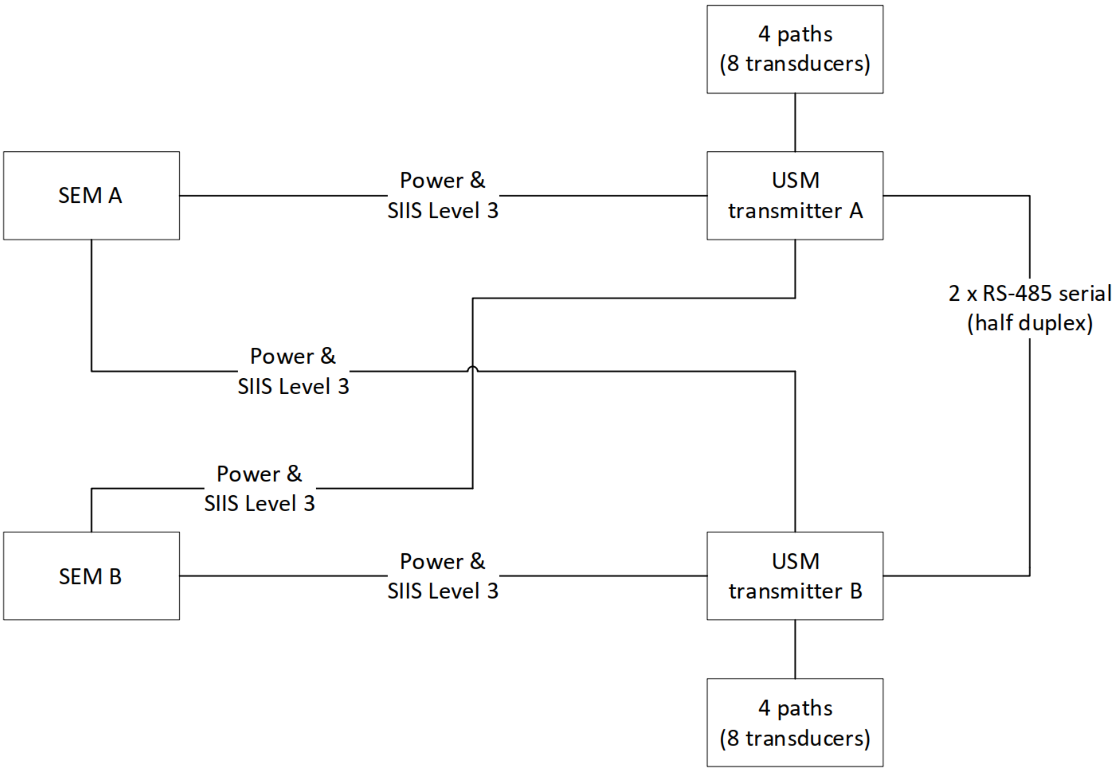


Figure 3 – Single-line redundancy diagram for an 8-path flowmeter.

The electronics sets are enclosed in a nitrogen filled housing at atmospheric pressure. The power, communication, and transducer connections are placed in a Pressure Compensated Electrical Penetrator (PCEP) housing filled with dielectric oil.  Oil-filled rigid steel conduits connected to the same pressure-compensated volume lead the signal wires to each transducer.  The connection between the electronics and the wires for power, communication, and transducers is performed through a glass-to-metal feedthrough. The PCEP is pressure compensated by a piston equalizing pressure between seawater and dielectric oil. Connection to Subsea Electronics Modules (SEM) is done through subsea connectors.

The key design features such as pressure compensation system and electronics housing are based on proven solutions from other OneSubsea products such as the Vx Omni. Also, many standard components such as connectors and the glass-to-metal feedthrough are used in the Vx Omni.

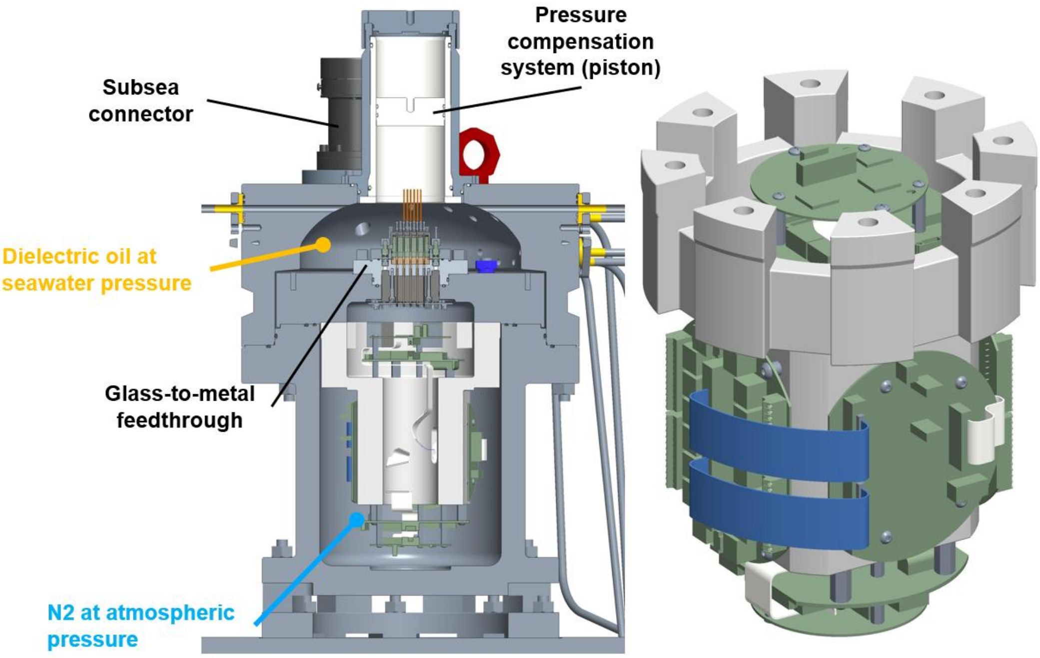


Figure 4 – Electronics housing section view (left) & dual electronics sets (right).

## 2.5 Applications and Variants

Subsea ultrasonic meters can be used for various applications. The main applications identified to build the product portfolio are custody transfer gas metering, gas metering for dry and lean gas production, and metering for CCS applications. The availability of a subsea ultrasonic meter that satisfies requirements for custody transfer gas metering enables direct export of gas from subsea processing facilities to export lines, and subsea transfer between export lines. In addition, the meter can be used to measure petroleum liquids, water, ammonia, hydrogen and other fluids. Ultrasonic flowmeters offer many advantages over Venturi and V-cone meters, such as better accuracy and repeatability, long-term stability, larger turn-down ratio, a non-intrusive full-bore design, and the absence of pressure drop.

Flowmeters for custody transfer applications are expected to be of large diameter and to operate typically at pressures below 5 ksi / 345 bar and temperatures below 70°C / 158 F. These flowmeters are usually engineered to order, but they use all the qualified standard product blocks of the subsea ultrasonic meter such as transducers, electronics, and electronics housing. Sizes are expected to range from 12 to 24 inches, but sizes down to 5 and up to 32 inches and more can be realized. A typical 8-path 16-inch meter for custody transfer is presented in Figure 5 (left).

The uncertainty of an ultrasonic meter depends on the various aspects of design, calibration, and installation. Two important and related variables are the number of measurement paths and the upstream pipe configuration. The technology elements qualified for subsea use can be configured with an appropriate number of paths depending on the accuracy and installation requirements. As mentioned previously, the subsea meters are based on the Caldon line of ultrasonic meters from Sensia. The Caldon LEFM line is the successor of the Westinghouse LEFM flowmeters first developed in the late 1960's and embodies more than 50 years of developments. The Caldon line includes a wide range of products with various capabilities and applications, including 4, 8 and 16-path meters for gas and liquid custody transfer and nuclear power applications. By adopting path configurations used in Caldon products, the effect of various upstream pipe configurations on uncertainty can be evaluated from the large database of testing that has already been performed.

The subsea 8-path gas meter design is based on the Caldon LEFM 380Ci and employs two crossed paths in each of four chordal planes. This particular 8-path configuration has been subjected to a wide range of tests with different upstream disturbances, including the combinations of single-bends, out-of-plane-bends, reducers, expanders, steps and half-moon plates that are specified in the type-testing requirements of ISO 17089-1 [5] and OIML R137 [6]. The 380Ci on which the subsea 8-path design is based is certified in compliance with the Accuracy Class 0.5 requirements of ISO 18079-1 and OIML R137 with respect to upstream disturbances, with a minimum upstream length of 5 pipe diameters and without the need for a flow conditioner.

For subsea gas applications, the subsea ultrasonic flowmeters are offered as a standard product line with the main specifications listed in Table 3.

Table 3 Standard subsea ultrasonic flowmeter, Main specifications

| Description | Specification |
|---|---|
| Design pressure | 10 000 psi / 690 bar |
| Design temperature | Process: -46 to +177 °C<br>Instrumentation: -18 to +70 °C |
| Material class | FF or HH trim as per API 6A |
| Number of paths | 2, 4, or 8 |
| Supply voltage [V] | 24 VDC |
| Power consumption [W] | < 15 W |
| Data output | Modbus TCP / SIIS Level 3 (Ethernet) |

A typical 4-path 5-inch ultrasonic meter is presented in Figure 5 (right).

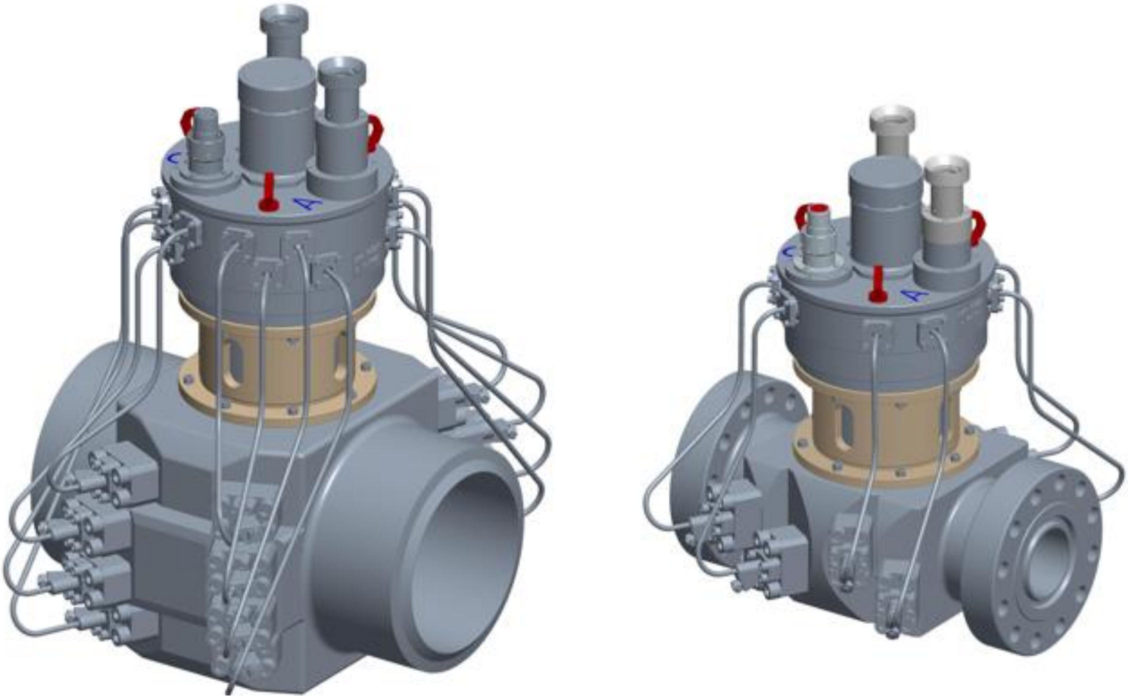

Figure 5 – 8-path 16-inch ultrasonic meter for custody transfer metering (left) and 4-path 5-inch ultrasonic meter for gas production and CCS (right).

For CCS applications, the meters are also offered as a standard product line with the same characteristics as the subsea gas production meters. The integration of a 4-path 5-inch ultrasonic flowmeter on a CCS tree is presented in Figure 6 (Left).

For subsea gas and CCS applications, it is also possible to offer ultrasonic meters different from the standard product line (different sizes, materials, number of paths, lengths, electronics housing orientation etc.). A typical example of an engineered-to-order 4-path meter integrated in a flow control module with the electronics housing oriented horizontally and customized end flanges is presented in Figure 6 (Right).

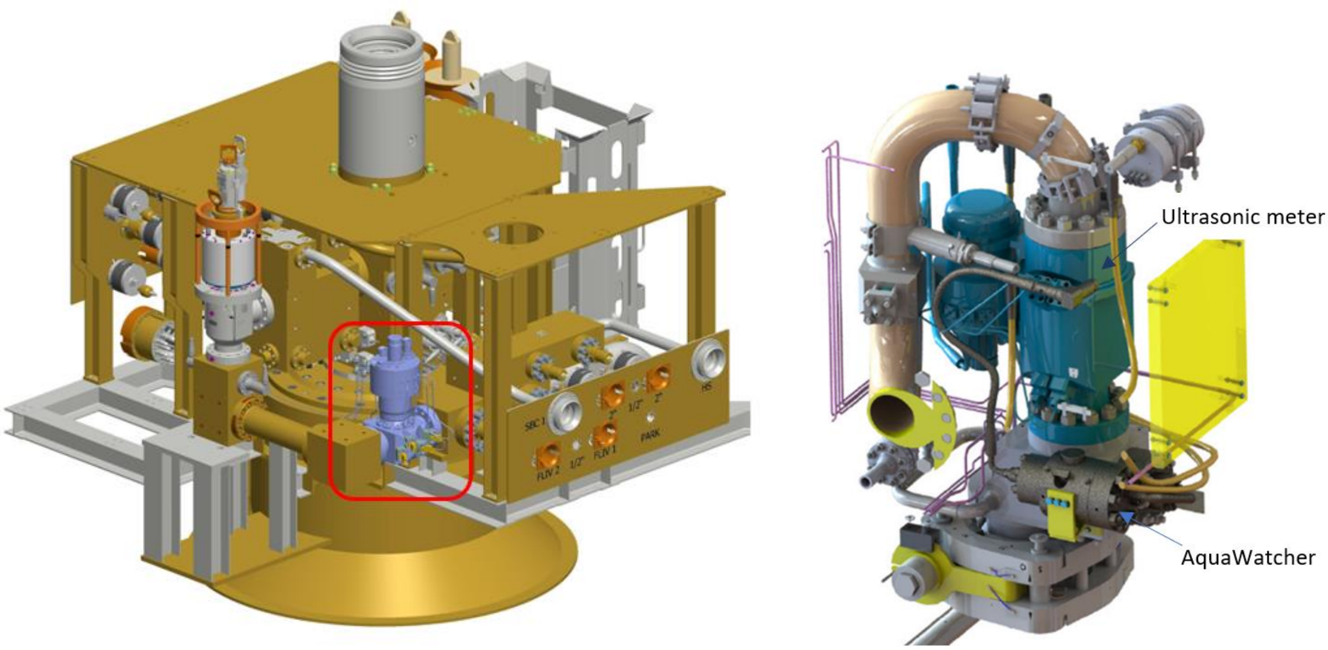


Figure 6 – 4-path 5-inch ultrasonic meter on a CCS tree (Left). In the figure to the right, the meter is customized to fit in a flow control module together with a OneSubsea AquaWatcher.

## 3 TEST RESULTS

Subsea ultrasonic meter prototypes have been subjected to a broad series of tests under both static and flowing conditions. Important aspects of transducer performance, such as signal waveforms, amplification (gain) requirements and signal-to-noise ratio, can be observed under static conditions. Static test results can be used to evaluate transit time measurement performance and the contribution of signal-to-noise ratio to the measurement uncertainty. Signal-to-noise ratio and its impact on transit time measurement uncertainty is one of the key parameters that has been evaluated under many varied conditions to validate the transducer performance.

Flow testing is performed to evaluate the performance of the complete measurement system, including acoustic and fluid dynamic effects. Flow testing has been performed both in the OneSubsea facility in Horsøy, and at the FORCE calibration laboratory in Denmark. The flow testing performed at the FORCE calibration laboratory was designed to enable evaluation of performance relative to custody transfer requirements (i.e. ISO 17089 and OIML R137 standards, and the Norwegian measurement regulations [7]).

### 3.1 Static Testing

Hydrostatic testing with water has been performed on assembled meter bodies up to 15 ksi (1050 bar) (see for example Figure 7). Static pressure testing with nitrogen, CO2, and CO2/Nitrogen mixtures (60/40 mol) has also been performed. During static testing full sets of diagnostics and signal waveforms have been recorded.

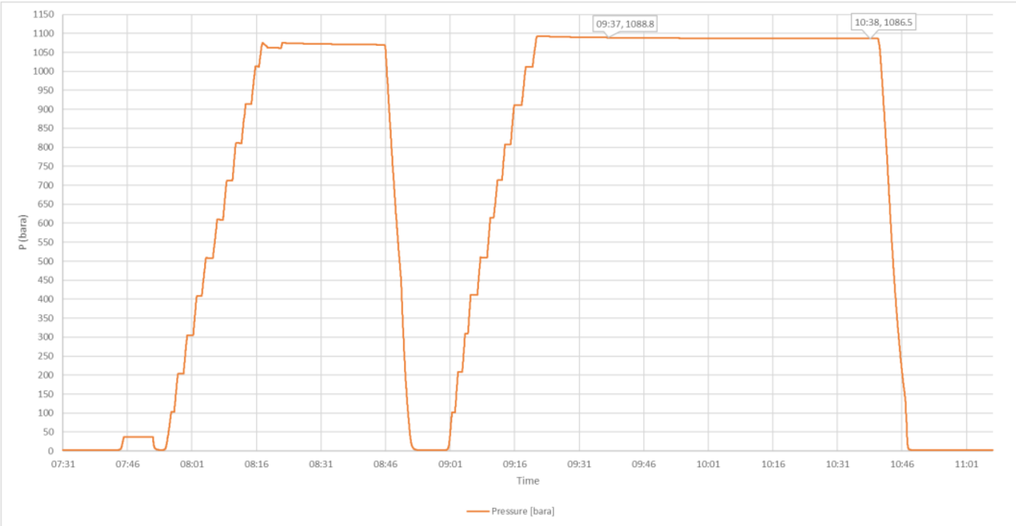


Figure 7 – Hydrostatic pressure test with water up to 15 ksi (1050 bar) – 2 cycles 15 min + 60 min holding time.

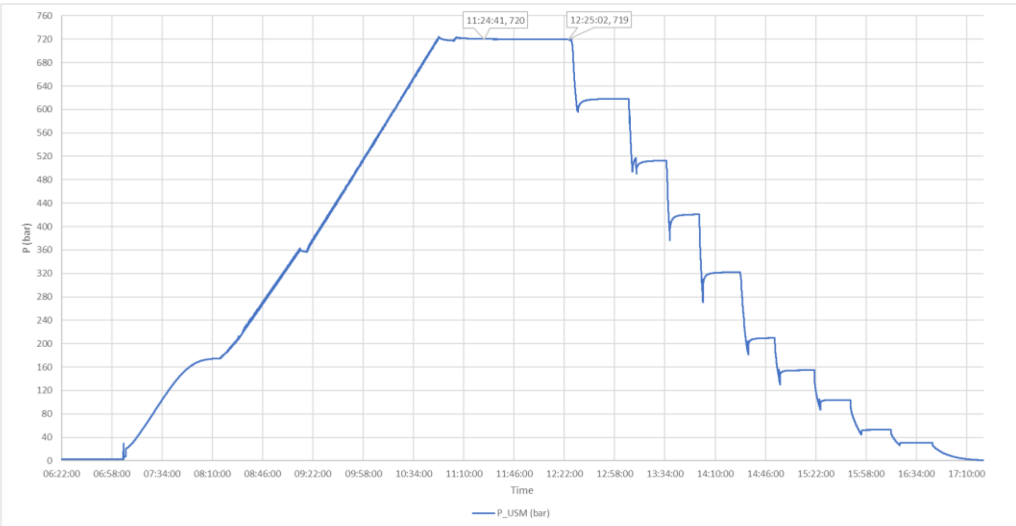


Figure 8 – Gas test with N2 up 720 bar (10 ksi / 690 bar requirement) – 60 min holding time.

From the data recorded during static testing it is possible to evaluate the uncertainty in the transit time measurements and to translate that into an uncertainty in flow measurement. This evaluation considers only one component of the overall uncertainty, that related to the signal-to-noise ratio, i.e. it does not include factors such as fluid dynamics and velocity profile effects. However, it is a useful and legitimate way of evaluating transducer performance with different fluid properties and variation of pressure and temperature. In particular, it is useful in the evaluation of uncertainty at low velocities where signal-to-noise ratio and transit time uncertainty is dominant in the overall uncertainty.

A selection of results obtained with 7-inch and 9-inch prototype meters are presented in Figures 9 and 10. All results in this section are for a nominal temperature of 20 °C. Typically, the flow measurement uncertainty owing to the transit time measurement accuracy does not rise above 0.5 % until the flow velocity is below 1 m/s. Nitrogen at high pressure produces the largest uncertainties owing to the relatively high speed of sound at the elevated pressure conditions.

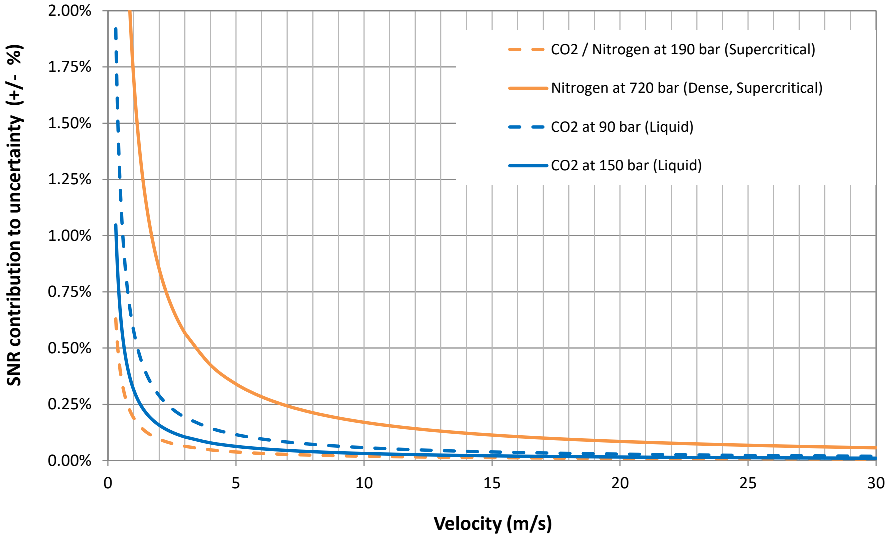


Figure 9 – Evaluation of the SNR-related contribution to uncertainty for a 4-path 7-inch meter.

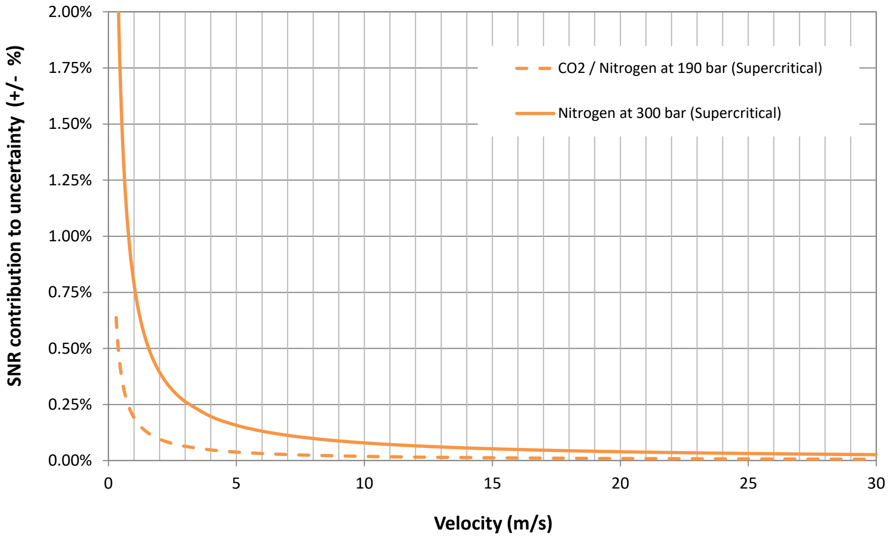


Figure 10 – Evaluation of the SNR-related contribution to uncertainty for an 8-path 9-inch meter.

Figure 11 below shows the uncertainty owing to the signal-to-noise ratio / transit time measurements for the 8-path 16-inch meter based on the static testing performed in the range of 40 to 60 bar with Nitrogen. The dotted blue line shows the results for the conditions of the test with Nitrogen. The solid line is calculated based on the Nitrogen data but adjusted to the calibration conditions at FORCE, i.e.

accounting for the speed of sound, density and attenuation characteristics of the FORCE natural gas composition, temperature and pressure. This result will be used again later in the paper.

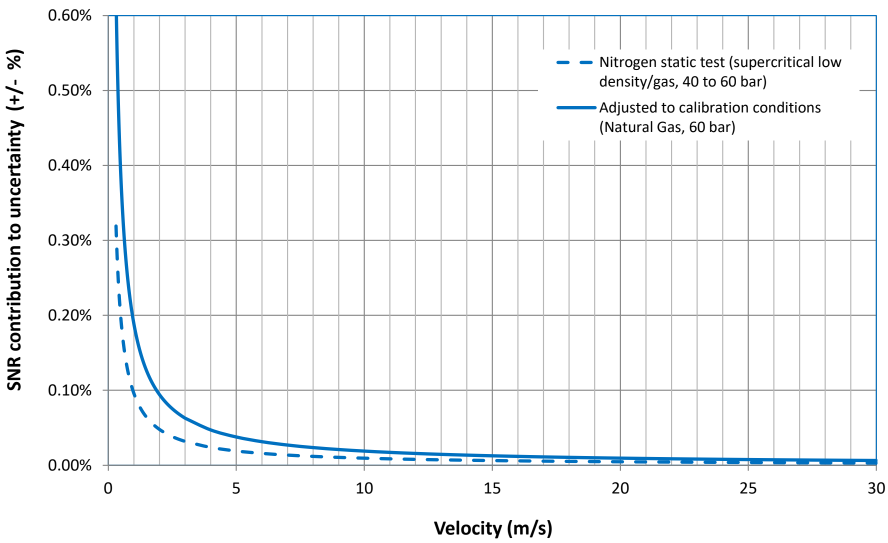


Figure 11 – Evaluation of the SNR-related contribution to uncertainty for the 8-path 16-inch meter. The solid line shows the result applicable for the calibration conditions at FORCE.

### 3.2 Carbon Dioxide at Temperature up to 65 °C

To demonstrate applicability and performance in CCS and $CO_2$ reinjection applications, static testing was performed with carbon dioxide in liquid, supercritical, and gas phase up to 65 °C. Tests were conducted at a range of pressures up to 100 bar, with temperatures of 15, 35 and 65 °C. An additional test was done with a 60/40 mixture of $CO_2$ and Nitrogen at 65 °C. An 8-path 6-inch prototype was used for all of these tests. Selected results are shown in Figures 12 to 15, showing the signal-to-noise ratio contribution to uncertainty versus velocity. Each figure shows two lines, a solid line representing 100 bar and a dashed line representing 30 or 40 bar. It can be observed that at high pressure the maximum uncertainty at a minimum velocity of 0.3 m/s is less than 0.2 % at 35 and 65 °C, increasing to approximately 0.5 % at 15 °C. At pressures of 30 and 40 bar in the gaseous phase, the uncertainty is increased, but is less than 2 % down to velocities of approximately 0.5 m/s. This demonstrates the capability of the meter to measure $CO_2$ in the gaseous phase, even though its intended use is for dense-phase transportation and injection applications. The lower pressure limit with $CO_2$ in the gas phase is a function of the meter size.

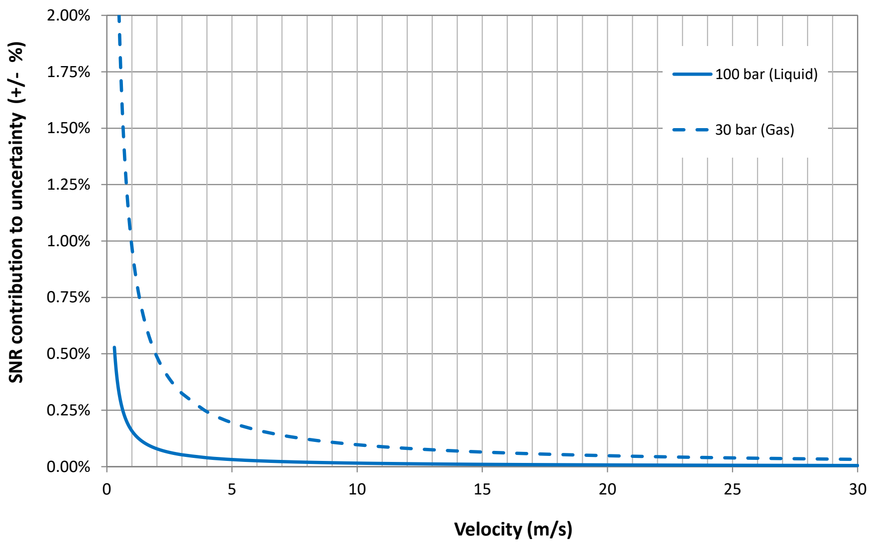


Figure 12 – Evaluation of the SNR-related contribution to uncertainty for $CO_2$ at 15 °C for an 8-path 6-inch meter.

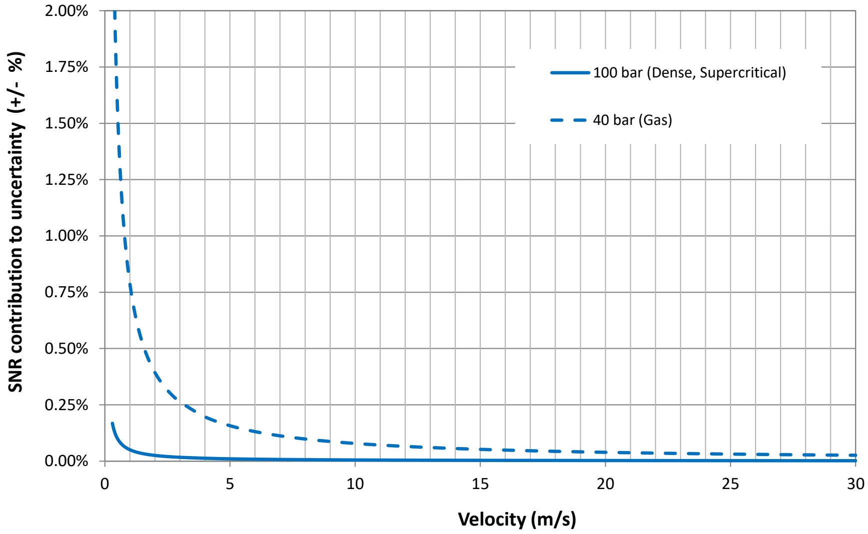


Figure 13 – Evaluation of the SNR-related contribution to uncertainty for $CO_2$ at 35 °C for an 8-path 6-inch meter.

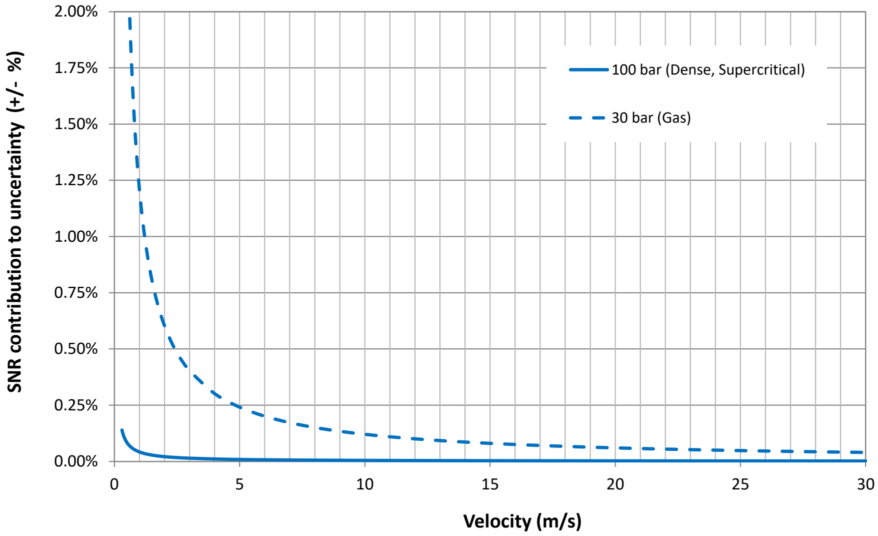


Figure 14 – Evaluation of the SNR-related contribution to uncertainty for $CO_2$ at 65 °C for an 8-path 6-inch meter.

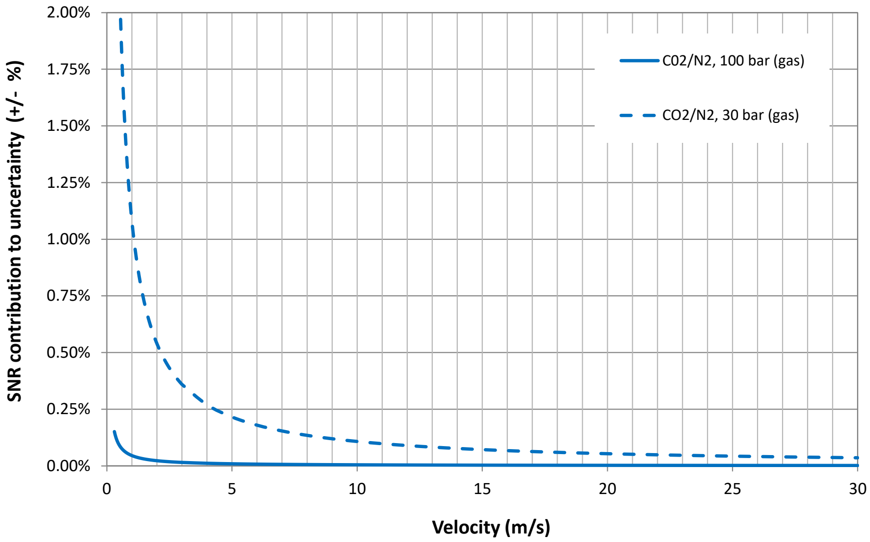


Figure 15 – Evaluation of the SNR-related contribution to uncertainty for 60/40 $CO_2/N_2$ at 65 °C for an 8-path 6-inch meter.

### 3.3 Calibration Testing with Natural Gas

Flow testing has been carried out to validate the performance of the complete system in conditions representative of the calibration that would be carried out for a custody transfer application. For this test, the meter was configured with geometry data and static calibration values for zero-flow transit times, with no secondary corrections of any form. In other words, path velocity values were calculated using geometry, non-fluid time delay and transit time difference at zero flow, and flowrate was calculated using a weighted average of those velocities multiplied by cross-sectional area, with no additional corrections for fluid dynamics or any other second-order effects.

The Device Under Test (DUT) is an 8-path 16-inch subsea ultrasonic flowmeter, as shown in Figure 16. This meter has single electronics operating all 8 paths. There is no difference in functionality between this configuration and with redundant electronics.

The test was done with natural gas at the high-pressure calibration test facility at FORCE Technology in Denmark, which is certified to ISO 9001 and ISO 17025. The test line has 20 diameters of 16-inch straight pipe upstream of the DUT, and a liner with length 3900 mm is used to provide an exact match with the inner diameter of the DUT. A liner with length 1950 mm is installed downstream the meter for the same purpose.


Figure 16 – The 8-path 16-inch subsea ultrasonic flowmeter installed in FORCE Technology's calibration test facility.

The test conditions are presented in Table 4.

Table 4 – Test conditions.

| Parameter | Value | Tolerance | Units |
|---|---|---|---|
| Pressure | 60 | +/- 2 | bara |
| Temperature | 20 | +/- 5 | °C |
| Gas | Natural gas from consumer grid (98,5% Methane, 0,6% Nitrogen, 0,9% $CO_2$) | NA | NA |
| Flow rates | 114 – 13 680 | NA | $m^3/h$ |

The flow test program is presented in Table 5. The duration of each flow point is minimum 120 s or 10 000 pulses.

Table 5 – Flow test program.

| | **Velocity** | **Flowrate** | **% $Q_{max}$** | **Repeats** |
|---|---|---|---|---|
| | m/s | $m^3/h$ | % | Baseline / Repeatability |
| | 36 | 13 455 | 120 % | 3 |
| $v_{max}$ | 30 | 11 213 | 100 % | 3 |
| | 21 | 7 849 | 70 % | 10 |
| | 12 | 4 485 | 40 % | 3 |
| | 7.5 | 2 803 | 25 % | 3 |
| | 3.0 | 1 121 | 10 % | 3 |
| $v_t$ | 1.5 | 561 | 5 % | 10 |
| | 0.8 | 280 | 2.5 % | 3 |
| $v_{min}$ | 0.3 | 112 | 1.0 % | 3 |

Pulse output was enabled for this flow test and was connected to the test facility's data acquisition system. This is used for the performance evaluation. Data was acquired in parallel through Modbus TCP/IP on a service computer with a sampling period of 1 s. The data are identical, as demonstrated by flow weighted mean deviation between pulse and digital data of 0.008% over the full test range, which is insignificant relative to the uncertainty. Pulse output is not a feature that is normally used in subsea operation, but it can be enabled for calibration tests like this one.

As previously stated, no meter factors or other calibration or correction factors were applied before or during the testing.

The results of the tests have been evaluated with reference to the accuracy requirements of ISO 17089-1:2019 [5], OIML R137 [6], and the Norwegian measurement regulations [7]. The flow measurement accuracy criteria against which the meter performance has been evaluated are given in Table 6 below. Note that the accuracy requirements of the Norwegian measurement regulations are equivalent to ISO 17089-1 Class 1.0.

Table 6 – Flow measurement accuracy criteria.

| **Subject** | **Accuracy Class** | |
|---|---|---|
| | 0.5 | 1.0 |
| Maximum Permissible Error (MPE), ISO and OIML | | |
| for $v_t < v < v_{max}$ | ± 0.5 % | ± 1.0 % |
| for $v_{min} < v < v_t$ | ± 1.0 % | ± 2.0 % |
| Maximum peak-to-peak error (ISO only) | | |
| for $v_t < v < v_{max}$ | < 0.5 % | < 1.0 % |
| for $v_{min} < v < v_t$ | < 1.0 % | < 2.0 % |
| Repeatabilty under flowing conditions during calibration ($r_{cal}$ per ISO, max-min error per OIML) | | |
| for $v_t < v < v_{max}$ | < 0.17 % | < 0.33 % |
| for $v_{min} < v < v_t$ | < 0.33 % | < 0.66 % |
| Reproducibility (for $v_t < v < v_{max}$), (ISO only) | < 0.17 % | < 0.33 % |
| Simulated path failure (ISO only) | < 0.17 % | < 0.33 % |
| Maximum permissible Flow Weighted Mean Error (FWME) prior to adjustment (ISO only) | 0.5 % | 1 % |
| Maximum permissible Weighted Mean Error (WME), Meter factor adjustment permitted (OIML only) | 0.2 % | 0.4 % |

### 3.3.1 Baseline Performance

The baseline performance without any correction factors is presented in Figure 17. There is a negative offset of approximately 0.5% and a rate-dependent error component with a maximum additional error of approximately -0.5% at $v_{max}$ (30 m/s).

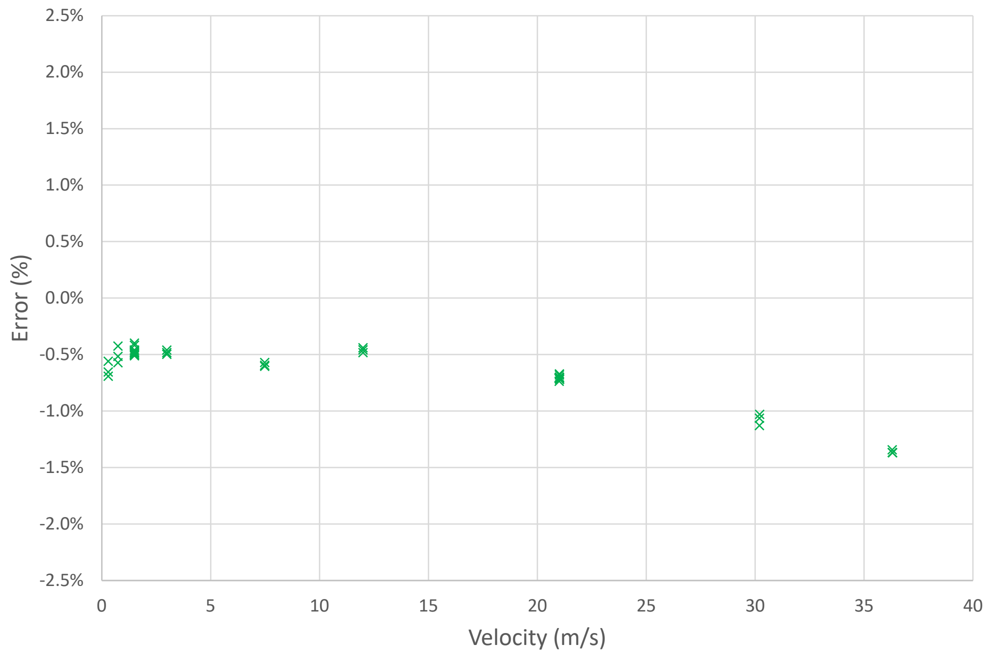


Figure 17 – Baseline performance without any correction factors.

The flow weighted mean error (FWME) calculated over the range of $v_{min}$ to $v_{max}$ according to ISO 17089-1:2019 Appendix B.2 is -0.7455 %. Applying the corresponding meter factor of 1.00751 results in errors within ±0.5% over the whole range of $v_{min}$ to $v_{max}$, including in the range $v_{min}$ to $v_t$, as shown in Figure 18.

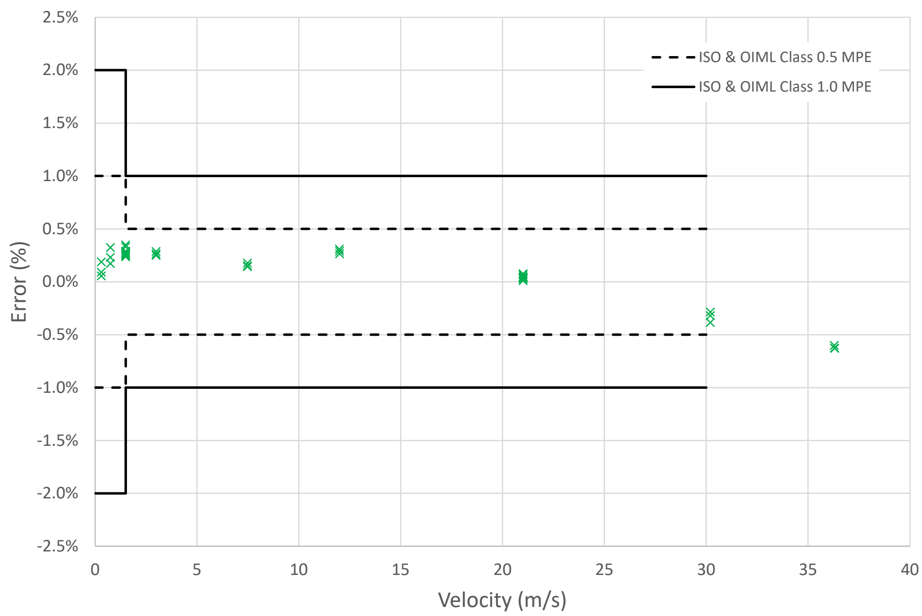


Figure 18 – Baseline performance with meter factor of 1.00751 applied. The solid black lines represent the Maximum Permissible Error limits of Accuracy Class 1.0, and the dotted lines represent Accuracy Class 0.5.

Per ISO 17089-1, the FMWE is evaluated before any adjustment is performed. Once adjusted with the Meter Factor of 1.00751, the FMWE calculated per ISO 17089 is zero. OIML R137 allows meter factor adjustment to be performed before evaluating the weighted mean error (WME). The OIML WME differs from the ISO calculation in that the rates above 0.7 x $q_{max}$ are weighted by (1.4 – $q/q_{max}$). Calculating the OIML R137 WME using the data presented in Figure 18, the result is a WME = 0.053 %.

Signal quality and detection was excellent throughout the test. Figure 19 below shows the % Performance (i.e. % of transmitted pulses passing all diagnostic tests) at each flowrate point. It can be observed that below the nominal maximum velocity of 30 m/s the % performance was 100 %, and it was ≥ 95% even at the over-range point of 120 % of max. velocity (~36 m/s).

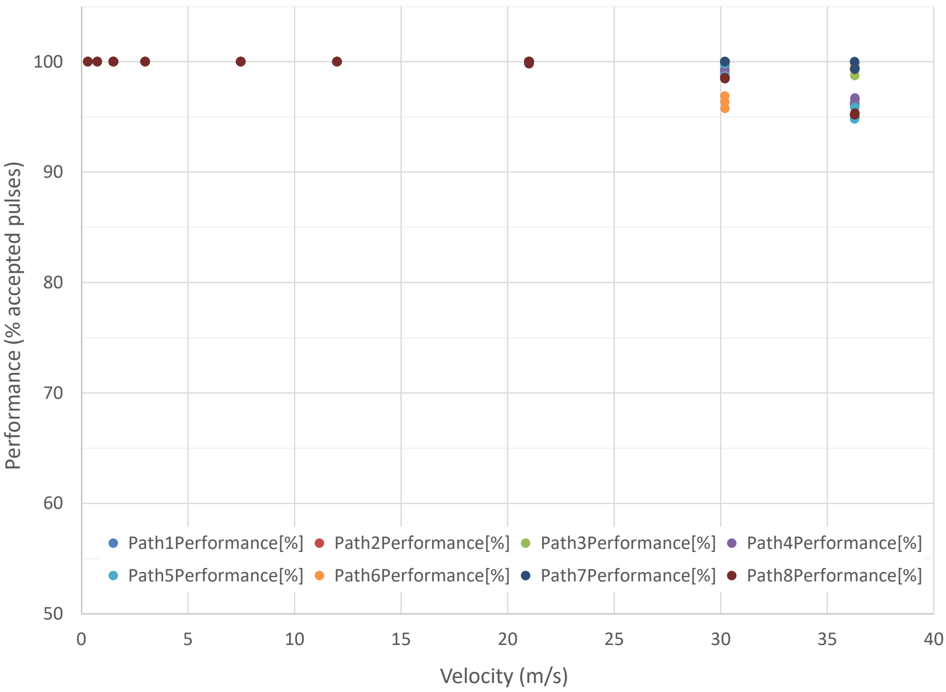


Figure 19 - Path performance data versus velocity.

In section 3.1, the results of static testing were presented. Figure 20 below shows the results of the calibration at velocities of 0.3, 0.75, 1.5 and 3 m/s compared with the uncertainty evaluation based on static testing previously presented in Figure 11. This comparison is only carried out at low velocity as it is only at the lower end of the velocity range that the uncertainty component corresponding to the transit time measurement uncertainty becomes dominant. To prepare this figure the calibration data has had a meter factor of 1.0048 applied, calculated from the flow weighted mean error over those four velocities, i.e. the calibration data has been shifted, but not linearized. The comparison shows that the deviations within the low-velocity range are comfortably within the uncertainty evaluation based on static testing.

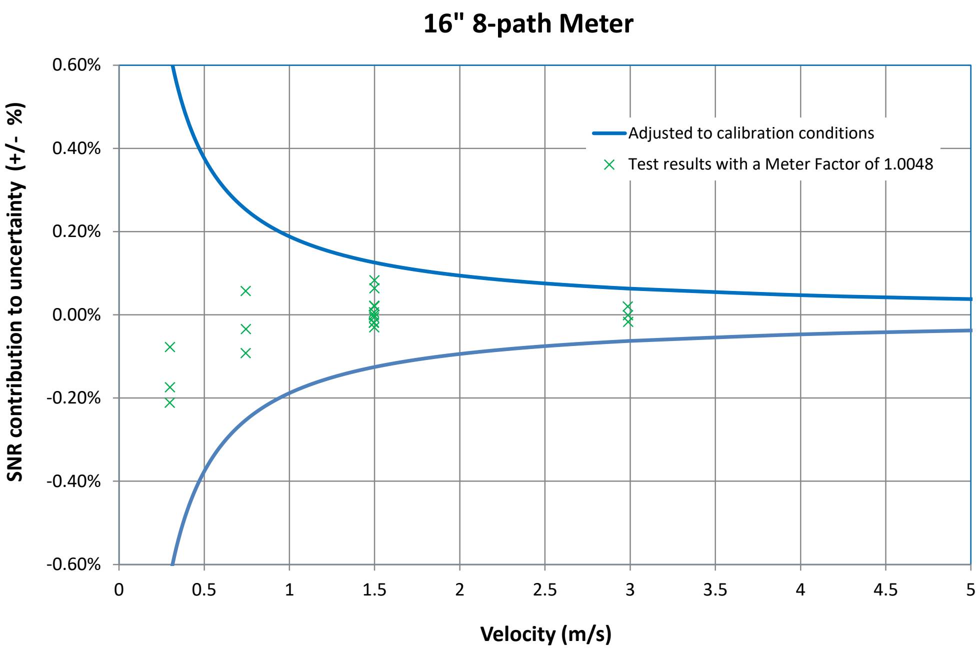


Figure 20 - Comparison of low-velocity performance with the uncertainty evaluation from static testing.

### 3.3.2 Repeatability

According to the type-testing requirements of ISO 17089-1, repeatability is evaluated from 10 consecutive measurements taken at each of two flowrates, one above and one below $v_t$. 10-point repeatability tests were performed at $v$ ~ 1.5 m/s (marginally below $v_t$) and $v$ = 21 m/s, where the repeatability to be calculated, $r_{cal}$, is the uncertainty of the mean. According to OIML R137, compliance with the repeatability requirement is "determined at the flowrates $Q_{min}$, $Q_t$ and $Q_{max}$. At each of those flowrates, the errors are determined three times and the difference between the minimum and maximum error is calculated." Results for both repeatability evaluations, ISO (at ~1.5 and 21 m/s) and OIML (at all flowrates including $Q_{min}$, $Q_t$ and $Q_{max}$) are shown in Figure 21, with the acceptance criteria for Accuracy Class 0.5 and 1.0 shown (with acceptance limits being equal in both standards).

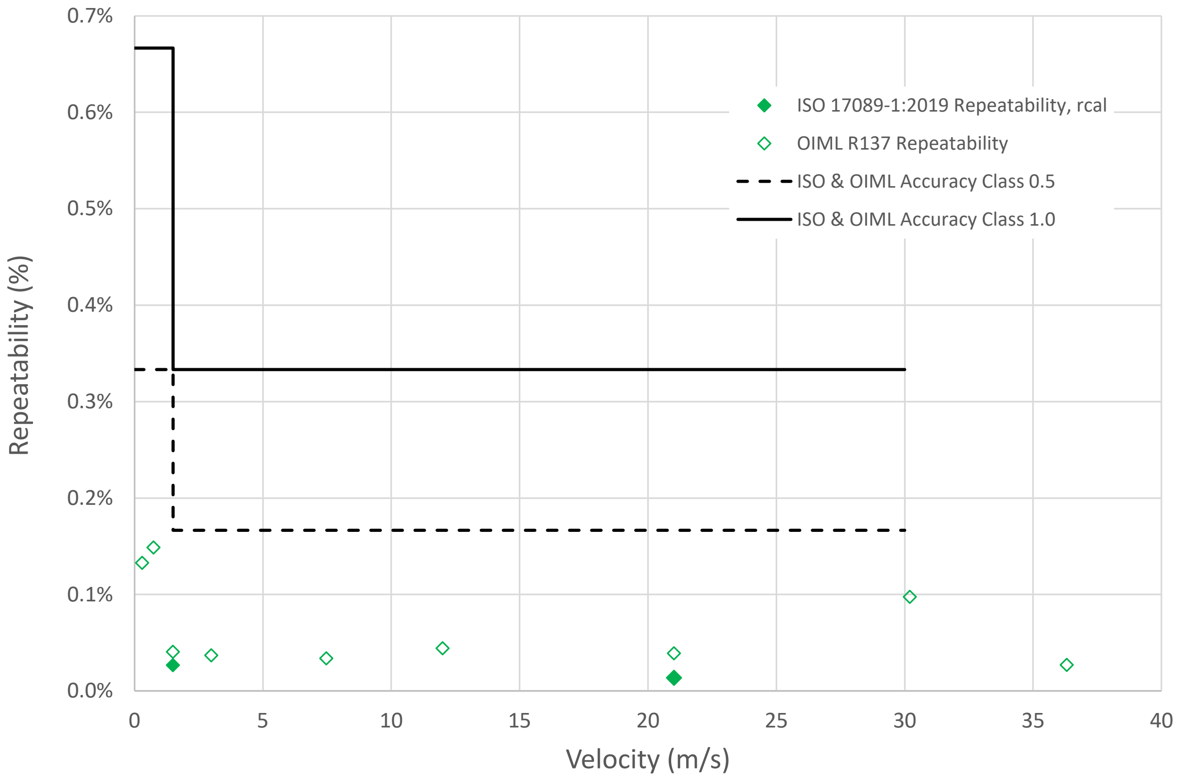


Figure 21 – 3-point (OIML) and 10-point (ISO) repeatability results. The solid black lines represent the repeatability limits of Accuracy Class 1.0, and the dotted lines represent Accuracy Class 0.5.

### 3.3.3 Path Failure Testing

Path failure testing was performed by physically disconnecting the wires from one of the transducers of path No. 4 (one of the pair of paths on the bottom chord) and repeating the test points at *v = 7.5 m/s*, *v = 12 m/s*, and *v = 21 m/s*. Figure 22 presents the error with path No. 4 disconnected versus the baseline measurement error. The magnitude of error relative to the baseline is < 0.05%.

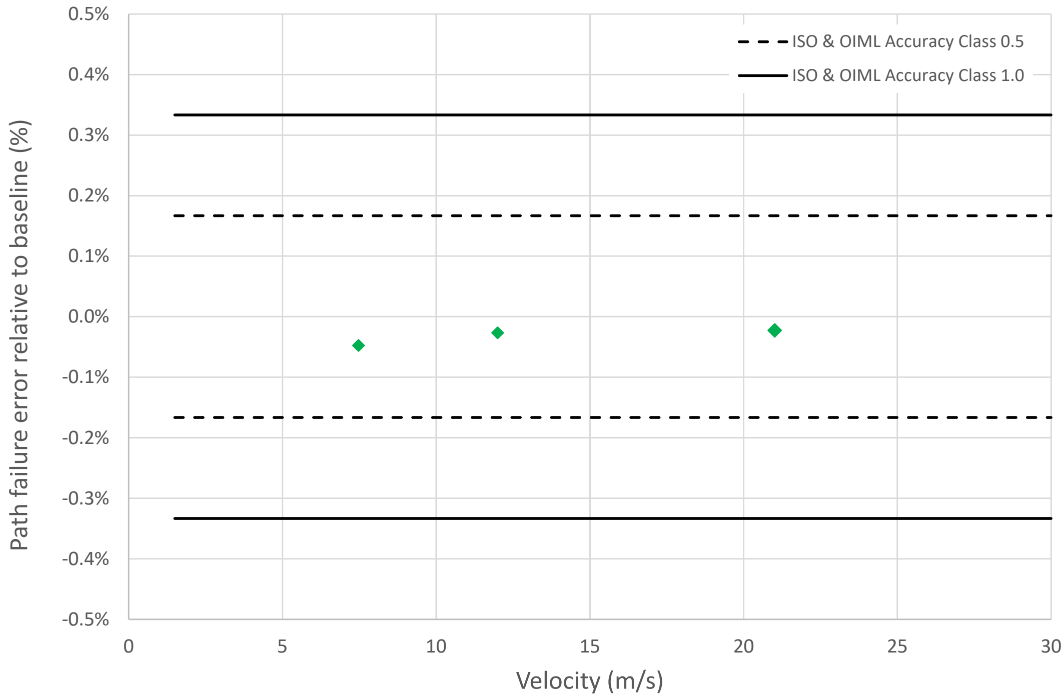


Figure 22 – Path failure testing comparing measurement error when all 8 paths are operational versus when path No. 4 is disconnected at *v = 7.5 m/s*, *v = 12 m/s*, and *v = 21 m/s*. The solid and dashed lines represent the acceptance criterial for ISO Accuracy Class 1.0 and Accuracy Class 0.5 respectively.

### 3.3.4 Reproducibility

Reproducibility was evaluated by re-connecting the disconnected path and performing test points at *v = 3 m/s*, *v = 12 m/s*, and *v = 21 m/s*. In addition, a test condition was added at *v = 25.5 m/s*, a velocity which had not been tested previously. The results at this velocity were compared to a value obtained by linear interpolation between the baseline results at *v = 21 m/s* and *v = 30 m/s*. The reproducibility results are presented in Figure 23. The magnitude of error relative to the baseline is < 0.05%.

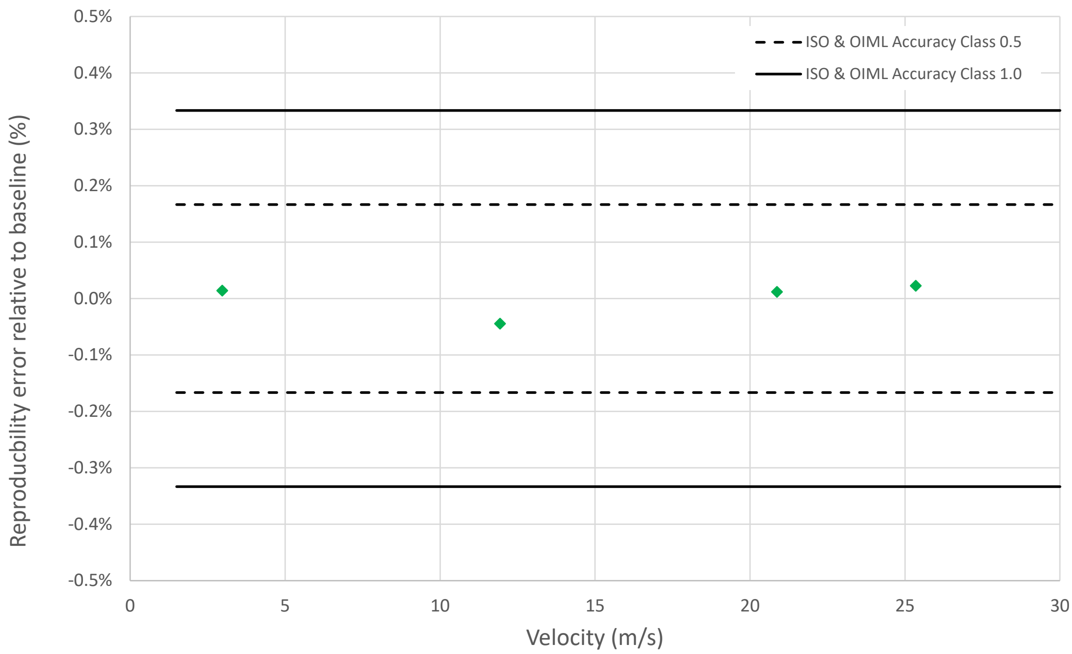


Figure 23 – Reproducibility, comparing measurement error before and after path failure testing at *v = 7.5 m/s*, *v = 12 m/s*, and *v = 21 m/s* and *v = 25.5 m/s*.

### 3.3.5 Summary

Table 7 below shows a summary of the data presented above. It can be observed that the results comply with the performance expectations of ISO Class 1.0 and OIML Accuracy Classes 0.5 and 1.0 in all respects. For ISO 17089-1 Accuracy Class 0.5, the linearity of the meter at velocities greater than 21 m/s was such that the results fell outside of two criteria, namely the unadjusted flow weighted mean error (FWME), and the maximum peak-to-peak error. Note that neither of these criteria are applied in OIML R137 and the calibration results, including the OIML calculation of weighted mean error (WME), are consistent with the requirements of OIML R137 Accuracy Class 0.5. The observed non-linearity at velocities greater than 21 m/s is understood and its reduction is one of the targets of on-going work to achieve further improvements in accuracy.

Table 7 – Summary of Results versus Accuracy Class Requirements.

| **Subject** | **Results** | | **Accuracy Class** | |
|---|---|---|---|---|
| | | | 0.5 | 1.0 |
| Maximum Permissible Error (MPE), ISO and OIML | | | | |
| for $V_t < V < V_{max}$ | -0.38 % to 0.31 % | | ± 0.5 % | ± 1.0 % |
| for $V_{min} < V < V_t$ | 0.05 % to 0.35 % | | ± 1.0 % | ± 2.0 % |
| Maximum peak-to-peak error (ISO only) | | | | |
| for $V_t < V < V_{max}$ | 0.69 % | | < 0.5 % | < 1.0 % |
| for $V_{min} < V < V_t$ | 0.29 % | | < 1.0 % | < 2.0 % |
| Repeatabilty under flowing conditions during calibration ($r_{cal}$ per ISO, max-min error per OIML) | ISO | OIML | | |
| for $V_t < V < V_{max}$ | 0.014% | < 0.1 % | < 0.17 % | < 0.33 % |
| for $V_{min} < V < V_t$ | 0.027% | < 0.15% | < 0.33 % | < 0.66 % |
| Reproducibility (for $V_t < V < V_{max}$), (ISO only) | < 0.048 % | | < 0.17 % | < 0.33 % |
| Simulated path failure (ISO only) | < 0.045 % | | < 0.17 % | < 0.33 % |
| Maximum permissible Flow Weighted Mean Error (FWME) prior to adjustment (ISO only) | 0.745 % | | 0.5 % | 1 % |
| Maximum permissible Weighted Mean Error (WME), MF adjustment permitted (OIML only) | 0.053 % | | 0.2 % | 0.4 % |

## 4 CONCLUSION

OneSubsea and Sensia have jointly developed a subsea ultrasonic flowmeter in collaboration with Equinor and Gassco and with support from the Norwegian Research Council under the DEMO2000 program. The subsea ultrasonic flowmeter features metal-to-metal sealing of the transducers. No non-metallic materials are exposed to the process fluids. An innovative transducer design mitigates transmission of coherent noise and ensures excellent signal transmission. This has been demonstrated across a wide range of pressures and process fluids, including water, nitrogen, supercritical $CO_2$, $CO_2$ in liquid and gas phase, and natural gas.

An 8-path 16-inch subsea ultrasonic meter has been flow tested in FORCE Technology's high-pressure gas calibration loop. The results show that the performance of the subsea ultrasonic meter meets requirements for custody transfer metering as defined ISO 17089-1, OIML R137 and the Norwegian measurement regulations. Repeatability and reproducibility are both excellent, as is the performance with one path disabled. The calibration test was performed without secondary corrections of any form. The meter performance was consistent with all aspects of ISO Accuracy Class 1.0 and OIML Accuracy Classes 0.5 and 1.0. The observations from the test will be used in ongoing work to improve the uncalibrated accuracy with the aim of achieving the full requirements of ISO 17089-1 Accuracy Class 0.5.

## 5 SYMBOLS AND ABBREVIATIONS

CCS Carbon Capture and Storage
D Diameter
DUT Device Under Test
ksi thousand *psi*
PCEP Pressure Compensated Electrical Penetrator
$Q_{max}$ Operational maximum flowrate
SEM Subsea Electronics Module
SNR Signal to Noise Ratio
$v_{max}$ Operational maximum velocity
$v_{min}$ Operational minimum velocity
$v_t$ Transition velocity
WME Weighted Mean Error

## 6 ACKNOWLEDGEMENTS

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## 7 REFERENCES

[1] API SPECIFICATION 6A – Specification for Wellhead and tree equipment, Twenty-first Edition, November 2018

[2] API SPECIFICATION 17D – Design and Operation of Subsea Production Systems – Subsea Wellhead and Tree Equipment, Third Edition, October 2021

[3] API STANDARD 17F – Standard for Subsea Production Control Systems, Fifth edition, April 2023

[4] TR1233 Subsea Production and Process Control System Ver. 8.01a, Equinor, June 2019

[5] ISO 17089-1 Measurement of fluid flow in closed conduits — Ultrasonic meters for gas Second edition, 2019

[6] OIML R137, Gas Meters, International Organization of Legel Metrology, 2012

[7] Regulations relating to measurement of petroleum for fiscal purposes and for calculation of CO2-tax (the measurement regulations) – The Norwegian Petroleum Directorate