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		Overview of Capabilities	Page 1 of 23	

# Expro Meters’ Clamp-on Production and Injection Well Surveillance Capabilities

## Table of Contents

1	Introduction .....	1
2	Overview of Well Head Surveillance .....	1
3	Clamp-on SONAR Flow Measurement.....	4
3.1	History of SONAR Flow Measurements .....	4
3.2	Principle of Operation .....	4
4	SONAR-based Clamp-on Production and Injection Surveillance .....	5
4.1	Injection Wells .....	7
4.2	Gas Production Wells .....	8
4.3	Gas Condensate Wells.....	8
4.4	Black Oil Wells.....	13
4.5	ESP Lifted Oil Wells .....	19
5	Proprietary Technology and Intellectual Property.....	23
6	Summary.....	23

## 1 Introduction

Expro Meters Inc has developed a versatile clamp-on well head Total Production Surveillance system. Termed TPS1000, the system is targeted toward gas, gas condensate, black oil production wells, and gas and liquid injection wells. The system is based on Expro Meters’ unique SONAR Clamp-on flow metering technology and leverages Expro Meters’ expertise in the Pressure, Volume, and Temperature (PVT) properties of produced and injected hydrocarbons.

This paper describes the methodology of the TPS1000 system and its components and provides examples of the TPS1000 providing well head surveillance on 1) injection wells, 2) gas production wells, 3) gas condensate production wells, and 4) black oil wells.

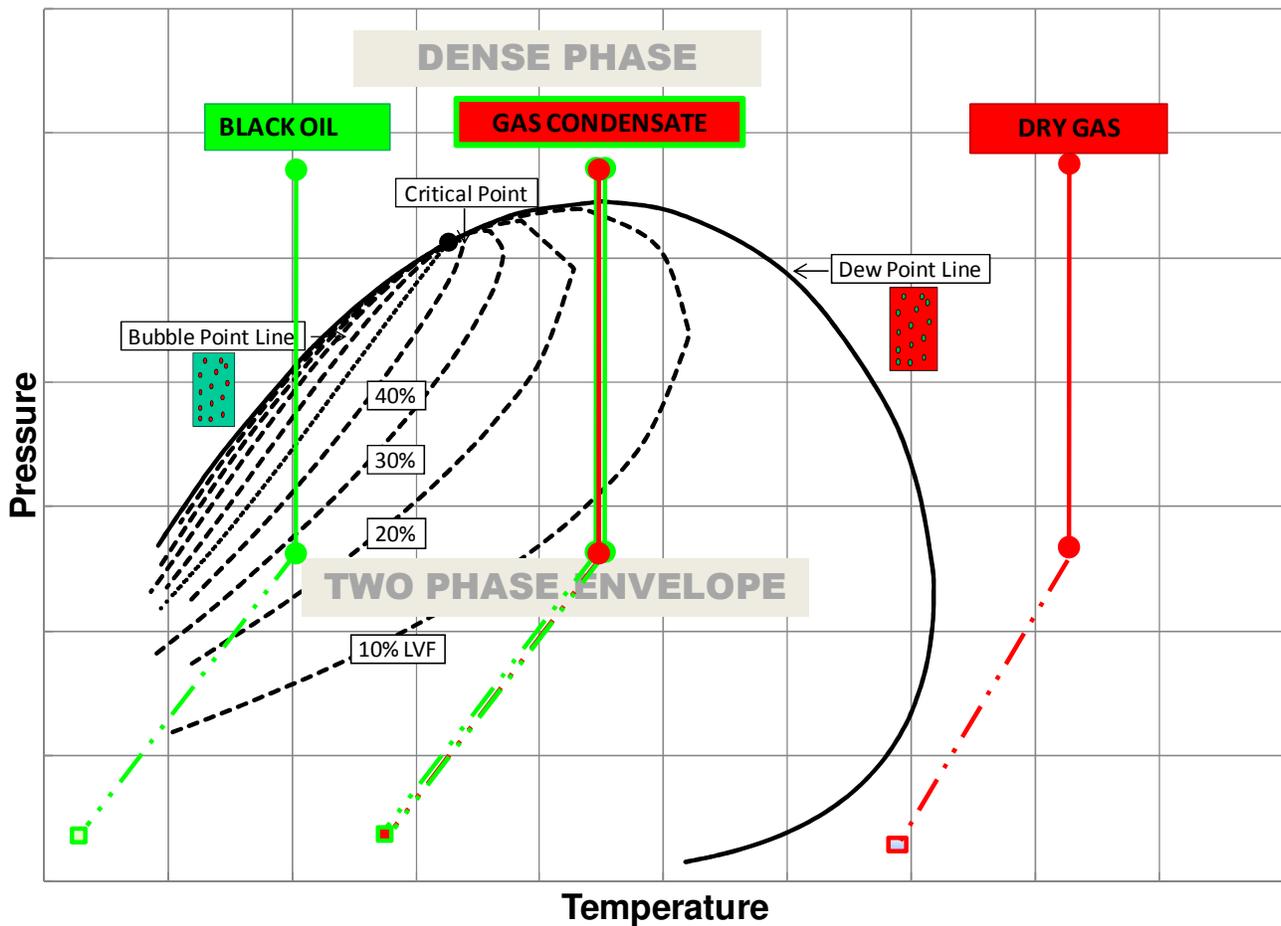
## 2 Overview of Well Head Surveillance

Monitoring produced oil, gas, and water waters from individual wells plays an important role in reservoir management. Monitoring injection rates provides additional important information for reservoir management. Obtaining timely and accurate well head measurements can be challenging due to a range of factors. Traditional well test separators are costly and can at best provide periodic measurements. In-line multiphase flow meters can be expensive as well and, due to their intrusive nature, can result in deferred production to accomplish a well test.

Expro's clamp-on production and injection monitoring systems are designed to provide rapid, cost-effective well head surveillance for a wide range of well surveillance applications.

The behavior of produced hydrocarbons is often depicted by its phase envelope. The type of hydrocarbon produced from a reservoir can be classified by the pressure and temperature of the hydrocarbon with respect to its critical point. Figure 1 shows representative trajectories of three broad classes of produced hydrocarbons: dry gas, gas condensates, and black oils as they are produced from the reservoir to the surface.

## PVT Behavior of Produced Fluids



**Figure 1: PVT Behavior of Produced Hydrocarbons**

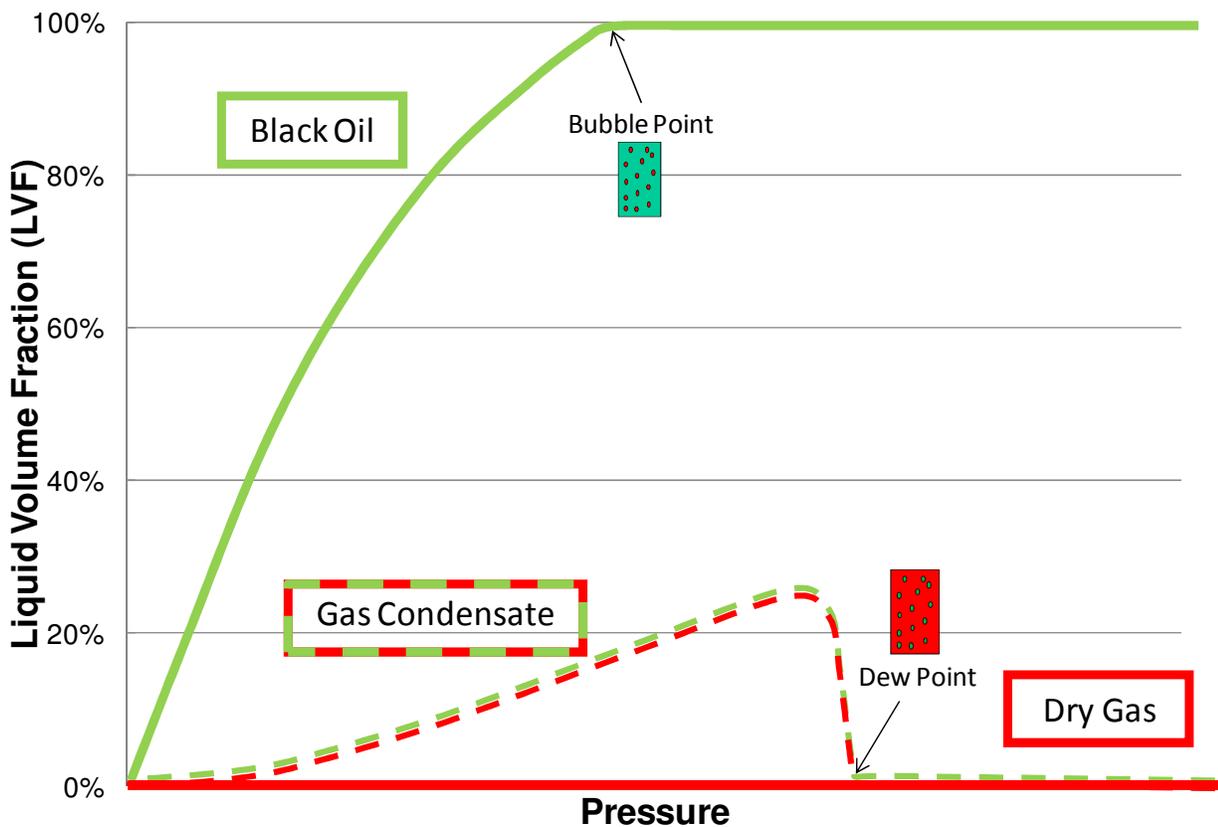
Typically, the phase envelope for a given produced hydrocarbon reservoir is known. The phase envelope can be measured experimentally in a PVT laboratory using samples extracted from the reservoir, or, more commonly, the phase envelope for a given composition is calculated using a PVT model. For pressure and temperatures that lie outside of the two phase envelope, the hydrocarbon is said to be in the “dense” phase. In the dense phase, the hydrocarbon exists as a single phase.

The key feature that characterizes the three types of hydrocarbons delineated above is the behavior of the fluid when and if it encounters the two phase envelope as the fluid is produced to the surface. Hydrocarbons

characterized as “dry gas” remain outside of the two phase envelope. Hydrocarbons that encounter a “dew point” as it is being produced to surface are typically characterized as “gas condensate” wells. The “dew point” is the point at which small droplets of liquids form within a gas continuous phase. If the hydrocarbon encounters the “bubble point”, the hydrocarbon is typically characterized as a “black oil”. The bubble point is the point at which small gas bubbles form within a liquid continuous mixture. The locus of dew points and bubble points are separated by the “critical point”. Note that water production can be present in any of the above reservoirs classifications.

From a production surveillance perspective, each of these three broad classes of reservoirs present distinctly different phase behavior as a function of pressure and temperature. Figure 2 shows the liquid volume fractions as a function of flow line pressure broadly representative of the three types of hydrocarbon reservoirs.

## Liquid Volume Fraction of Produced Fluids



**Figure 2: Liquid Volume Fraction as Function of Pressure for Produced Hydrocarbons**

As shown, the Liquid Volume Fraction (LVF) of “Dry Gas” reservoirs remains at zero as it is produced to the surface. The liquid volume fraction of “Gas Condensate” reservoirs increase rapidly upon encountering the “dew point”. “Black Oil” reservoirs are 100% liquid until they encounter the bubble point, after which the liquid volume fraction decreases precipitously as the pressure is reduced toward surface conditions.

 <b>EXPRO</b> <small>EXPRO METERS, INC.</small>		Expro Meters, Inc.	DLG	29Sept2011
		Overview of Capabilities	Page 4 of 23	

### 3 Clamp-on SONAR Flow Measurement

#### 3.1 History of SONAR Flow Measurements

Sonar-based flow measurement technology was first introduced to the oil and gas industry with the deployment of the first down-hole, fiber-optic-strain, multiphase flow meter from the Shell Mars Platform in October, 2000 [1]. The fiber-optic-strain sonar meter used sonar-based passive-listening techniques to provide flow rate and compositional information for downhole oil, water, and gas mixtures.

Expro Meters SONAR flow measurement technology was specifically designed to provide clamp-on flow measurements of upstream oil and gas flow lines.

The PassiveSONAR meter was introduced in 2003 as the first generation clamp-on SONAR meter. PassiveSONAR employs piezo-strain sensors to replace the fiber optic strain sensors in the first generation, downhole SONAR flow meter. The piezo-strain sensors simplified the installation and operation of the meters for top side applications while lowering cost and maintaining performance. PassiveSONAR is well suited for high liquid loading multiphase flows typical of black oil wells and low pressure gas wells.

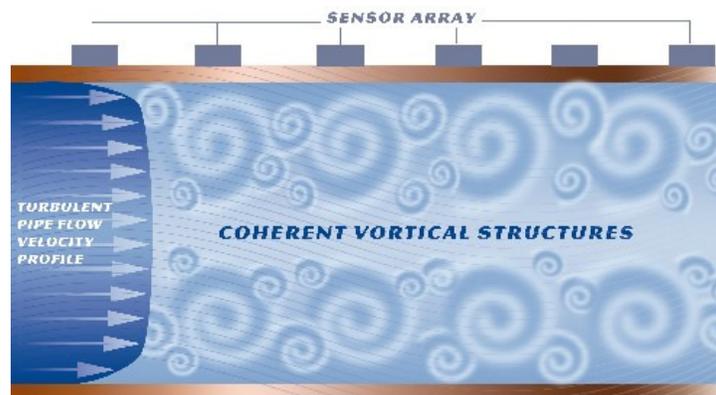
In 2009, Expro Meters introduced ActiveSONAR, the second generation Clamp-on meter SONAR meter. The ActiveSONAR meter is well suited for Gas and Gas Condensate wells in heavy schedule pipes.

Expro Meters utilizes both types of Clamp-on SONAR flow measurement technologies to address a wide range of flow line conditions.

#### 3.2 Principle of Operation

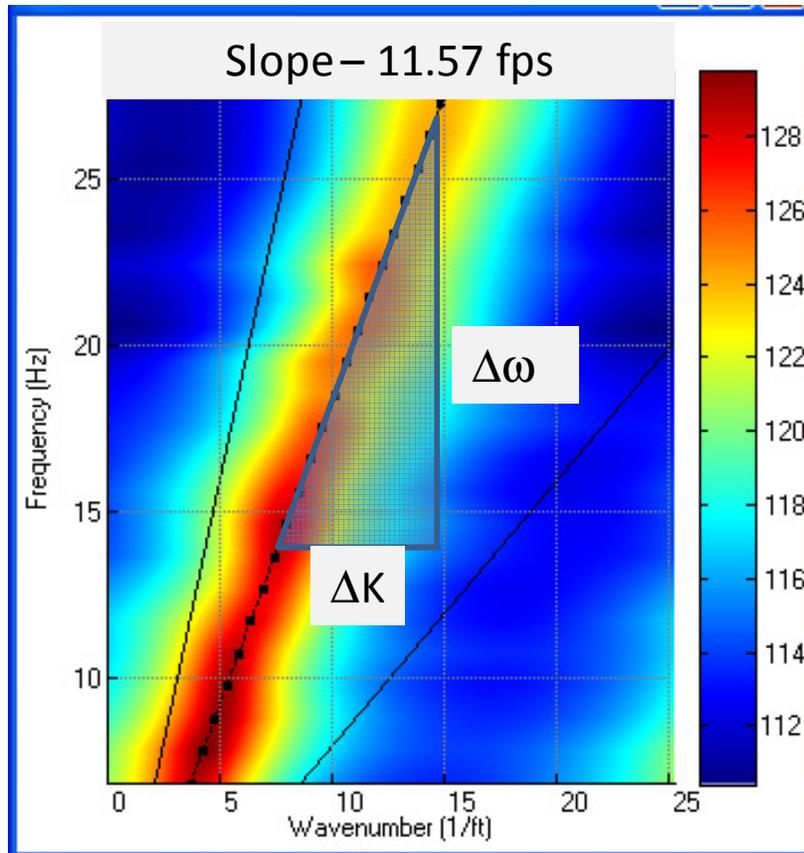
Clamp-on SONAR-based flow meters utilize sonar processing techniques to determine the speed at which naturally occurring, coherent flow structures convect past an array of sensors clamped-on to the outside of the pipe.

Figure 3 illustrates the naturally occurring, self-generated, coherent structures present within turbulent pipe flows. Naturally occurring, self-generating, turbulent eddies are superimposed over the time-averaged velocity profiles. These coherent structures contain fluctuations with magnitudes on the order of 10 percent of the mean flow velocity and are carried along with the mean flow. These eddies remain coherent for many pipe diameters and convect at, or near, the volumetrically-averaged flow rate in the pipe.



**Figure 3 : Sonar-based Flow Meters with Coherent Structures within Pipe Flows**

In sonar array processing, the spatial / temporal frequency content of sound fields are often displayed using “k- $\omega$ ”plots. k- $\omega$  plots are presented as surface plots in which the power of a sound field is allocated to bins corresponding to specific spatial wave numbers and temporal frequencies. On a k- $\omega$  plot, the power associated with coherent structures convecting along with the flow is distributed along “the convective ridge”. The slope of this ridge indicates the speed of the turbulent eddies. Thus, identifying the slope of the convective ridge determines volumetric flow rate.



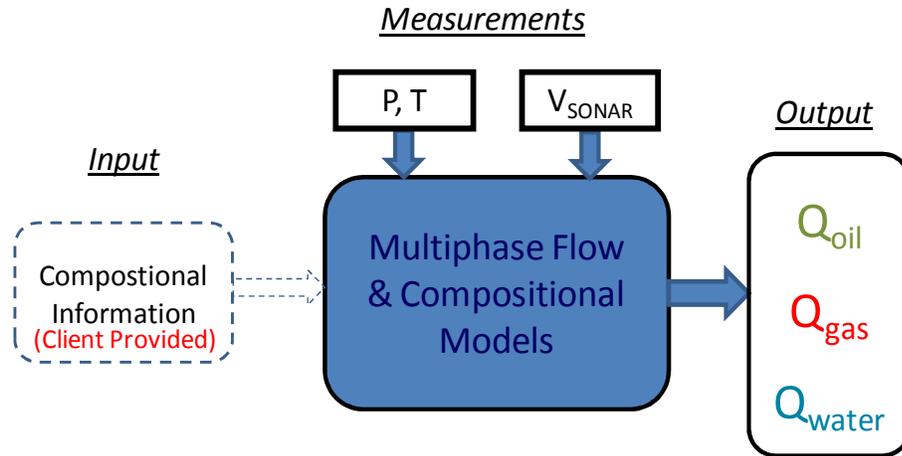
**Figure 4: K-w plot from a Clamp-on, SONAR meter on Gas Well**

Figure 4 shows an example of a k- $\omega$  plot generated from the diagnostic output of a sonar flow meter clamped on to an 8 inch, schedule 120 pipe operating with ~3 mmscfd of methane gas flowing at 5 barg. As shown, the k- $\omega$  plot exhibits a well-defined convective ridge. The slope of the convective ridge was determined to be 11.57 ft/sec by the SONAR flow meter.

#### **4 SONAR-based Clamp-on Production and Injection Surveillance**

Expro Meters has developed a versatile and cost-effective means to provide well head surveillance to a broad range of gas, gas condensate, and black oil wells. The Total Production Surveillance (TPS1000) System utilizes PassiveSONAR and ActiveSONAR flow meters (depending on the application) to clamp-on to well head piping to measure mixture volumetric flow rate at actual conditions. The measurement is then combined with measurements of the process pressure and temperature and user supplied compositional information to determine

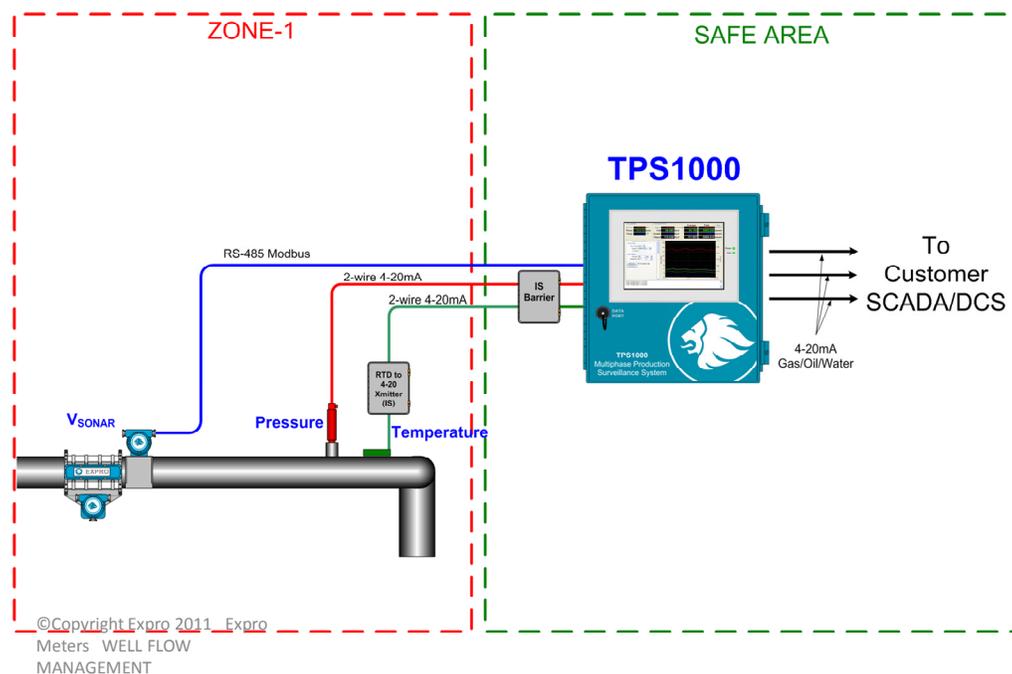
flow rates. This process, shown schematically in Figure 5, is broadly applicable to a wide range of production and injection wells.



**Figure 5: Schematic of TPS1000 Total Production Surveillance Methodology**

Figure 6 shows a schematic of the TPS1000 system installed on a well head flow line. The TPS1000 Multiphase flow computer can provide surveillance for gas, gas condensate, and black oil production wells and gas and liquid injection wells. The surveillance can be provided on a survey or permanent monitoring basis.

## TPS1000 System Diagram



**Figure 6: Schematic of TPS1000 Installation**

## 4.1 Injection Wells

For gas injection wells, Expro Meters Clamp-on Surveillance system provides a measurement that is equivalent to a standard in-line single phase flow meter. AGA-8 composition is provided by the client and Expro Meters Flow computer calculates a gas compressibility factor using a real time Equation of State algorithm, and the system report gas rates at standard conditions. The system works in a similar manner for water and other signal phase liquid systems.

Expro Meters clamp-on ActiveSONAR meters was specifically designed to address the high pressure, heavy schedule piping typical of injection well applications. Additionally, Expro's Equation of State PVT models are well suited to accurate convert flow rates measured at high pressure to standard conditions.

Figure 7 shows an ActiveSONAR meter operating on a 6 inch, heavy schedule (XXS+) gas injection well in the Middle East. Wells were injecting gas (91% C1, 5% C2, 1% C3, 3% C4+) at 300 barg, 70 C. The ActiveSONAR meter measured actual velocities of ~20 ft/sec, corresponding to 55 mmSCFD injection rates.

### Middle East Injection Well – 6 inch XXS+

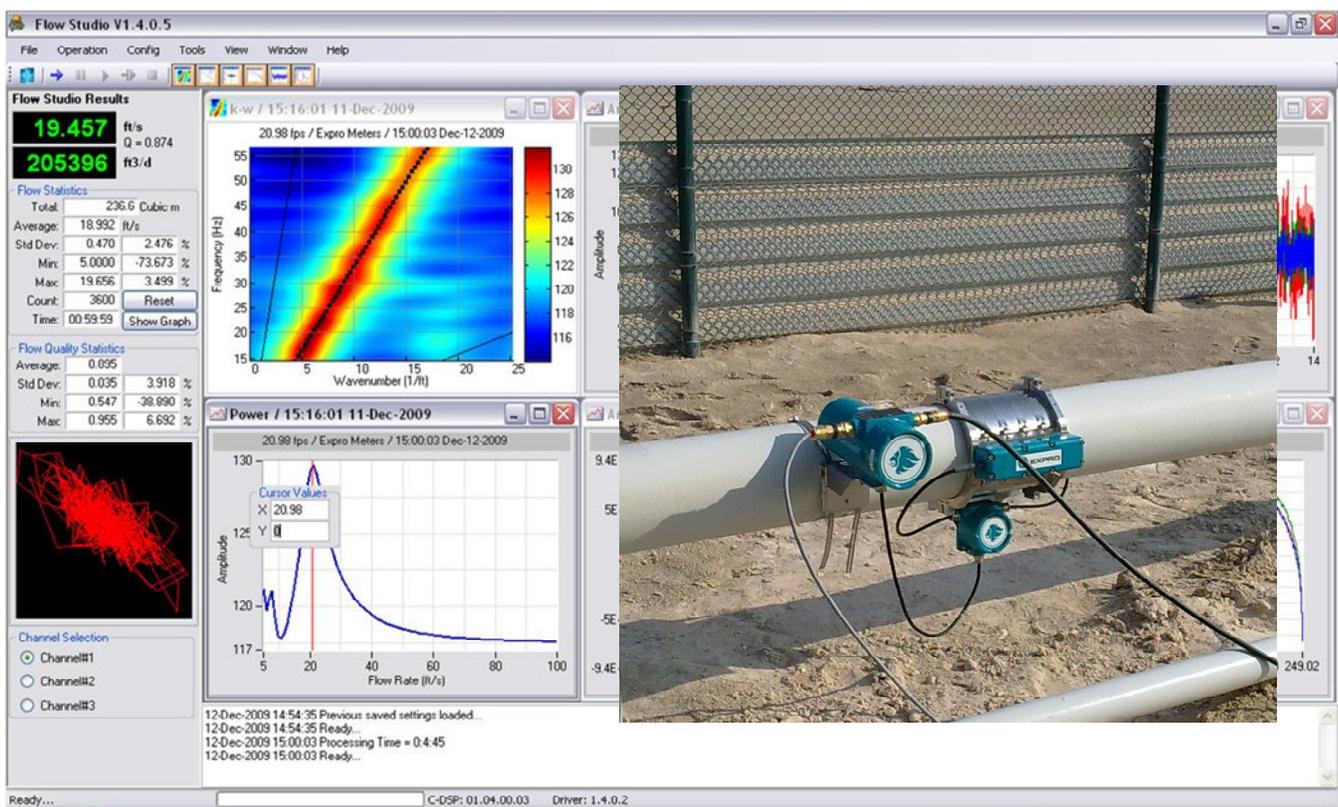


Figure 7: SONAR Meter Operating on High Pressure Gas Injection Well in Middle East with Flow Diagnostics

 <b>EXPRO</b> EXPRO METERS, INC.	Expro Meters, Inc.	DLG	29Sept2011
	Overview of Capabilities	Page 8 of 23	

## 4.2 Gas Production Wells

Expro Meters SONAR Production Surveillance Systems are widely used to measure gas well production rates throughout the world. SONAR meter meters provide gas production rates on a temporary, survey-based, well testing program, or on a permanently installed basis for real-time, 24x7x365 surveillance.

Figure 8 shows an ActiveSONAR meter installed on an 8 inch, schedule 120 gas well flow line. This meter is one of 40 permanently installed ActiveSONAR meters in this field in the Irish Sea monitoring the production from declining gas wells. The meter is operating at ~5 barg at 11ft/sec, corresponding to ~3 mmscfd.

Irish Sea Gas Well – 8 inch schedule 120

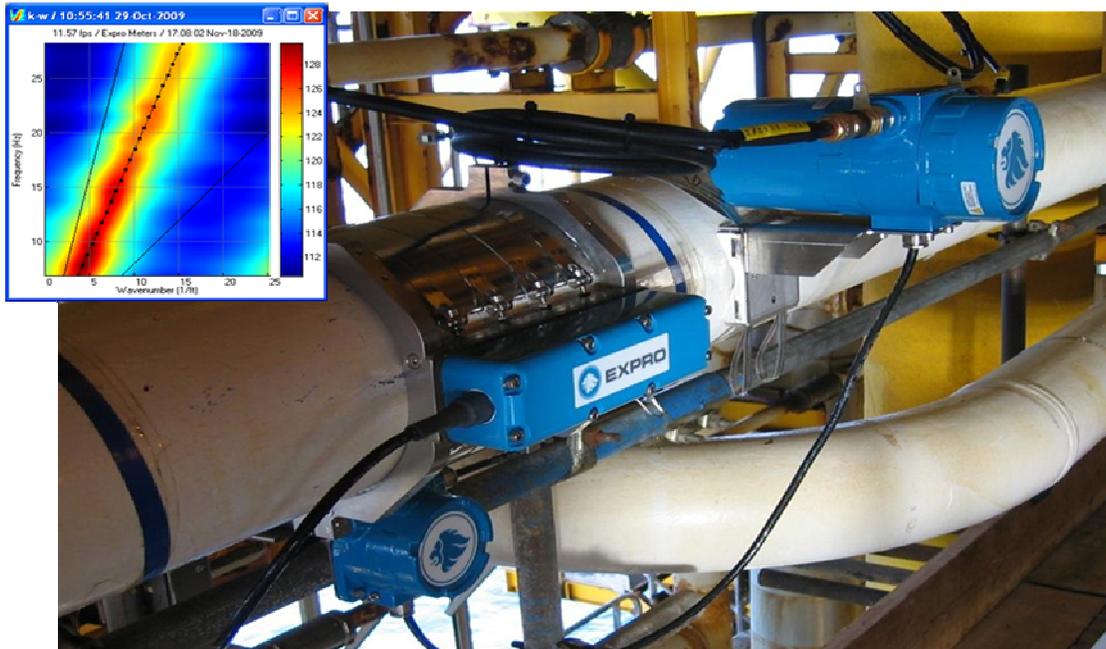


Figure 8: SONAR Meter Operating on Low Pressure Gas Production Well in Northern Europe with Flow Diagnostics

## 4.3 Gas Condensate Wells

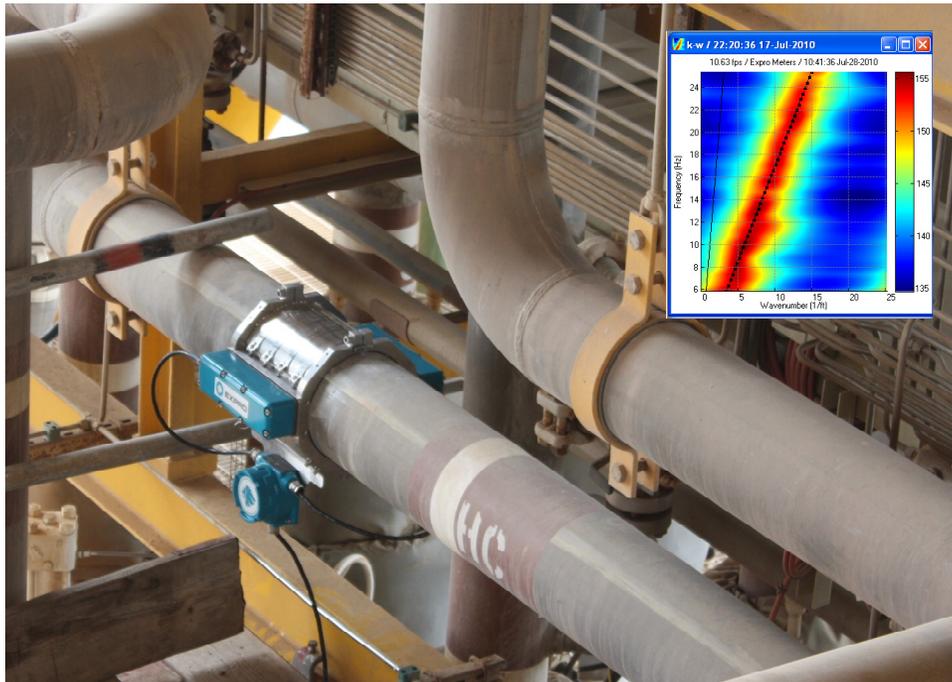
Gas Condensate wells often exhibit complex gas liquid phase behavior with the liquid loading varying with pressure and temperature as the wells are produced. Expro's Total Surveillance System was designed to address the challenging multiphase and PVT fluid behaviors often encountered in Gas Condensate wells.

For Gas condensate wells, the TPS1000 utilizes a user defined well bore composition. Often, the customer supplies a historical PVT report for the well and a recent well test result indicating the current producing condensate to gas ratio (CGR) and producing water to gas ratio (WGR). Using this information, Expro meters configures the TPS1000 system to accurately interpret measured SONAR flow velocity, pressure and temperature in terms of gas rates and then calculating the condensate and water rates from the compositional information provided. Two examples of the TPS1000 System applied to gas condensate wells are given below.

### Gas Condensate Well with Sonar Meter Operating in Dense Phase

The goal of this trial was to evaluate the suitability of the clamp-on production surveillance system to measure the production rates of high pressure gas condensate wells. The availability of a permanently installed test separator at the facility made it particularly well suited for this evaluation. Figure 9 shows a sonar flow meter clamped-on to an 8-inch, schedule 100 pipe (0.59 inch wall thickness) positioned upstream of the production choke on a gas condensate well producing gas condensate with a condensate-to-gas-ratio of 37 bbl/mmscf and a water-cut of 1.8%.

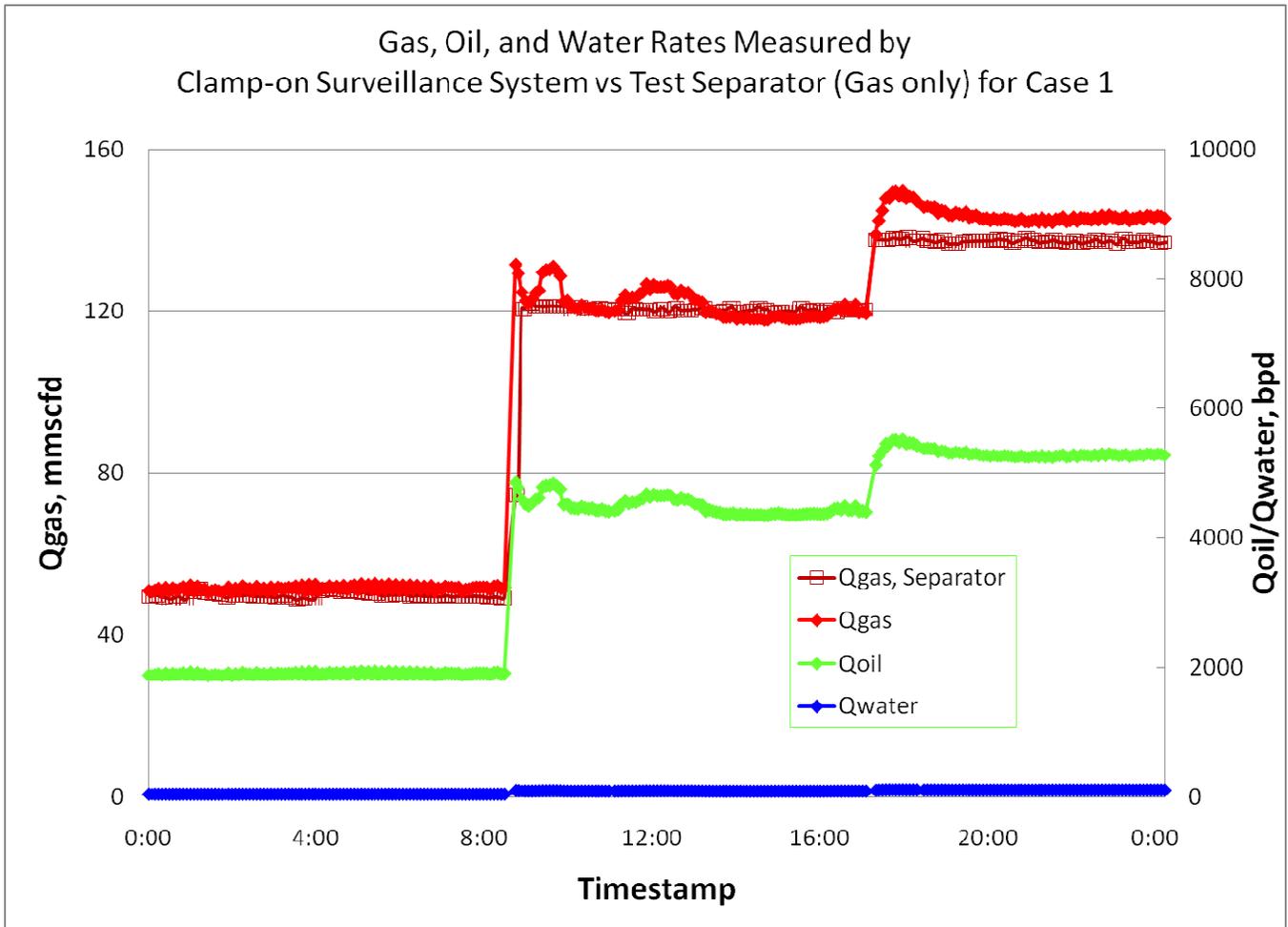
A sonar-based k-w plot recorded during the testing is also shown in Figure 9, reporting a mixture velocity of ~10 ft/sec. The diagnostic plot from the sonar meter indicates that the sonar meter was performing well under these dense phase conditions..



**Figure 9: SONAR flow meter clamped-on to an 8-inch, schedule 100 pipe upstream of the production choke on a gas condensate well and its recorded k-w plot**

Customer supplied well bore composition specified a producing CGR of 37 bbls/mmscf. The line pressure at the location of the sonar meter was between 3000~3500 psia and the line temperature was around 190 Deg F, resulting in the sonar meter operating in the dense phase region of the phase envelop for these fluid.

Figure 10 gives production surveillance results for gas / oil / water flow rates. The gas flow rates predicted by the clamp-on production surveillance system (TPS 1000) are compared with those measured from the gas leg of the well test separator. The gas flow rates reported by the surveillance system are in good agreement with the reference values. The associated oil (condensate) and water rates for the same period reported by the clamp-on production surveillance system are also reported. Unfortunately, no field reference data were available for either oil or water rates. The average gas flow rates measured by the production surveillance system are within 5% of those measured by the well test separator.



**Figure 10 : Results From TPS1000 System applied to a High Pressure Gas Condensate well operating in the dense phase with Gas rate reference from Test Separator**

### 5.2 Case 2: Gas Condensate Well During Clean-Up

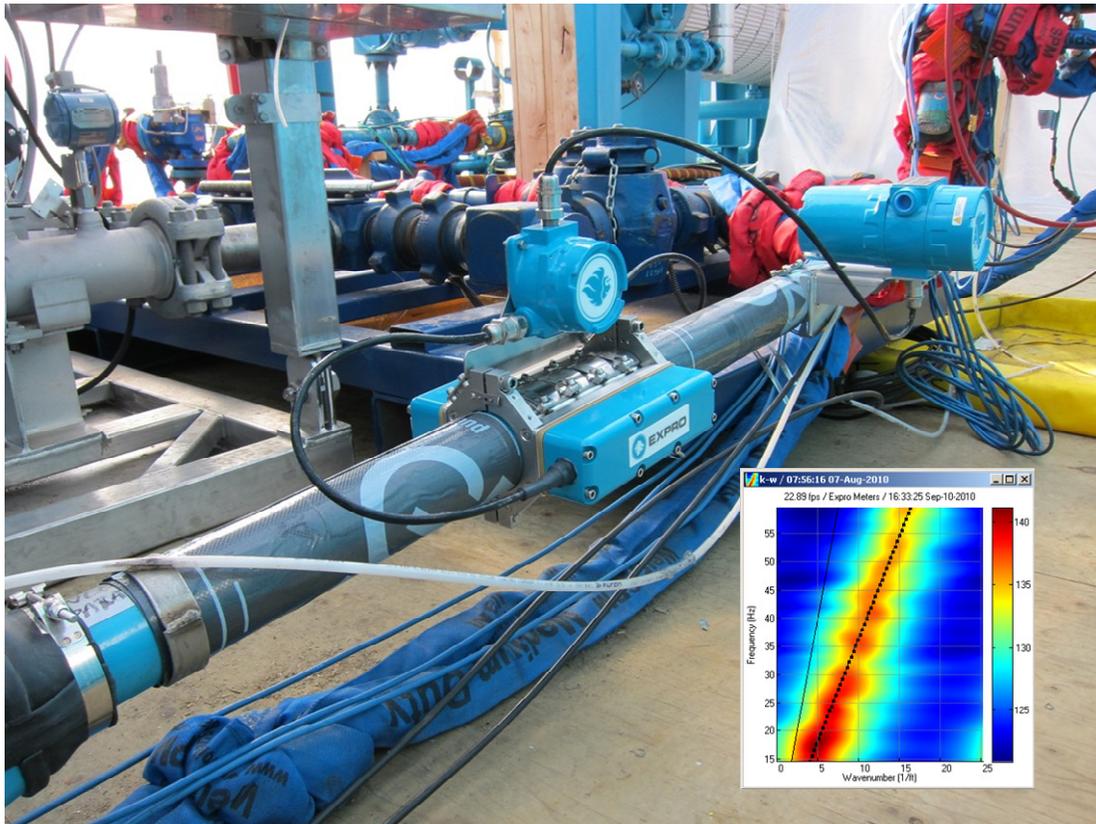
The goal of this trial was to evaluate the utility of the clamp-on production surveillance system during the clean-up phase of a well. Specifically, the clamp-on production surveillance system is capable of providing well production measurement when the test separator or other intrusive in-line multiphase metering systems are either 1) off-line due to instrumentation reconfiguration (i.e. changing out orifice plates) or 2) on by-pass due to, for example, heavy solids production.

Figure 11 shows a sonar flow meter clamped-on to 3-inch, schedule 160 temporary piping on a well test package, downstream of the production choke and upstream of the test separator.

The gas condensate had a CGR of 77 bbl/mmscf with 4.2% water-cut. The line conditions where the sonar meter was clamped-on were 657 psia and 97 DegF. Referencing these conditions on the phase envelope indicates that the meter was operating with both gas and liquid hydrocarbons present. At the production line conditions, the PVT model indicated that the liquid volume fraction was ~3% and the Lockhart-Martinelli parameter value was ~0.10. A

 <b>EXPRO</b> EXPRO METERS, INC.	Expro Meters, Inc.	DLG	29Sept2011
	Overview of Capabilities	Page 11 of 23	

sonar-based k-w plot recorded during the testing under similar conditions is also shown in Figure 11, indicating a mixture velocity of ~23 ft/sec. As with the previous example, the diagnostic plot from the sonar meter indicates that the sonar meter was performing well for this type II wet gas conditions.



**Figure 11: SONAR flow meter clamped-on to a 3-inch, schedule 160 temporary piping on a well test package, downstream of the production choke and upstream of the test separator during Well Clean-up**

Figure 12 shows the gas rate reported by the TPS1000 system compared to that reported by the test separator during a series of choke changes during the clean up process. As shown the TPS1000 system is in good agreement with the reference test separator.

Figure 13 shows the oil (condensate) rate reported by the TPS1000 system compared to that reported by the test separator during the same clean-up period. As shown the oil rates are in good agreement, indicating that the CGR was indeed fairly constant during the clean-up at a value close to 77 bbls/mmscfd.

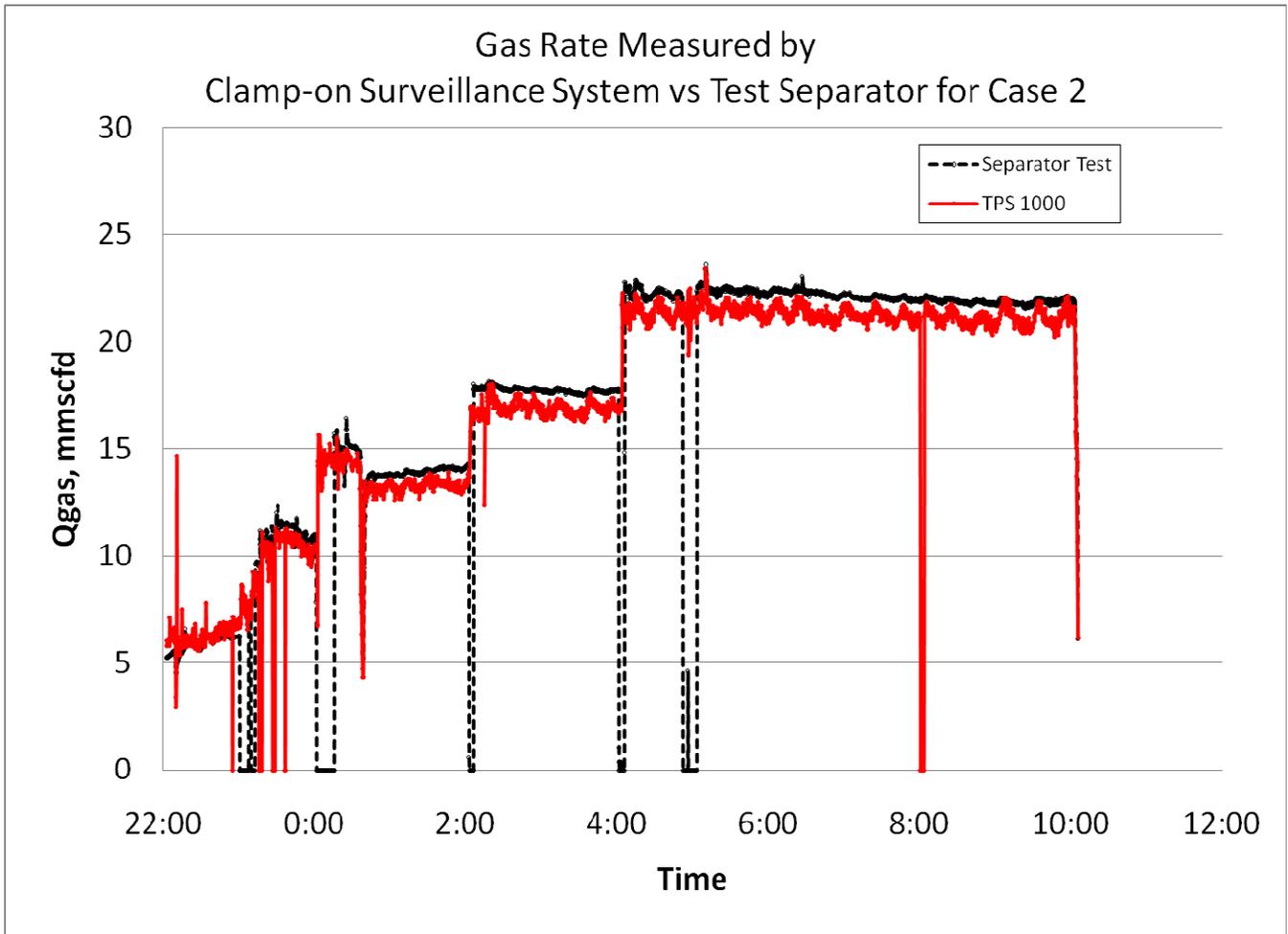
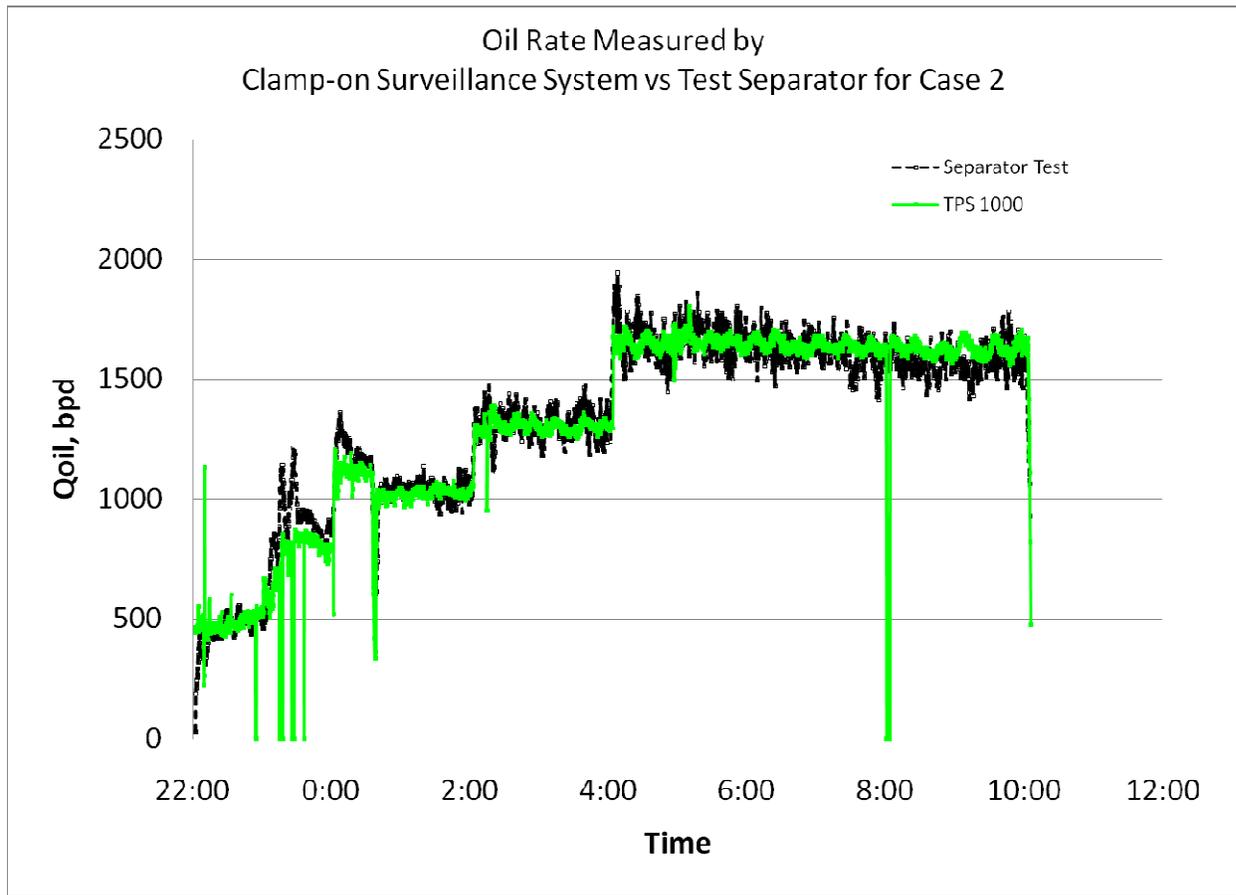


Figure 12: Comparison of Gas rates reported from TPS1000 System and Gas rates from a Reference Test Separator During Well Clean-up



**Figure 13 Comparison of Oil rates reported from TPS1000 System and Oil rates from a Reference Test Separator During Well Clean-up**

#### 4.4 Black Oil Wells

Compositional analysis and equation of state PVT modeling of black oils can be quite complex. Unlike gas and gas condensate wells for which the hydrocarbon composition is made up primarily of short length hydrocarbons (C7+ >~10%), black oils typically contain a large fraction of very long hydrocarbon chains rendering detailed compositional characterization and subsequent EoS PVT modeling quite challenging. Historically, the oil and gas industry has modeled the PVT properties of produced oils using “black oil” models. These models utilize readily measurable physical characteristics of produced hydrocarbons (such as Gas to Oil Ratio (GOR), Watercut, and bubble point pressure) as input to empirical correlations to predict the PVT properties of the black oil over a range of pressure and temperatures.

In an approach that is analogous to using Equation of State PVT models for gas condensate wells, Expro Meters TPS1000 System utilizes “black oil” models for oil wells to interpret the output of the SONAR meter using flow line pressure, temperature and well bore composition in terms of flow rates of gas, oil and water at standard conditions.

The SONAR meter measures mixture flow rate at line pressure and temperatures. The flow computer then calculates the liquid volume fraction at actual conditions within the process flow line using a Black oil model and

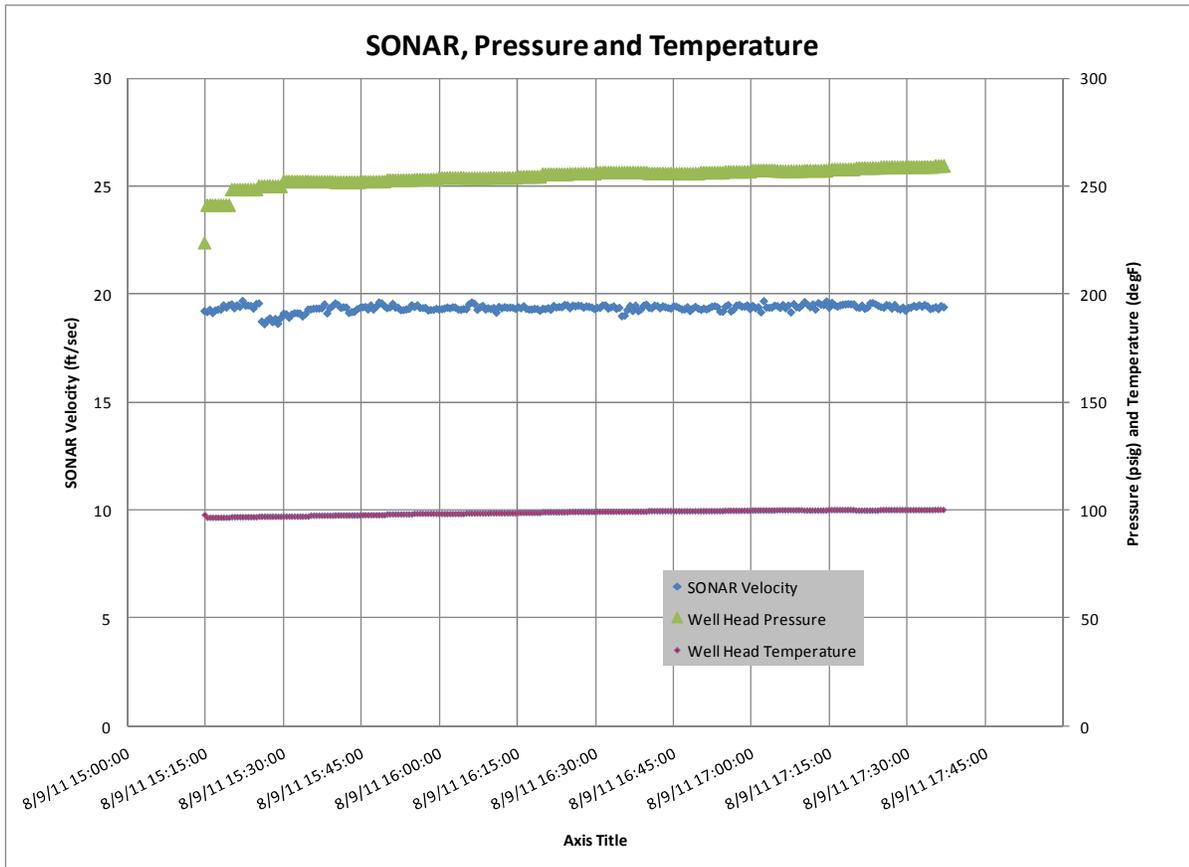
 <b>EXPRO</b> EXPRO METERS, INC.		Expro Meters, Inc.	DLG	29Sept2011
		Overview of Capabilities	Page 14 of 23	

using input watercut. This provides a measure of the oil rate at actual conditions. A shrinkage factor calculated by the black oil model is applied to report oil rate at standard conditions. The gas and water rates associated with the produced oil are then inferred from the measured oil rate.

Figure 14 shows a PassiveSONAR meter installed on the inlet flow line to a mobile well test separator. Figure 15 shows the flow velocity recorded by the SONAR meter as well as the pressure and temperature recorded for a three hour period over which a well test was conducted. PVT report indicated that the bubble point of the reservoir oil was 1935 psig and well test indicates a producing GOR of 335 scft/stb of oil with negligible water cut. This information was supplied to the TPS1000 which interpreted the sonar flow measurement in terms of produced oil and gas rates.

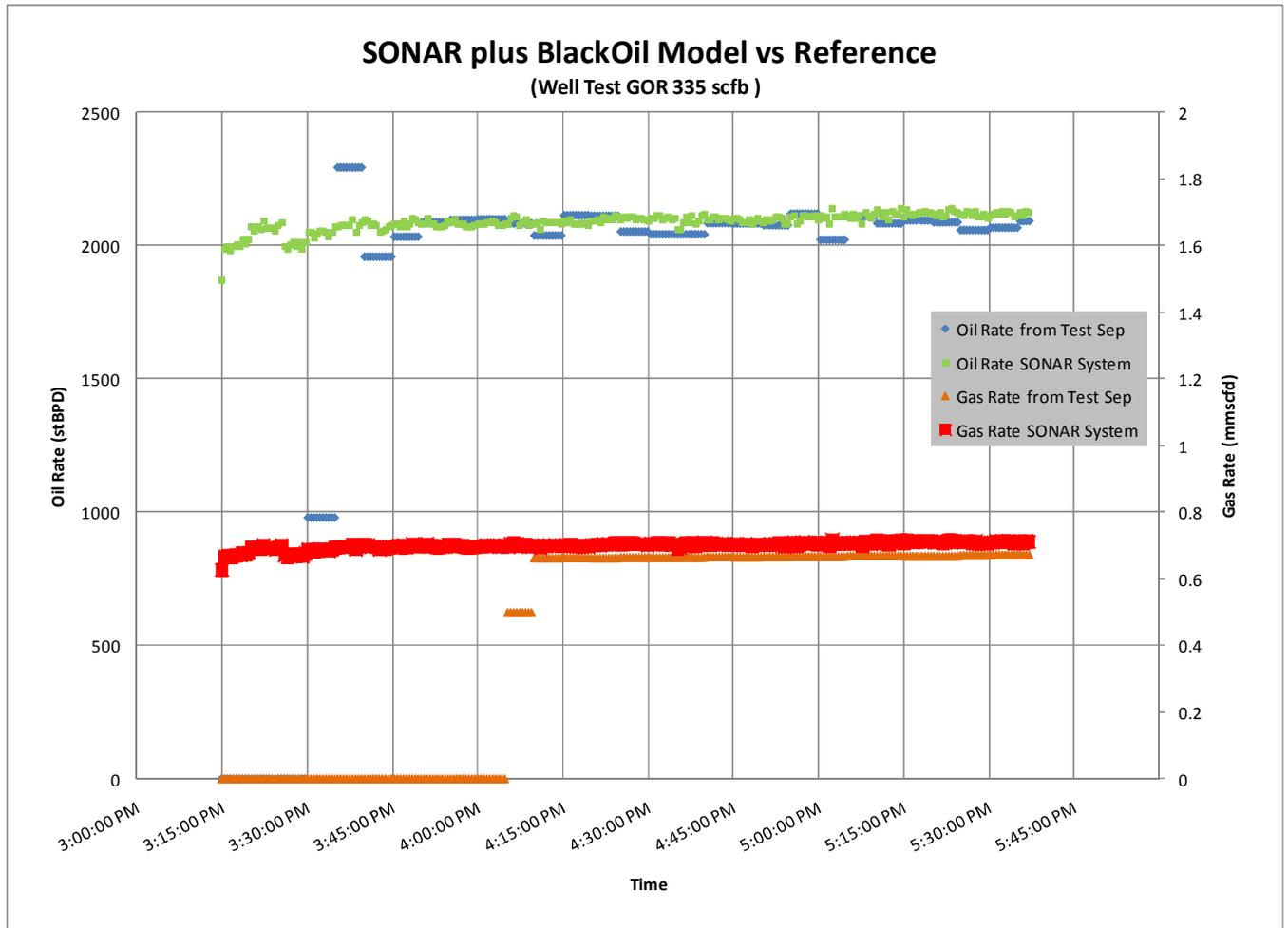


**Figure 14 SONAR Clamped-on to the Inlet flow line to a Portable Well Test Separator Package in Middle East**



**Figure 15: Pressure, Temperature, and SONAR Flow Velocity for 3 hour Well Test on Black Oil Well**

Figure 16 shows the reported oil and gas rates from the TPS1000 system compared to the oil and gas rates reported from the separator. As shown, the oil and gas rates reported from the SONAR surveillance system are in good agreement with the reference rates from the separator. Note that during the initial part of the test the SONAR meter began reporting results before the test separator was stabilized and readied to provide well test data. Note that the SONAR surveillance system is relying on a total volumetric flow rate measurement from the SONAR meter and input compositional information for interpretation of phase fractions. However, for wells for which reliable compositional information is available, SONAR based TPS1000 system may be able to provide the required surveillance on a significantly more convenient and cost effective basis.

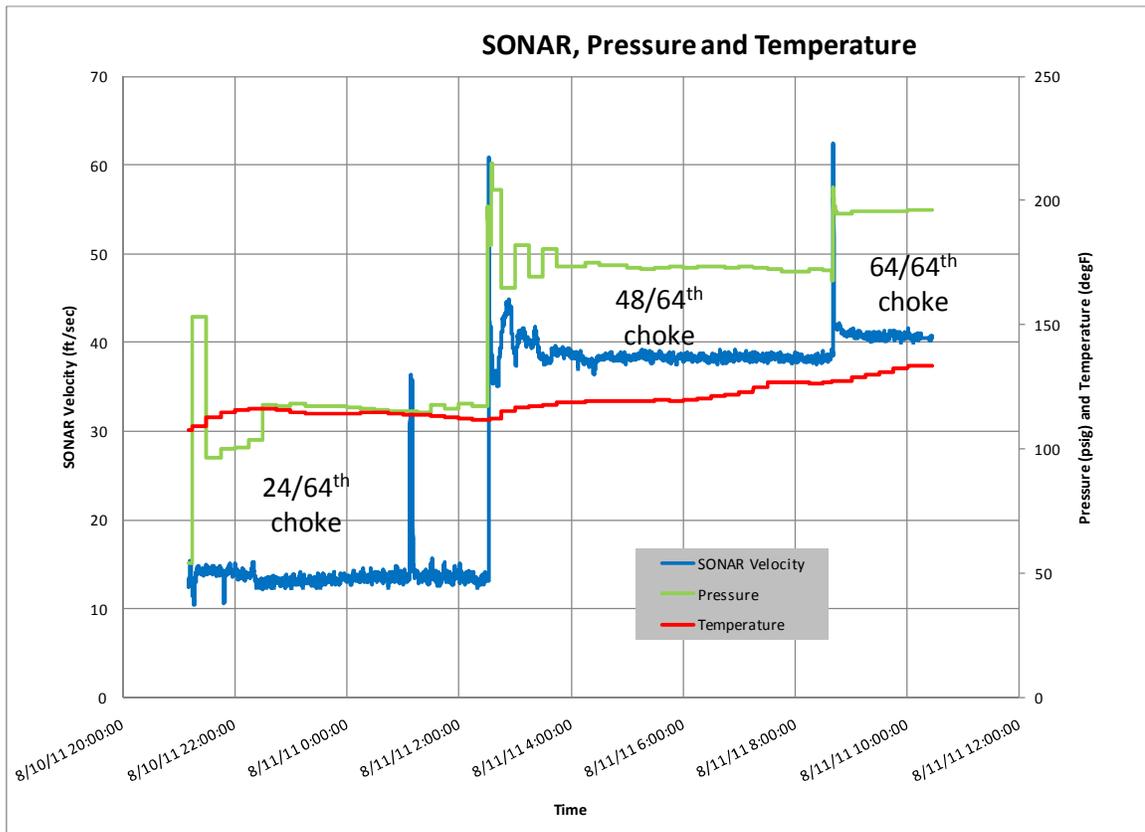


**Figure 16: Gas and Oil Rates Reported By TPS1000 Compared to Gas and Oil Rates from Well Test Separator for 3 hour Well Test on Black Oil Well**

Figure 17 shows a PassiveSONAR meter installed on the inlet flow line to a mobile well test separator in Iraq in August, 2011. Figure 18 shows the flow velocity recorded by the SONAR meter as well as the pressure and temperature recorded for a three hour period over which a well test was conducted. The choke was set at three points during the test: 24/64 at start up, then opened to 48/64 and finally to 64/64. PVT report indicated that the bubble point of the reservoir oil was 2353 psig and well test indicates a producing GOR of 708 scft/stb of oil with negligible water cut. This information was supplied to the TPS1000, which interpreted the sonar flow measurement in terms of produced oil and gas rates.

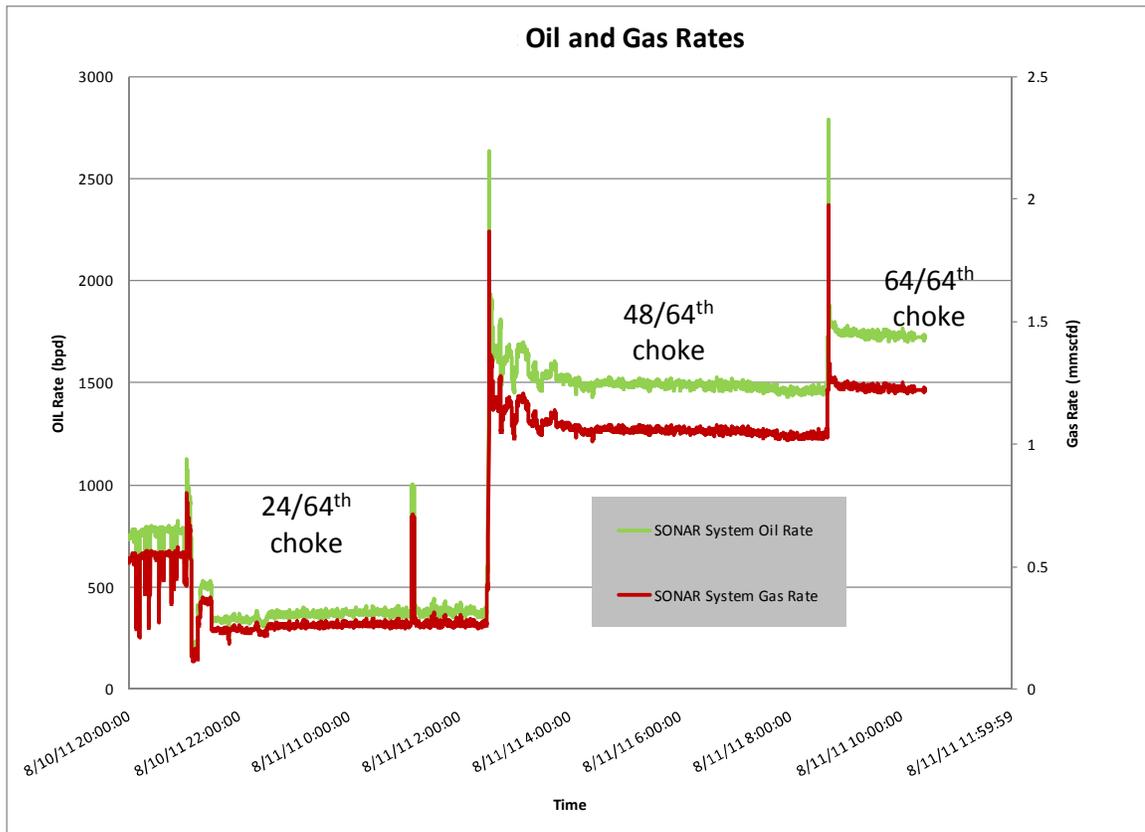


**Figure 17 Clamped-on to the Inlet flow line to a Portable Well Test Separator Package in Iraq**



**Figure 18: Pressure, Temperature, and SONAR Flow Velocity for 3 Hour Well Test**

Figure 19 shows the reported oil and gas rates from the TPS1000 system during the test period. As shown, the oil and gas rates reported from the SONAR surveillance system increase as the choke is opened. Note that the velocity as measured by the SONAR meter increases in direct response to the opening of the choke. Note that the SONAR surveillance system is relying on a total volumetric flow rate measurement from the SONAR meter and input compositional information for interpretation of phase fractions. The client reported that the rates reported by the TPS1000 system were in close agreement to the test separator rates, although the test separator data was not made available to Expro.



**Figure 19: Gas and Oil Rates Reported By TPS1000 Compared to Gas and Oil Rates from Well Test Separator for 3 hour Well Test on ZFOD well ZB3**

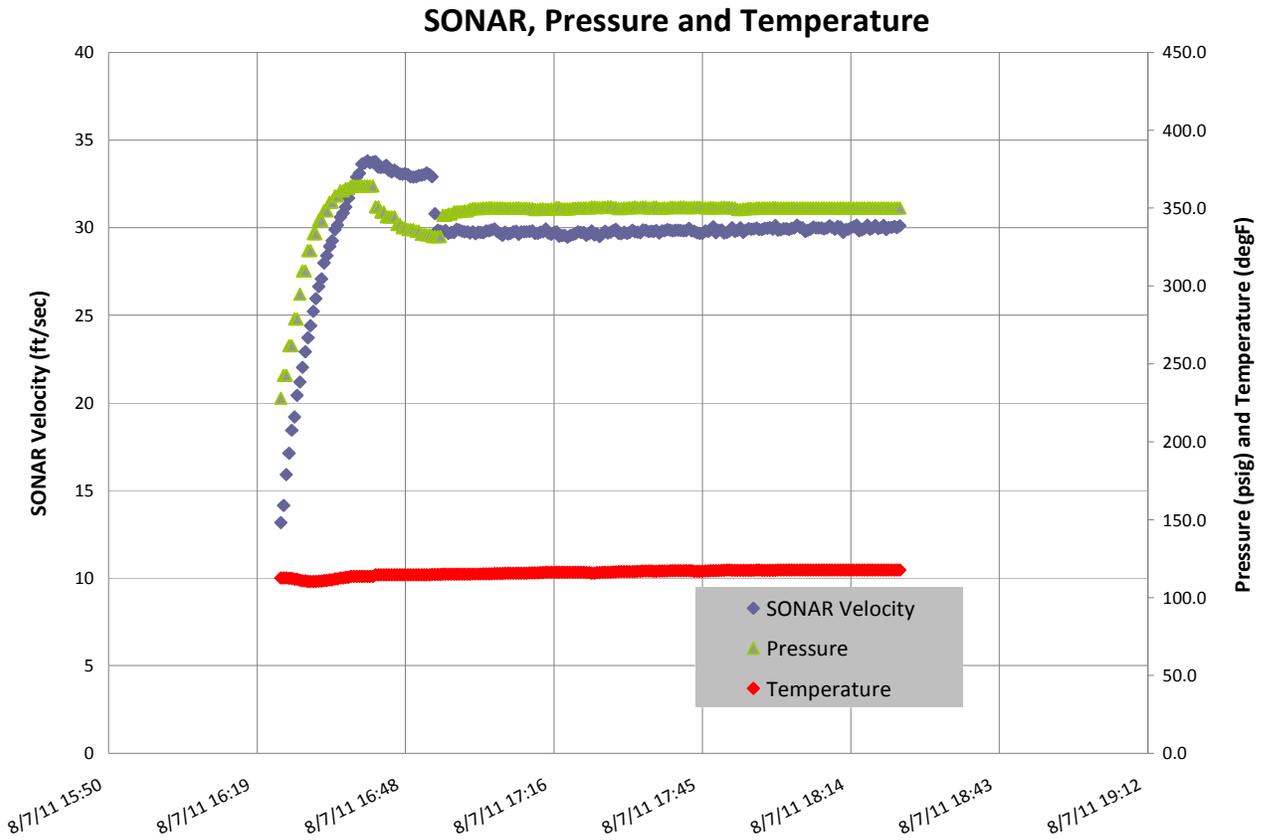
#### 4.5 ESP Lifted Oil Wells

Well head surveillance for oils wells with electrical submersible pumps (ESP) is important to ensure proper installation and operation of the ESP and to measure the performance of the ESP relative to the expected production. For ESP surveillance, Expro Meters employs the TPS1000 System and “black oil” models for oil wells (as described above) to interpret the output of SONAR meter using flow line pressure, temperature and well bore composition in terms of flow rates of gas, oil and water at standard conditions. This approach has proven to be successful for ESP surveillance in the Middle East, where reservoir conditions are compatible with this approach.



**Figure 20: SONAR meter installed on an ESP Well in Middle East**

Figure 20 shows a PassiveSONAR meter installed on the well head tubing of an ESP lifted well in the Middle East. Figure 21 shows the flow velocity recorded by the SONAR meter as well as the pressure and temperature recorded for a three hour period over which a well test was conducted. PVT report indicated that the bubble point of the reservoir oil was 2353 psig and well test indicates a producing GOR of 558 scft/stb of oil with negligible water cut. This information was supplied to the TPS1000, which interpreted the sonar flow measurement in terms of produced oil and gas rates.



**Figure 21: Pressure, Temperature and SONAR Flow Velocity on ESP Well in Middle East**

Figure 22 shows the reported oil and gas rates from the TPS1000 system compared to the oil and gas rates as the ESP was switched on and ramped to 49 Hz rate. As shown, the oil and gas rates reported from the SONAR surveillance system are in approximate agreement to expected flow rates as derived from pump curves. The SONAR surveillance system is relying on a total volumetric flow rate measurement from the SONAR meter and input compositional information for interpretation of phase fractions. However, for wells for which reliable compositional information is available, SONAR based TPS1000 system may be able to provide the required surveillance on a convenient and cost-effective basis relative to other alternatives, such as separator based well test packages or in-line multiphase flow meters. The SONAR with TPS100 system measures well flow without shutting in production. Frequent shut-in and re-starts of ESP's can be problematic to the well and the mechanical integrity of the pump.

### SONAR Oil and Gas Rates

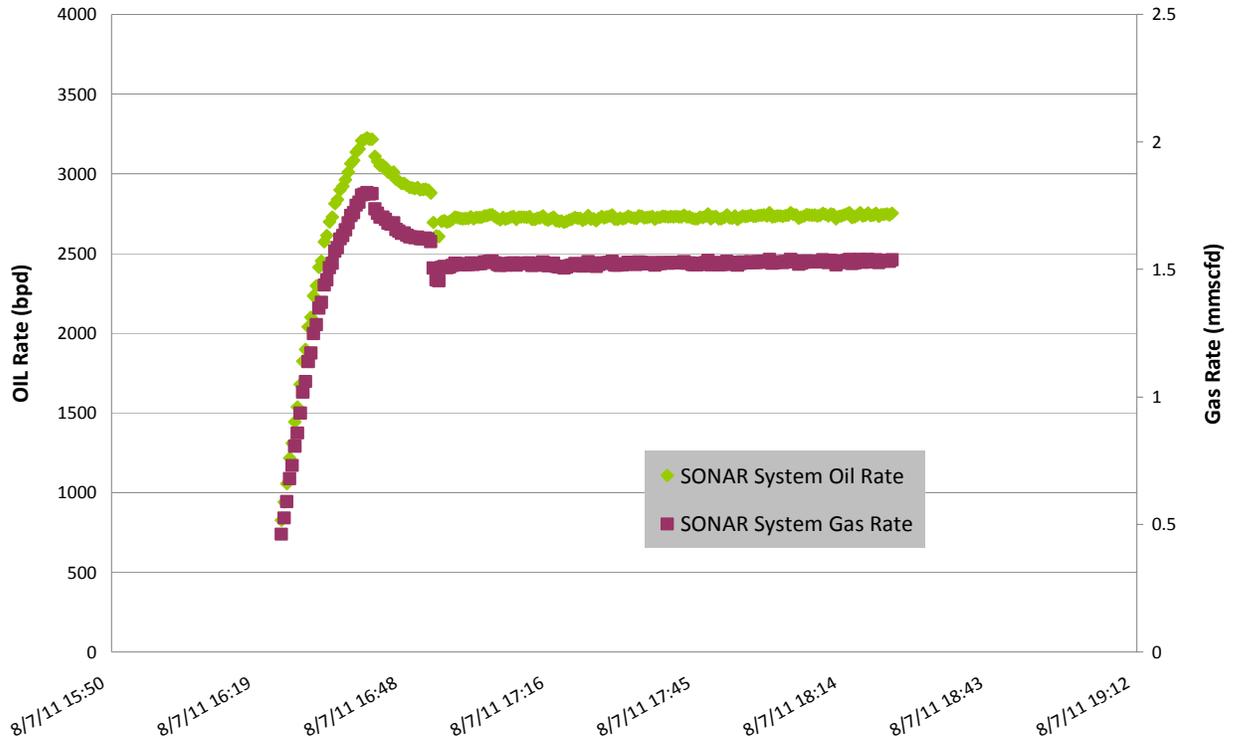


Figure 22: Gas and Oil Rates Reported By TPS1000 Compared to Gas and Oil Rates for 3 hour Well Test on ESP Lifted Oil Well

 <b>EXPRO</b> <small>EXPRO METERS, INC.</small>		Expro Meters, Inc.	DLG	29Sept2011
		Overview of Capabilities	Page 23 of 23	

## 5 Proprietary Technology and Intellectual Property

Expro Meters, Inc. (a wholly owned subsidiary of Expro Group) owns all necessary patents and licenses to sonar flow measurement technology for the oil and gas fields of use (except down-hole measurements). Expro Meters owns or has rights to dozens of patents covering the manufacturing and use of sonar flow measurement. These patents and licenses are exclusive to Expro Meters for oil and gas wellhead application. No other company can offer ActiveSONAR or PassiveSONAR for clamp-on oil and gas wellhead surveillance.

In addition to its proprietary patent and license position, Expro Meters has unique know-how which it employs in its non-intrusive wellhead surveillance products and services. This know-how is proprietary and, we believe, unavailable from any other source.

The PVT/Equation of State multiphase flow model employed by Expro Meters is essential in order to derive oil, gas and water rates. These models are built on proprietary software and are integrated with our sonar meters in a proprietary manner. To the best of our knowledge, no other vendor couples a clamp-on meter with multiphase flow interpretation.

Expro Meters offers its SONAR meters and multiphase software as a package operated by full trained and certified SONAR surveillance technicians. To the best of our knowledge, no other company offers a full service well testing package inclusive of non-intrusive metering, multiphase flow software specifically designed for SONAR wellhead surveillance, and trained technicians to perform the well test.

Several vendors offer clamp-on flow meters which are not specifically designed for wellhead applications. These flow meters have been available in the market for decades and have been used for single phase flows with some success. It is widely recognized in the flow meter industry, particularly among the oil and gas sector, that these flow meters have achieved very limited success in multiphase flow regimes.

## 6 Summary

Expro Meters Total Production Surveillance (TPS1000) system is a non-intrusive well head surveillance system that is capable of measuring production and injection rates from a wide range of wells including gas, gas condensate, and black oil wells.

The system uses multiphase tolerant, non-intrusive SONAR meters in conjunction with user supplied composition information to determine gas, oil and water rates. The TPS1000 is applicable to single phase and multiphase flows.