North Sea Flow Measurement Workshop

16-19 October 2007

Tomography powered multiphase and wetgas meter providing measurements used for fiscal metering

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INTRODUCTION

Multiphase meters were initially developed by several companies during the 1990's and operating companies have gained about 10 – 15 years of operational experience by using them. The meters are offering significant benefits in several applications such as

- Allocation Metering
- Well Testing and Reservoir Management
- E-field implementation
- Field developments without new platforms

While the benefits are great and the potential savings are large, the concept of multiphase metering has not yet emerged to the extent one should expect. This is mainly caused by the fact that multiphase measurements are complex, and far more difficult than what was earlier believed. An appreciable number of the meters deployed may not have performed to user expectations to measurement accuracy and - perhaps more important - reproducibility and operational stability. Also, some meters have not been able to perform satisfactory when the operational conditions have changed from initial/design conditions.

This paper presents the basis for the development of the MPM HighPerformance Flowmeter, and describes the steps taken to arrive at an instrument that's capable of providing measurements to be used for fiscal metering, for both multiphase and wetgas conditions.

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ACKNOWLEDGEMENT

The development of the High Performance Flowmeter by MPM has been supported technically and financially by the six oil companies; ENI, ConocoPhillips, Hydro, Shell, Statoil, and Total.

Their involvement in the project as technical advisors and though active participation in the Steering Committee has been of great value, and enabled the development and qualification projects be completed over a relatively short time period.

CHALLENGING APPLICATIONS

Understanding, describing and modeling the local conditions inside a pipe, where unknown constituents of water, oil and gas are flowing at unknown velocities, is very challenging. Measuring the flow rates of the three constituents at an acceptable uncertainty is may be even more difficult.

Measuring the multiphase flow rates is very important of several reasons.

- Firstly, the amounts of hydrocarbon must be measured precisely to allocate the production (and revenue) to the different partners.
- Secondly, the measurements are important to be able to monitor and thereby maximize production from the well and the reservoir, to enhance the recovery and increasing the revenue.
- Thirdly, it will help avoiding operational problems. To give an example; for several fields measuring the water fraction to mitigate hydrate formation is of importance, as is the possibility to detect formation water break-through in particular wells. and
- Finally it is used to minimize environmental issues by contributing to reducing and optimizing the use of chemicals and inhibitors.

The operating conditions and challenges for wetgas and multiphase metering are quite different, which has led to the development and manufacture of different meters by some vendors. For this reason, the operators have had to select in advance of production start-up, which type of meter to install. In many cases, this might pose a large problem; the production of a particular well is often not well-known in advance of start-up, and the behavior of a well may very well change over its lifetime. In such case, the performance of the installed meter might be very poor, and the Operator might be required to replace the multiphase meter with a wetgas one.

A typical oil well may start producing without any water coming with the oil. As the well matures, water normally starts breaking through, and the Water Liquid Range (WLR) may increase to as high as 90-95% before the well is shut in. At the same time, the GVF might increase, both as a result of the pressure in the well being decreased, but also as a

result of gas lift or other related techniques. From being initially in the range of 50 to 60%, the GVF may increase to 90 to 95 % and even above. Figure 1 shows typical well development patterns, where the developments in GVF and WLR are illustrated. Similar examples may be found in the presentation by Lex Scheers /ref 1/.

The particular case where the gas fraction of a multiphase flow is in the high 90 percent level (typically 96 to 99+ % of gas) is denoted WetGas. Measuring the tiny amounts of liquid flowing with the gas, at a satisfactory accuracy is extremely challenging. Even more difficult is it to correctly being able to split the tiny amount of liquid into water and hydrocarbons. On top of this, operators would like to know what is the salinity of the produced water.

In Figure 2 is sketched out the perceived measurement uncertainty for existing multiphase meters. The x-axis represents the GVF, while the Y-axis describes the measurement uncertainty of the hydrocarbons. As is seen, the uncertainty is in line with that obtained with a test separator for GVF's below 50 %. For higher GVF's, the uncertainty increases to unacceptable levels. The figure is of course illustrative only, but the main message is very clear.

The need for high performance meters has been expressed by the oil companies since quite many years back. One example was the paper by Andy Jamieson at the NSFMW in 1999 /ref2/. Statoil has voiced similar needs, for instance in a paper by Eirk Aabro /ref3/.

The above reasons and several years operational experiences with the existing products have made the major oil companies support the development of new concepts and methodologies.

CLOSING THE GAPS

MPM started more than four years ago addressing these challenges, and decided after careful considerations to do an attempt to closing the above mentioned gaps, and to provide a new type of instrument.

Being a very challenging task, MPM sought support for its work from the oil industry. MPM considered it extremely important to aligning the project goals and results with the needs of the industry, and established a Joint Industry Project (JIP), with a Steering Committee comprising some of the most experienced and skilled measurement people from the oil companies.

MPM further decided to build a very advanced flow laboratory, which today comprises five different flow loops. These are tailored to different tasks, and offer a unique set of tools for performing the enormous amount of tests that have been done. The test facilities also function as a training centre.

An international co-operation model was established, with participants from many different universities, laboratories, specialist companies and suppliers.

The JIP partners helped defining the overall goals of the MPM High Performance Flowmeter, as follows:

1. High operational stability
2. Unique sensitivity and reproducibility
3. Improved measurement uncertainty
4. Easy field configuration and operation

To achieve the above, MPM realized that a completely new technology basis was required. In addition, all aspects needed to be addressed with special focus on the following issues:

- The measurement errors due to the presence of annular gas concentration, as is in vertical flow, had to be eliminated. An example of this effect is shown in Figure 5. Whereas the actual GVF is 36%, the gamma meter will measure 55%, since the result is based on the shaded area only (i.e. the beam of the gamma meter) and not the full pipe area. MPM decided that rather than trying to mixing the flow, the MPM meter should be made capable of providing the right result, independent of the flow regime and the presence of annular gas concentrations.
- Extremely fast measurements must be obtained to correctly capture rapid fluctuations in the flow (slugs, etc). In multiphase flow conditions, a multiphase meter's sampling frequency must be several Hz., to enable it to track the naturally found and fast changing flowing conditions.
- Very accurate watercut measurements must be made at high watercuts and at high GVF's (as liquid fraction becomes smaller) to measure flow rates of oil more precisely.
- One single meter should be capable of covering both multiphase and wetgas applications, since replacing meters in an operating asset is very costly and implies operational risks. This is particularly important for subsea meters.
- The conductivity of the produced water should be measured, rather than be required as a user input. An error in water conductivity may imply large measurement errors, and how would the operator know the water conductivity for wells that are commingled? Again, this is particularly important for subsea meters.

MPM HIGHPERFORMANCE FLOWMETER

The High Performance Meter from MPM represents an important technological step in multiphase metering and instrumentation. It will facilitate the in-line allocation metering of produced hydrocarbons and allow for low-cost offshore tie-backs and subsea metering.

The Meter is built with all parts in one unit with minimum need for final assembly on site. The electronics are designed and built to survive in severe and violent conditions and the transmitters are fixed to the sensor body. The MPM Meter is shown in Figure 3.

The MPM meter is using tomography and the patented 3D Broadband™ method (5 patents) in combination with a Venturi and other sensors to obtain unparalleled performance in multiphase and wetgas flowing regimes. With its dual mode functionality and capability to measure water salinity, the MPM Meter bridges existing measurement gaps in conventional multiphase and wetgas meters. The main physical components of the MPM Meter are shown in Figure 4. The special features of the Meter are, however, software based.

The Meter performs measurements over the full Gas Volume Fraction (GVF) range, and covers watercuts from 0 to 100%. One of the Meters really unique properties is the ability to measure the watercut equally well at high watercuts (water continuous flow) and lower watercuts (oil continuous). As a consequence, the MPM Meter performs reliable oil flow rate measurements even at high watercuts and high GVFs. This has until now been the perceived a weakness by the users of all of the multiphase meters on the market.

MPM has recently finalized the development and qualification program for the subsea version of the MPM Meter. In a special made test rig, the subsea meter was tested at operating pressures of up to 1000 bars while, at the same time, the temperatures varied from from -50 to + 250 °C. The Subsea meter can be delivered for use in water depths of 3500 meters maximum.

MPM METER MEASUREMENT PRINCIPLES

Multi sensor system

The MPM Meter encompasses several sensors for different measurements, which are combined in a multi-modal tomographic measurement system.

The flow first passes through a Venturi, which is used to measure the total mass flow rate. MPM has developed special Venturi models in close co-operation and on license from its partners. The Venturi is also used to create radial symmetrical flow conditions in the 3D Broadband™ section downstream the Venturi.

The MPM Meter utilizes a special gamma densitometer solution, as well as temperature and pressure transmitters.

3D Broadband™

The 3D Broadband™ technology is used to establish a three dimensional picture of what's flowing inside the pipe. The basis for the technology is often referred to as 'process tomography' which has many parallels to tomographs used in medical applications.

In the oilfield, the challenges are however different than in a hospital. Firstly, the meter is measuring fluids and gases under high temperature and pressure. Secondly, the multiphase mixture can be mowing at velocities of more than 30 meters per second inside of the pipe, and the amounts of gas, water and oil are normally unstable and changes all the time.

The 3D Broadband™ system is a high-speed radio- frequency (RF) based technique for measuring the watercut, the composition and the liquid/gas distribution within the pipe cross section. By combining this information with the measurements from the Venturi, accurate flow rates of oil, water and gas can be calculated.

The MPM Meter is extremely fast. Averaging of measured raw data is very limited, to avid errors due to non-linearities in the flow. The result is measurements at an unparalleled performance in multiphase and wetgas flowing regimes. With its dual mode functionality, which means that both multiphase and wetgas applications are addressed with the same hardware, and its capability to measure water salinity, the MPM Meter bridges existing measurement gaps in conventional multiphase and wetgas meters.

Capturing rapid fluctuations in the flow rate

The MPM Meter performs RF measurements in many different planes. At each plane, measurements are done at many frequencies over a broad frequency range, and combined with gamma ray absorption measurements. Each measurement frequency in each direction forms a unique and independent equation resulting in many thousand equations per second for accurate determination of the multiphase cross sectional composition and distribution. The principle is illustrated in Figure 6.

Flow changes in the longitudinal axis are captured precisely by doing many measurements every second, which also enables flow characteristics like slug intervals & lengths to be monitored, as illustrated in Figure 7.

Dual Mode Operation

The MPM Meter is designed to perform accurate flow rate measurements on all types of wells, throughout their entire life. The MPM Meter can address both multiphase– and wetgas applications; at oil-, gas- and water continuous flow regimes.

In the multiphase composition chart in Figure 1 are displayed some typical well trajectories, (A, B and C) which indicate the need to have a meter that can handle both wetgas- and multiphase flow.

In Wetgas mode the MPM Meter's sensitivity is used to obtain extremely accurate water fraction measurements. In MultiPhase Mode, the Meter performs high speed measurements to detect and compensate for variations and changes in the flow regime.

Oil & water continuous flow

The MPM Meter is able to perform accurate measurements of the WLR (watercut) with both oil and water continuous liquid emulsions.

In Figure 8 are presented results from a large number of two-phase (oil, water) tests, covering water salinities from 0 to 20%, which were performed to verify the performance of the watercut measurement. The WLR was varied over the full range from 0 to 100%.

For WLR's in the range 30-55% the emulsion is either oil or water continuous depending on the flow conditions. As seen from the graph, the measurement performance has been demonstrated to be equally good in both oil- and water continuous flow conditions, and even in the transition region between oil and water continuous liquid emulsion.

RESULTS FROM QUALIFICATION TESTING

The MPM Meter has gone through a comprehensive qualification process, after several years of intensive development work.

The MPM Meter used in the qualification testing was a 3" device built to requirements and specifications for Gullfaks A (GFA). The Meter was delivered from MPM after completing the Factory Acceptance Test (FAT).

The first external test was performed at K-lab /Kårstø during fall of 2006, where the Meter was exposed to high pressure conditions. During tests at K-lab, a large series of tests points were completed, covering both wetgas and multiphase conditions.

Subsequently the meter was shipped directly to GFA for testing and permanent installation. The testing covered a variety of wells and flowing conditions, in series with a reliable test separator. In Figure 9 is shown the different phases of the qualification process.

The different sites provided a large variety of test conditions, both in terms of fluids used, pressures and temperatures, and other aspects. As seen in Figure 10, a large part of the tests were conducted for conditions normally considered very difficult, with high GVF's and high WLR's.

All tests were performed and supervised by Statoil on the behalf of the six JIP companies. It is especially pointed out that no modification was done to the MPM meter during the whole qualification program.

Field configuration

The field configuration performed at K-lab and Gullfaks A followed the standard procedure, consisting of

- A single point calibration in air at commissioning (Nov 06)
- Water Density and Water Conductivity measured online by MPM Meter
- Oil and Gas Density calculated by online PVT package in FMC flow computer
  - Two different well composition used for all wells
    - One composition for high GOR wells
    - One composition for low GOR wells

The MPM Meter's sensitivity to the configuration parameters (oil and gas density) is exemplified in Figure 11, based on results in the MPM Flow Laboratory.

Operational Stability

During testing and use in the field the MPM Meter has demonstrated high operational stability, with no hardware or software problems on the Meter side.

The in-built self diagnostics functionality provides a means for the user to verify the performance, and to validate the field configuration data.

Accuracy – Reference system

The reference systems used during the testing of the MPM Meter are believed to be of a high standard.

At K-Lab, the reference system is of a very high and proven standard. Stabilisation time was what had to be considered with care, especially for those tests involving very small increments of a small fraction. The time to achieve stable flow conditions at the point where the MPM meter was located (15 m downstream of the mixing point), had to be managed and monitored.

At GFA, the reference system is good, in particular following a few upgrades which had to be implemented for the second round of testing (from December 06 to Jan 07).

In Figure 12 is shown the data flow at Gullfaks A, between the MPM Meter and the Platforms Flow Computer.

Sensitivity

The MPM meter is extremely sensitive to small changes in the composition. At K-Lab, a special test set-.up was configured, with highly reliable reference instrumentation, to verify this feature.

During the tests, gas was flowing at a constant rate of 300 m3/h, while tiny amounts of water only was injected just upstream the MPM Meter in three steps. The amounts of water, and the corresponding fraction of total flow is as follows:

	M3/h	water fraction
Step 1	0,008	0,0026 %
Step 2	0,043	0,0143 %
Step 3	0,086	0,0287 %

The results are presented in Figure 13. As is seen from the graph, the MPM Meter proved capable of detecting a change in water fraction of less than 0.0025% water.

Measurement uncertainty

The measurement uncertainty of the MPM Meter was within the specifications for all the different test campaigns.

In the following are presented examples and a summary of the results obtained. Reference is made to Figure 10, and it should be noted that tests cover a wide variety of operating conditions. Most of the tests points are made at flowing conditions that normally are perceived very challenging. In particular, they cover GVF from 0 % to 99,9%, and WLR's from 0 to 95 %. Most of the wells at GFA have WLR's above 50%.

In Figure 14 are shown comparisons of flow rates of oil, water and gas, for the MPM Meter versus the reference system, for tests simulating GFA wells, performed in the MPM Flow Laboratory.

Figure 15 presents a screen-print of a tests at K-lab, for GVF of 99,7 % and a WLR of 30%. While the gas rate was around 300 m3/h, the oil rate was 0,6 m3/h and the water rate was less than 0,3 m3/h. As is seen in the Figure, there are only very small differences between the reference and the MPM Meter measurements.

The same good match between the meter and the reference is seen in Figure 16. In this chart, the GVF is 98 %, and the WLR is around 5%.

Quite different flow conditions were experienced at K-Lab when the GVF was reduced to 93 %. As is seen in Figure 17, there was quite a lot of rapid slugging at the point where the Meter was installed. This was as expected, since the Meter was installed 15 meters downstream of the mixing point. While the Meter was installed in a vertical position, the

piping leading up to its location consisted of a horizontal 8" pipe. The measured values were, however, very much in line with those of the reference system.

In Figure 18 are shown comparisons of flow rates of oil and gas, for the MPM Meter versus the reference system for all test points. As is seen, the delta in oil rate was within 4 to 10 % for the full range of GVF's and WLR's. For gas rates, the corresponding delta was within 3 to 5 % when the pressure was above 10 bars.

In Figure 19 are shown similar deltas, but in this case on an accumulated basis. This is representative for the Meter performance, if used to measure the accumulated production from a series of wells. An example could be when commingling and tying back several subsea wells to a host platform. As is seen from the Figure, the deltas between the MPM Meter and the reference measurements are in less than 1,5 % for all the three sites, for flow rates of both oil and gas.

Repeatability

The repeatability of the MPM Meter has proved to be beyond the level which is quantifiable with the available reference instrumentation in a field location. It was concluded that for oil and gas rates, the reproducibility was within tenths of a percent.

In Figure 20 is shown an example of the Meter's stability and repeatability. It shows the measured WLR (increasing from 73 to 74 %) for a given well at GFA for a number of tests covering a time period of two months, both for the MPM Metter and the reference.

In Figure 21 is shown the liquid flow rate for the same well and the same test periods. The drop in flow rate, for the two December points, was at first not easy to understand, since no change was made to the test set-up. As is seen in Figure 13, nor was any change observed for the WLR. After carefully analyzing the logs of the reference system and the Meter, it was found that the change was caused by a leaking valve located between the test and the production manifolds. What had happened was that the pressure setting of the production header was lowered by 2,5 bars, while the test manifold pressure was kept constant. Consequently, a portion of the liquids went over to the production header. After fixing the valve, results for the Meter and the reference were back to normal.

Water Salinity Measurement

The MPM Meter is capable of measuring the conductivity of the produced water at actual conditions. The measured conductivity is converted to conductivity at 25 °C and used to calculate the measured water salinity and water density. During the conversion, it is assumed that the salt is constituted of NaCl, or as specified by the user.

The salinity measurement can be implemented as an automatic function, and no field configuration at all is required.

The graph in Figure 22 is prepared based on the results of the qualification testing at K-lab and GFA. It shows the measured water conductivity by the MPM Meter compared to the water conductivity of the reference water sample.

As is seen in the graph, all the conductivity measurements are within the target band of ± 2 mS/cm.The reproducibility of the water conductivity measurement was demonstrated to be within ± 0.5 mS/cm for all the wells in the reproducibility tests at GFA and within ± 0.25 mS/cm for 60% of the tests.

SUMMARY AND CONCLUSIONS

The MPM High Performance Flow Meter has been developed and thoroughly tested and qualified in a JIP with six oil companies.

The qualification testing has demonstrated the four overall goals of the JIP Project to be achieved; it is an instrument with high operational stability; with high sensitivity; which is very accurate; and which is easy to configure and to use.

The overall conclusions drawn by the Field Operator (Statoil) are:

- The MPM Meter's performance is such that it is capable to replace the existing test separator, and for some wells, the MPM Meter provided more reliable measurements than the existing test separator.
- The MPM Meter can be used to increase the production capacity of the Gullfaks A platform (significant NPV increase).
- Testing of wells at Gullfaks A can be done in 0.5 hour compared to typical 4 hours with the existing test separator.

During the qualification testing, installation and commissioning was done in a few hours. The Meter was started-up and the signal interface came quickly in place. The MPM meter has demonstrated superb operational stability, with 100 % uptime since commissioning. The Meter performance has been verified to be within specifications, and the repeatability of the MPM Meter was demonstrated to be extremely good, by testing the same wells at several times. The field testing concluded that the self calibration modus is imperative at high WLR's and changing water properties.

A very important conclusion was that the meter proved flexible to operate at different operating conditions, and it was demonstrated that the Meter can go directly from the MPM lab to the field whilst maintaining its specified performance.

Figure 23 summarizes the performance of the MPM Meter relating to measurement uncertainty, compared to conventional products with respect to measurement uncertainty and operating range. It can be concluded that the MPM Meter represents a leap-change

in multiphase and wetgas metering. Providing high accuracy over a large operating range, it enables in-line allocation metering of produced hydrocarbons at a standard acceptable for fiscal allocation metering.

The qualification of the subsea version of the MPM Meter is recently completed. This will be covered in a later presentation

REFERENCES

/1/ *Challenges at High Accuracy MultiPhase and WetGas Measurements*, by Lex Scheers and Arnstein Wee, MMR Galveston US, 27 April 07

/2/ *High performance multiphase metering - a personal perspective,* Mr A.W. Jamieson, Shell U.K. Exploration and Production, Norflow seminar, 9th June 1999

/3/ *Status på våtgass/flerfasemålere i drift*, by Eirik Aabro, Temadag NFOGM, 23 mars 2006.

Figure 1: Typical oil well trajectory in 3-phase Flow Chart

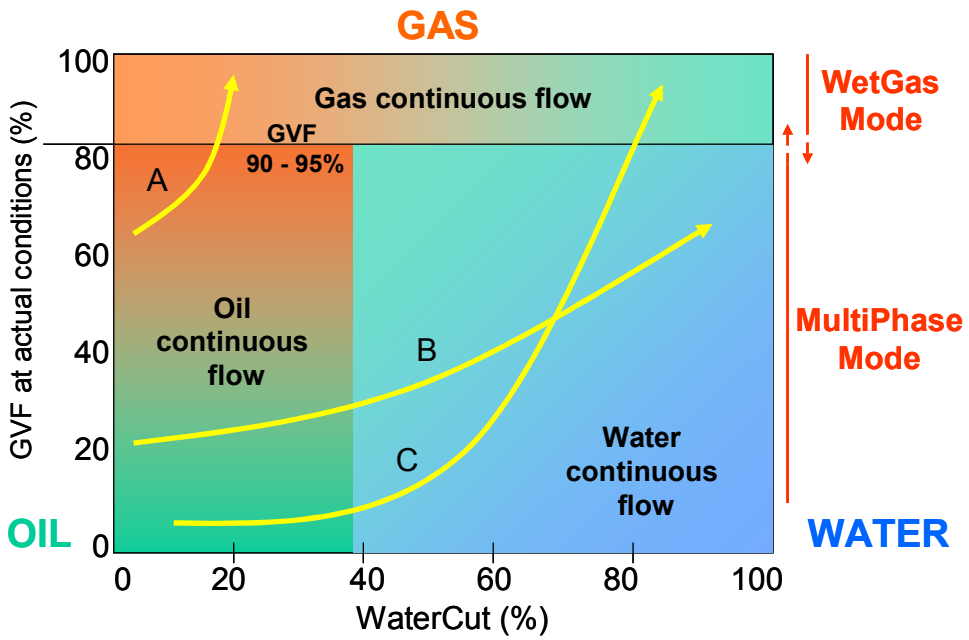


Figure 2: Perceived measurement uncertainty – conventional meters

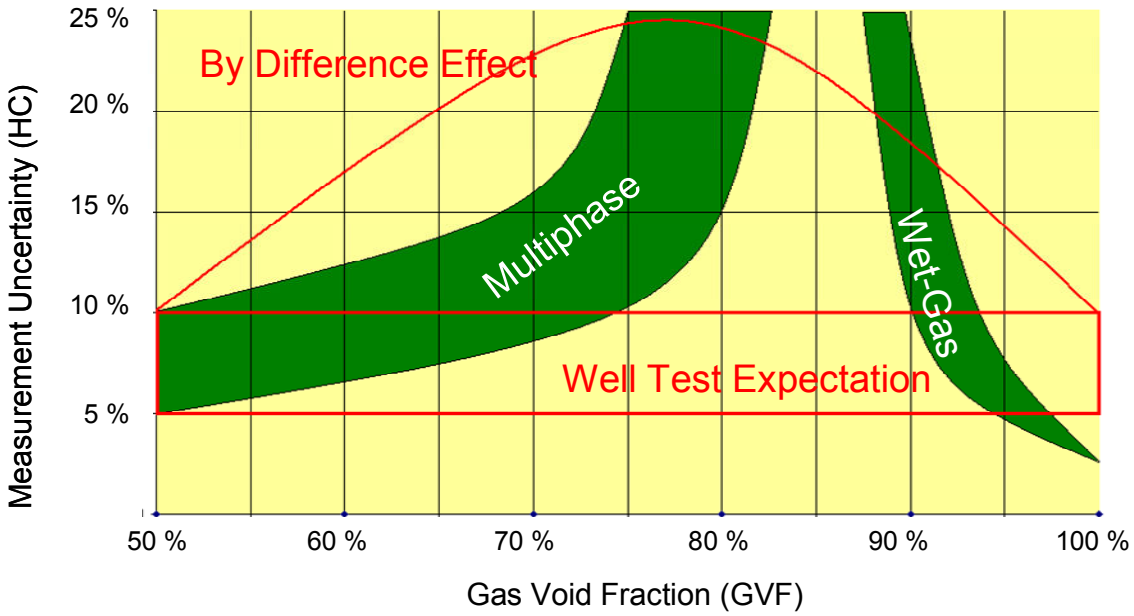


Figure 3: MPM HighPerformance Flowmeeter

Figure 4: MPM Meter – Main components

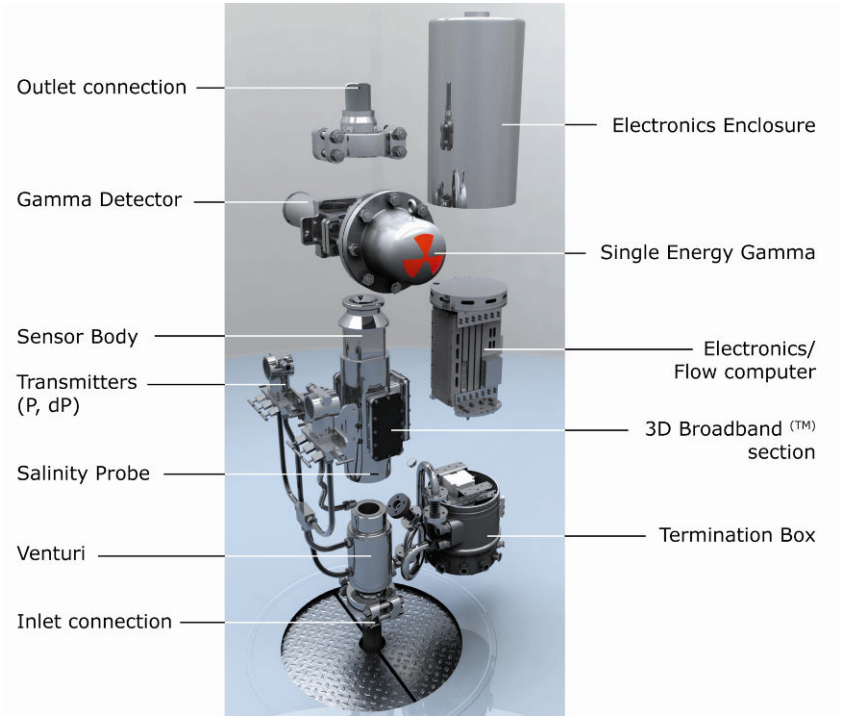


Figure 5: Effects of annual gas concentration

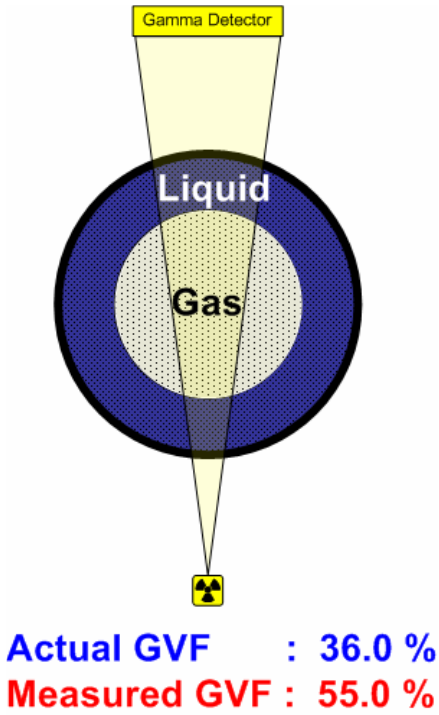


Figure 6: Establishing a 3D picture of the cross section

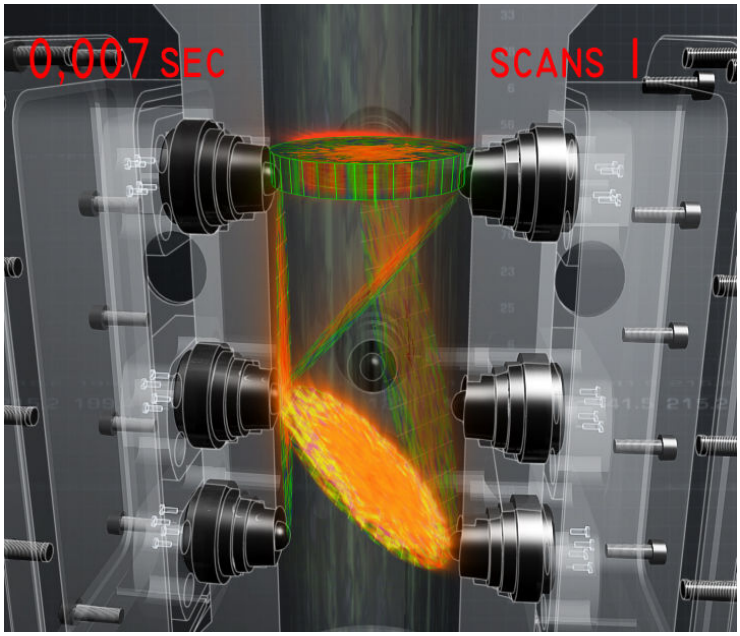


Figure 7: Capturing longitudinal flow variations

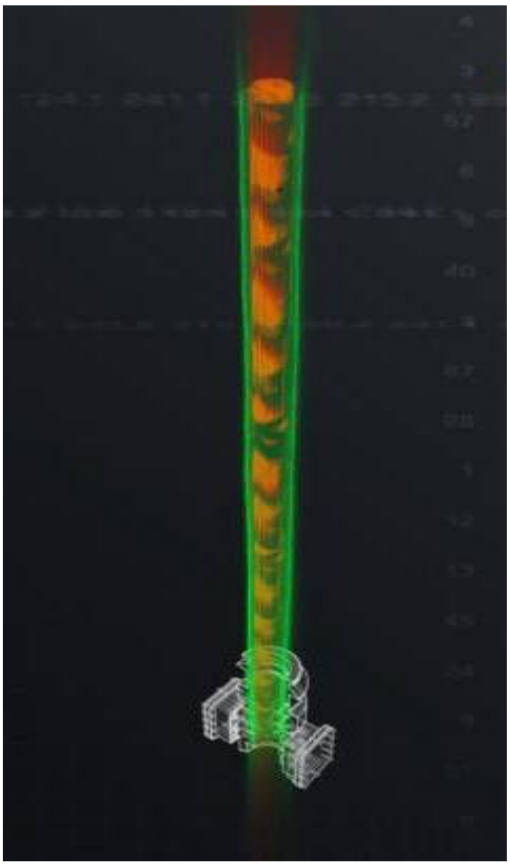


Figure 8: Results from test of WLR accuracy

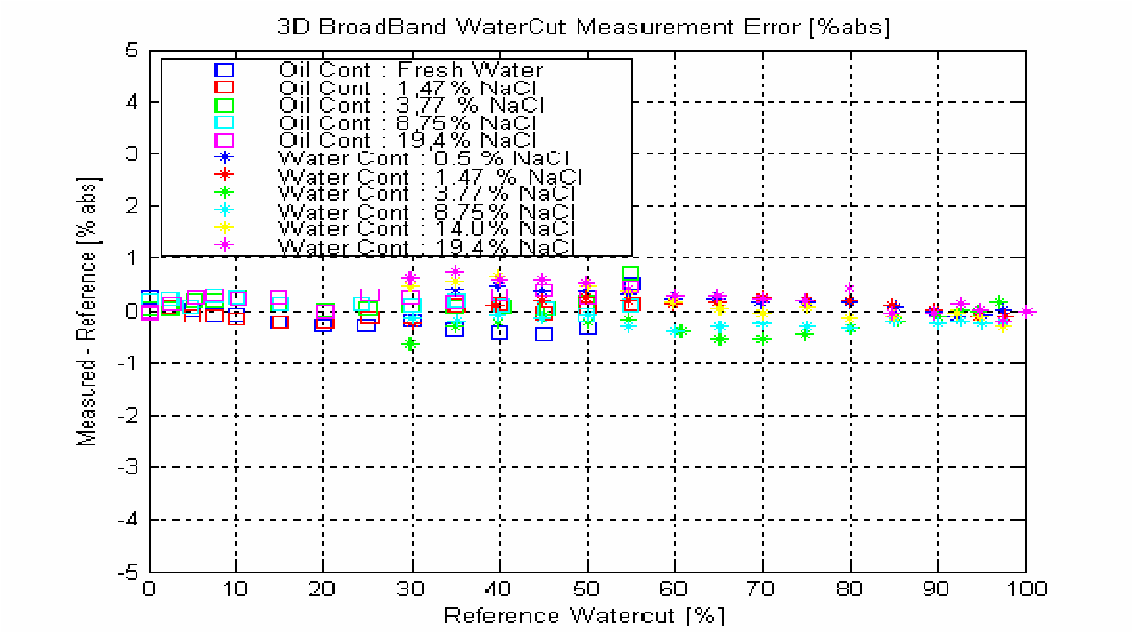
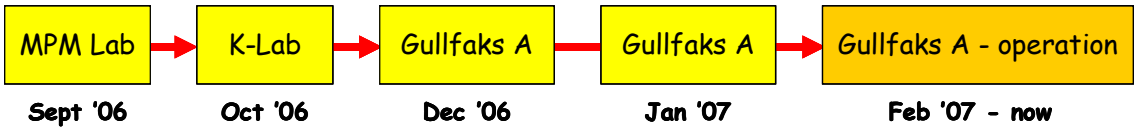


Figure 9: Qualification Test Program



- All tests performed using the same unit
  - 3" MPM Meter
  - Made as per Gullfaks Specifications
- Field test program conducted by Statoil

Figure 10: Overview of qualification test conditions

	MPM Flow Lab FAT Sept '06	K-Lab Test Oct '06	Gullfaks A Dec '06	Gullfaks A Jan '07	Gullfaks A March '07
GVF	0 - 99,9 %	25 - 99,9 %	40 - 96 %	20 - 95 %	10 - 85 %
WLR	0 - 95 %	0 - 70 %	2 - 78 %	2 - 85 %	25 - 93 %
Pressure	< 10 bar	120 bar	60 bar	60 bar	60 bar
Oil	Exxol D 140 830 kg/m3	Condensate 620 kg/m3	Crude 780 - 840 kg/m3	Crude 780 - 840 kg/m3	Crude 780 - 840 kg/m3

Note: Reference system improvements at GFA from Dec '06 to Jan '07
Meter taken into permanent use in Feb '07 – for well testing

Figure 11: Sensitivity to changes in configuration data

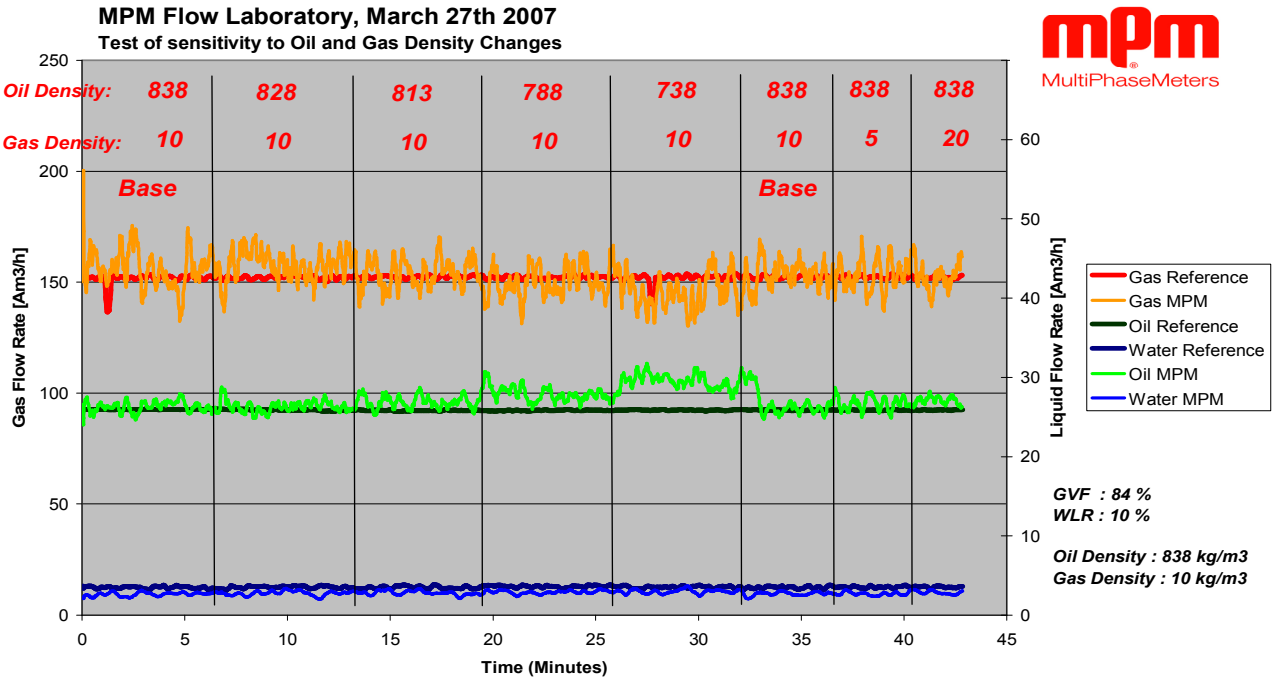


Figure 12: MPM Meter installation at Gullfaks A

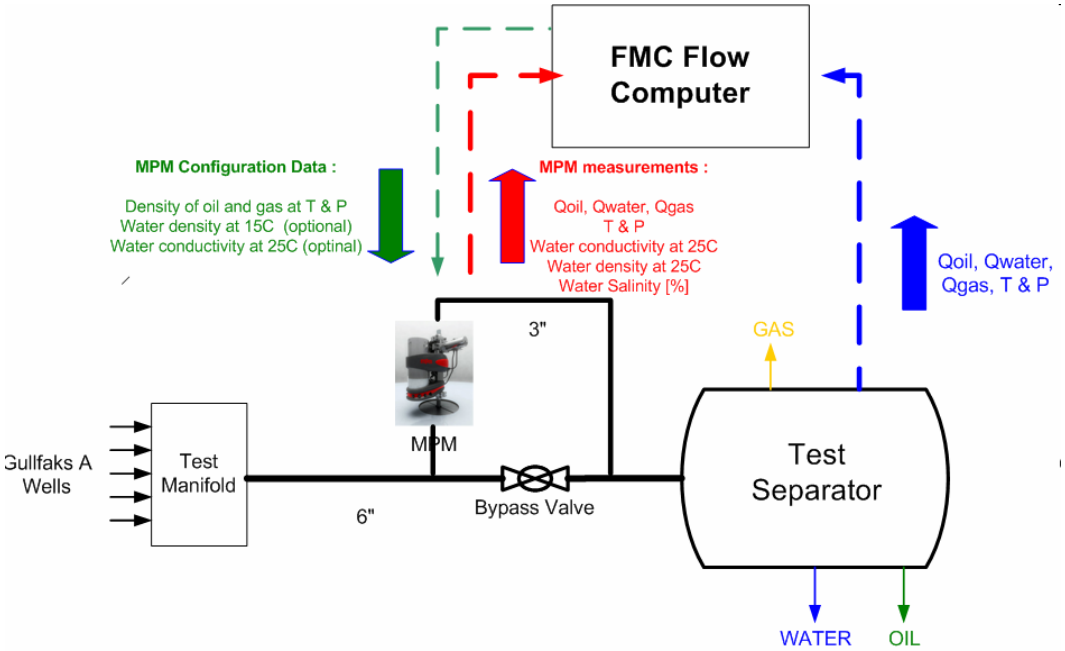


Figure 13: Sensitivity to injection of tiny water amounts in wetgas flow

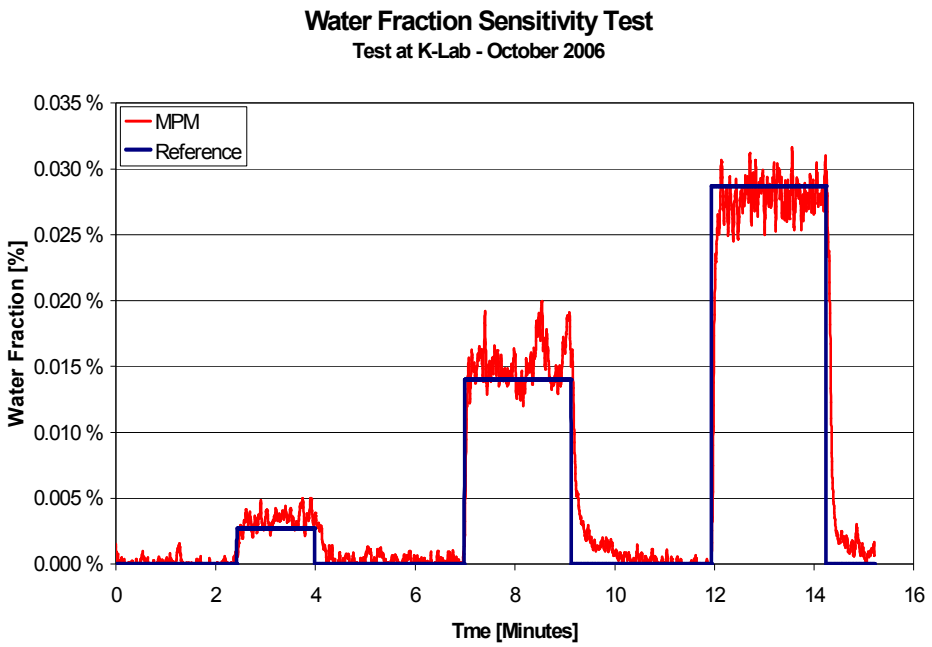


Figure 14: Flow test of Gullfaks A "wells" - MPM Flow Laboratory

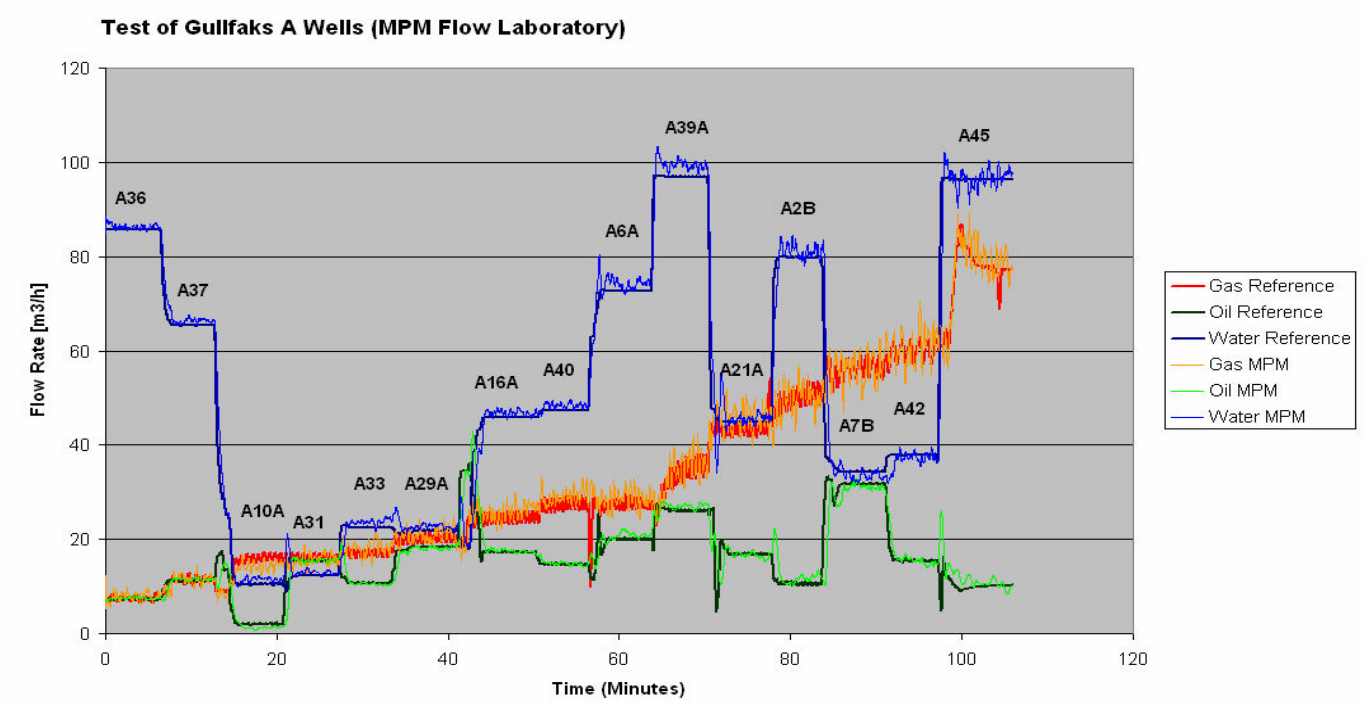


Figure 15: Qualification Testing - Wetgas

K-Lab test
Wetgas Mode GVF 99,7%, WLR 30 %

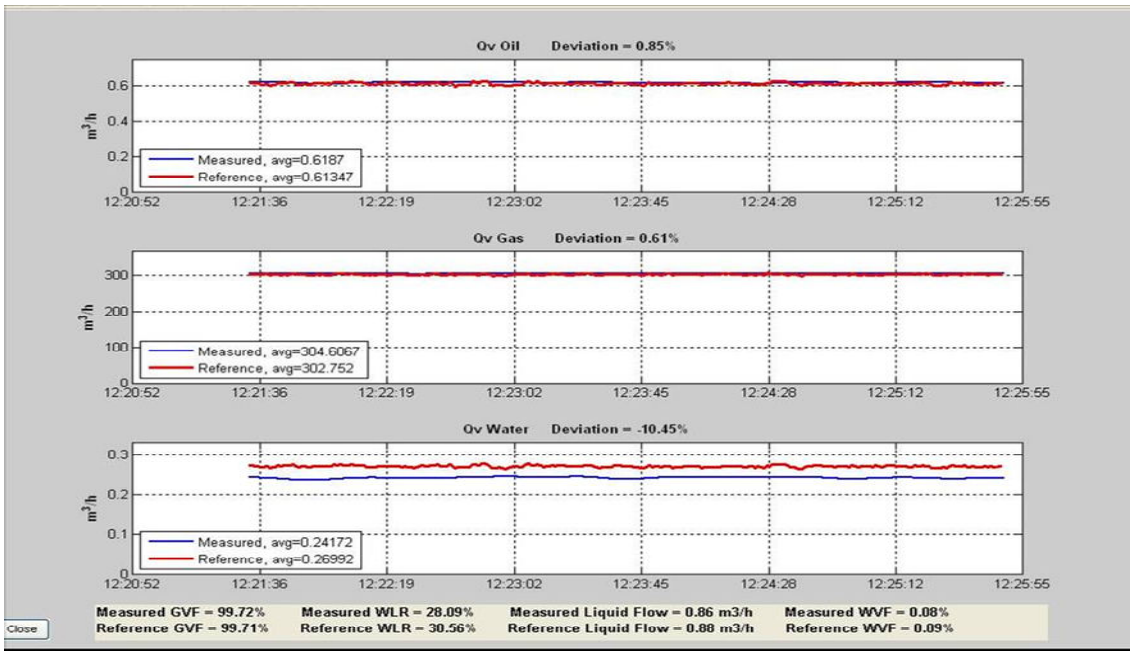


Figure 16: Qualification Testing - Wetgas

K-Lab test
Wetgas Mode GVF 98%, WLR 5 %

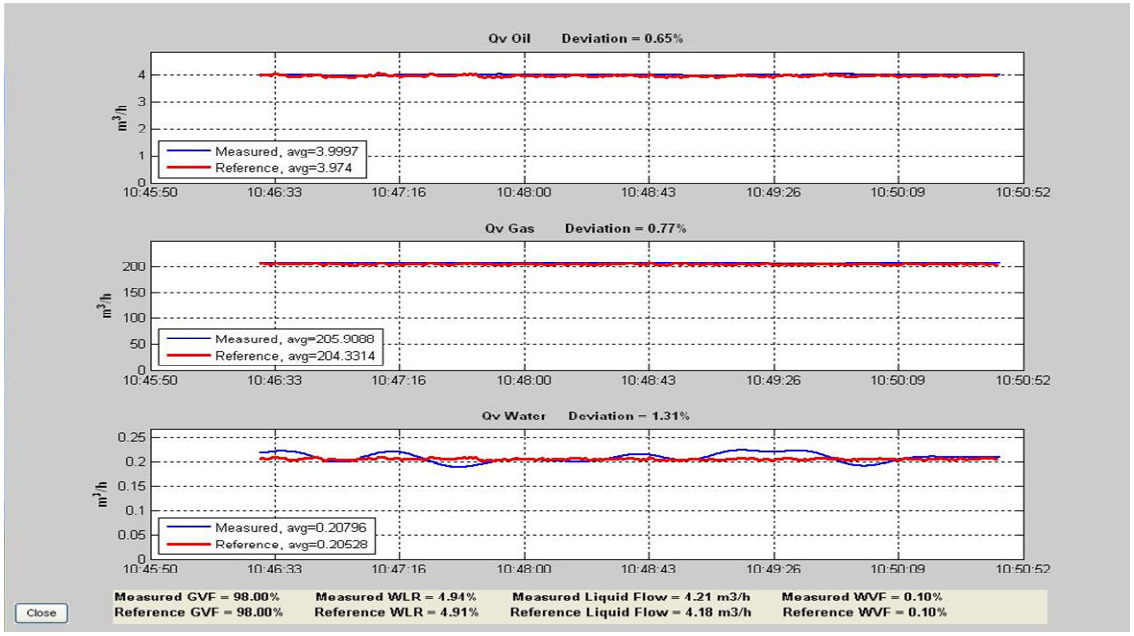


Figure 17|: Qualification Testing – MultiPhase

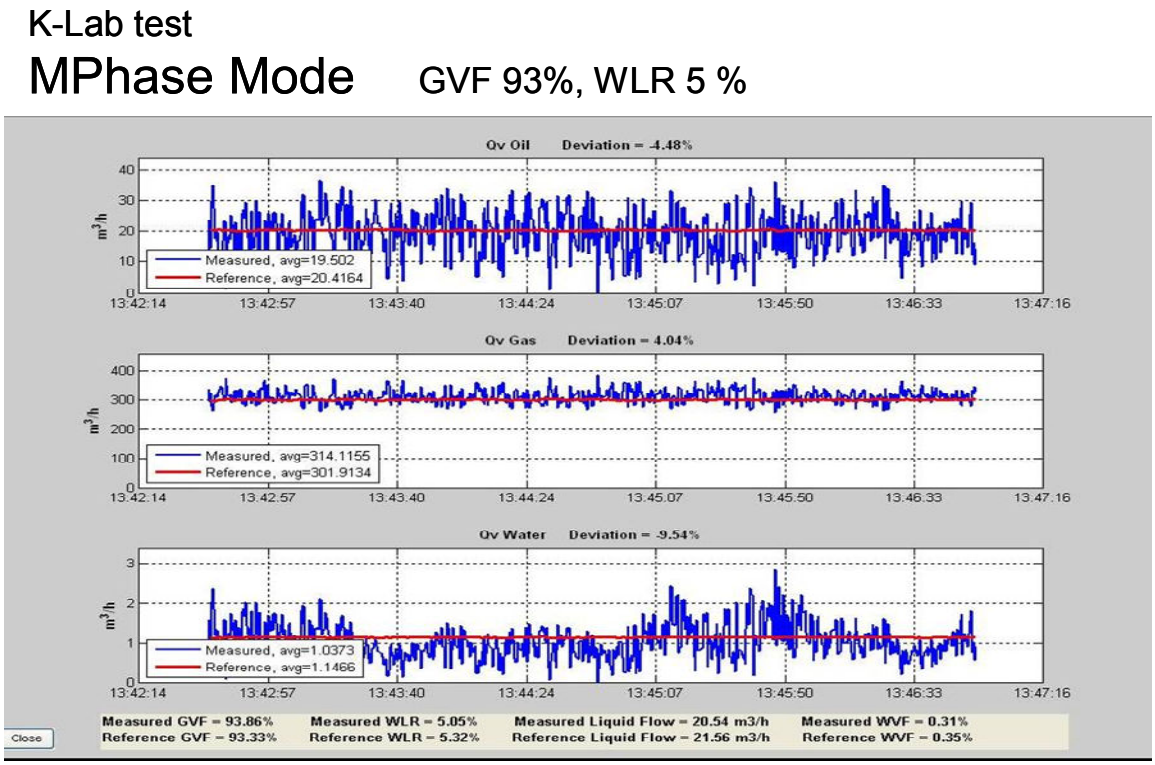


Figure 18: Summary – Qualification program – individual tests

	Individual wells / test points			
	MPM Lab	K-Lab	Gullfaks Dec	Gullfaks Jan
Oil Flow rate	± 5 to 10 %	± 4 to 10 %	± 8 %	± 6 %
Gas Flow rate	± 6 %	± 5 %	± 8 %	± 3 %

Notes:
- Accross full range of GVF and WLR
- Difference includes measurement uncertainty of reference and MPM meter, as well as other potential errors
- 90 % confidence level

Figure 19: Summary – Qualification program - Cumulative

	Cumulative rates - all wells / tests combined			
	MPM Lab	K-Lab	Gullfaks Dec	Gullfaks Jan
Oil Flow rate	+ 1,1 %	+ 0,1 %	+ 3,4 %	+ 1,4 %
Gas Flow rate	+ 1,4 %	+ 1,3 %	+ 1,4 %	+ 0,1 %

Note: (1)
- Accross full range of GVF and WLR
- Difference includes measurement uncertainty of reference and MPM meter, as well as other potential errors
- 90 % confidence level

Figure 20: Tests of operational stability and reproducibility at Gullfaks A

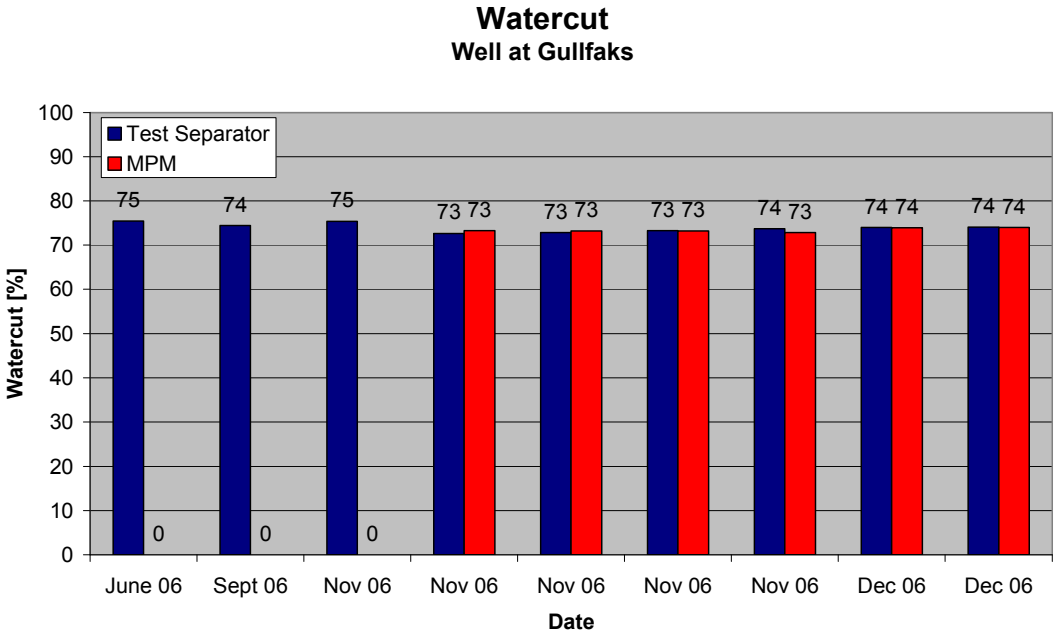


Figure 21: Repeatability tests at Gullfaks A

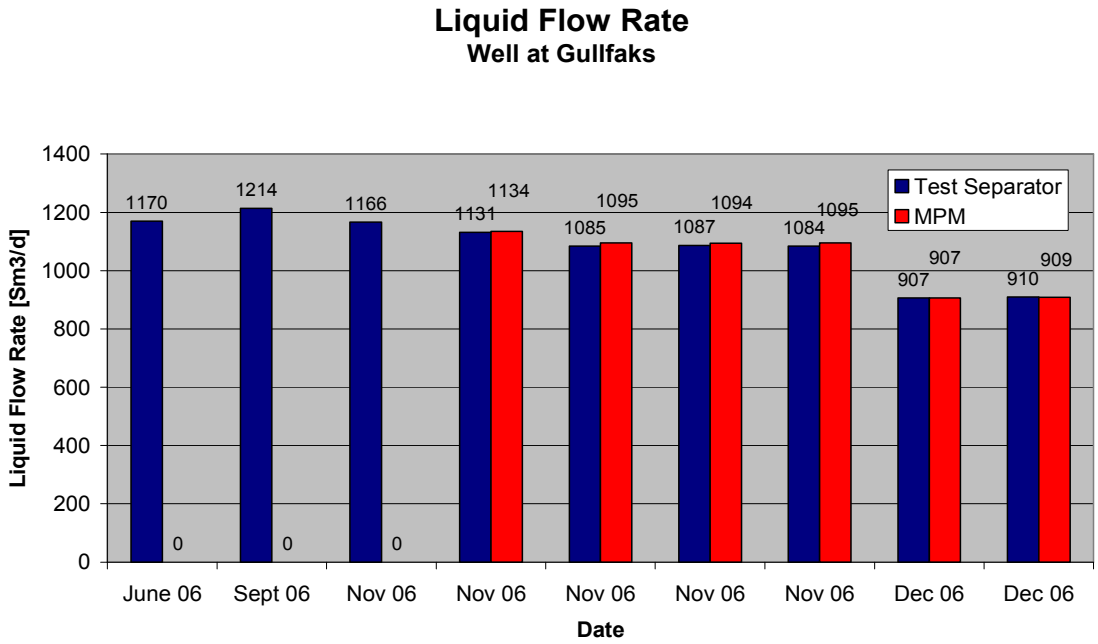


Figure 22: Verification of water salinity measurement method

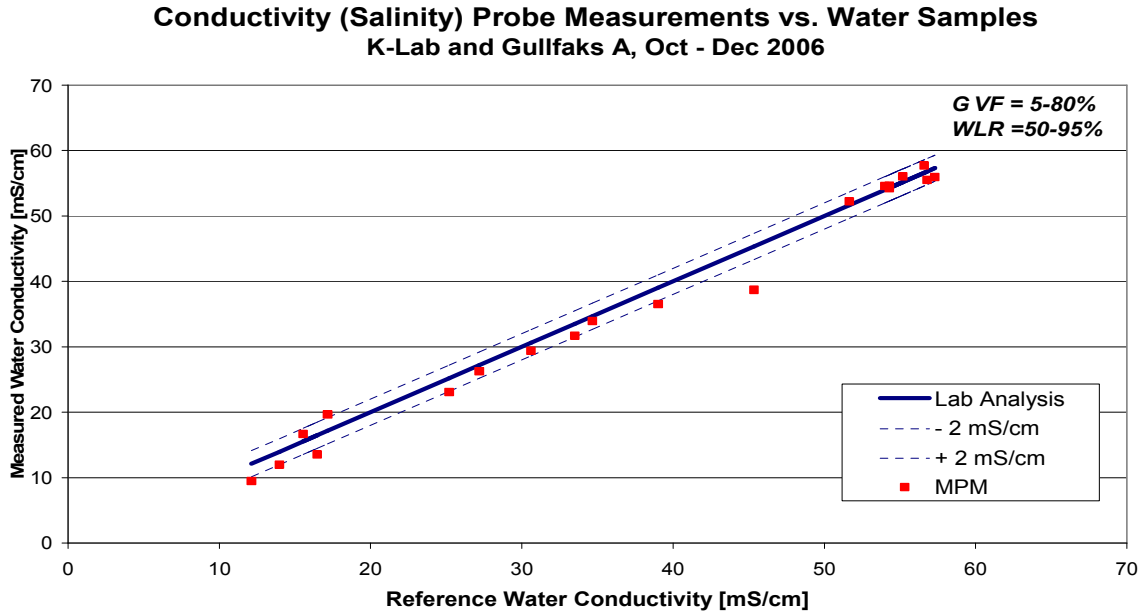
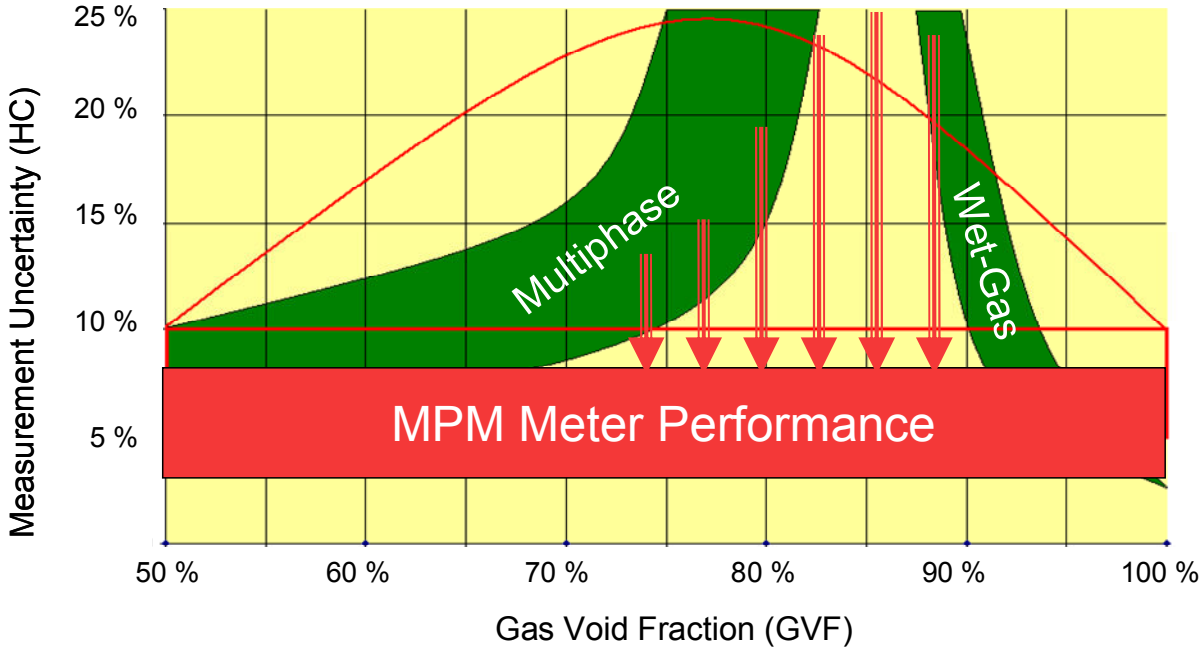



Figure 23: MPM's contributions to closing the gaps.