APPLICATIONS OF REAL-TIME WELL MONITORING SYSTEMS

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Introduction

It has been an accepted industry practice to utilize continuous measurement in the control and optimization of production facilities, however upstream reservoir and production Engineers are challenged to make important decisions based on little or no downhole data.

The development of real-time well monitoring technologies for land-based applications has furthered Engineer's ability to make pro-active decisions based on continuously monitored bottomhole parameters including pressure, temperature and flow.

This paper will provide an understanding of the emerging applications of continuous well monitoring related to production optimization, pump control, well stimulation and reservoir development. Casing and tubing conveyed monitoring systems are also discussed. Where possible, actual client case studies will be used to quantify the value achieved through utilization of these technologies.

MORE^{C} and MORE^{CEX} Casing Conveyed Applications

MORE^{C} Casing Conveyed Well Monitoring System

Casing conveyed systems utilize integral pressure and temperature sensors located within a casing mandrel (Figure #1).

Figure #1 – MORE^{C} (Casing Conveyed) Well Monitoring System

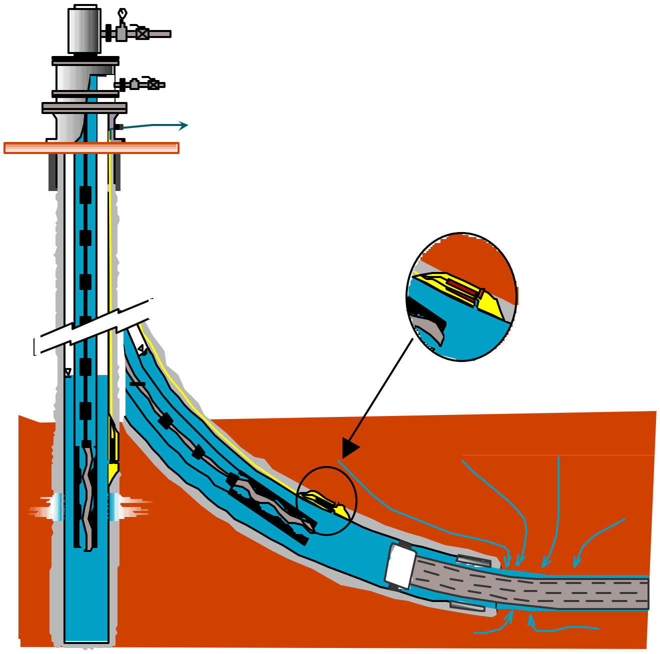

Figure #2-MORE^{C} System with Internal/External Measured Pressure and Temperature

The tool can be configured to provide internal, external or concurrent external and internal pressure measurements from one or more zones (Figure #2).

The casing conveyed monitoring system is commonly run as part of the intermediate casing string. It provides the understanding of operational pressures and temperatures associated with drilling, cementing and well stimulation procedures. In many cases, cementing pressures will have exceeded reservoir pressure, which significantly hinders production. Figure #3 (following page) shows the common occurrence of cementing wells in excess of formation fracture pressure.

Accurate knowledge of bottomhole pressures is especially important during underbalanced

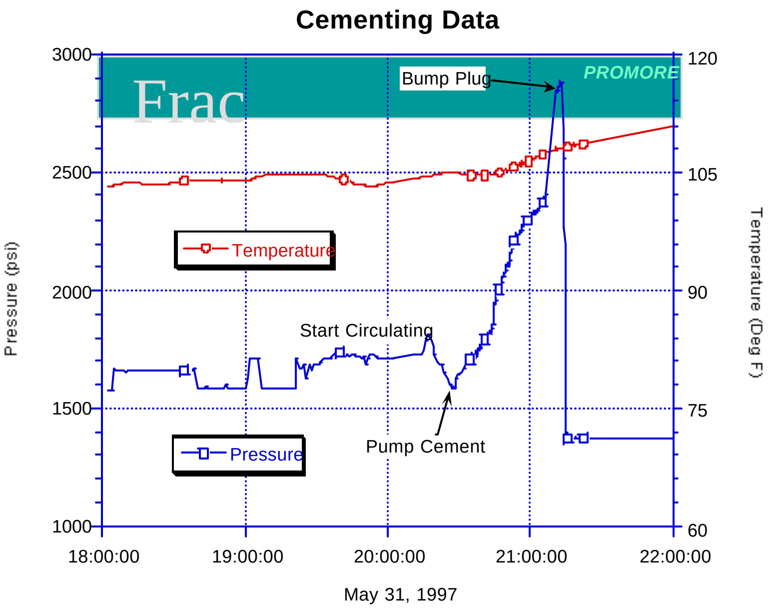

Figure #3 – Cementing Pressures in Excess of Formation

drilling of the production zone, where excessive pressure has been known to cause formation damage and cementing problems. Figure #4 shows the relationship of internal and external pressure and temperature during cementing and drilling the horizontal section of a well.

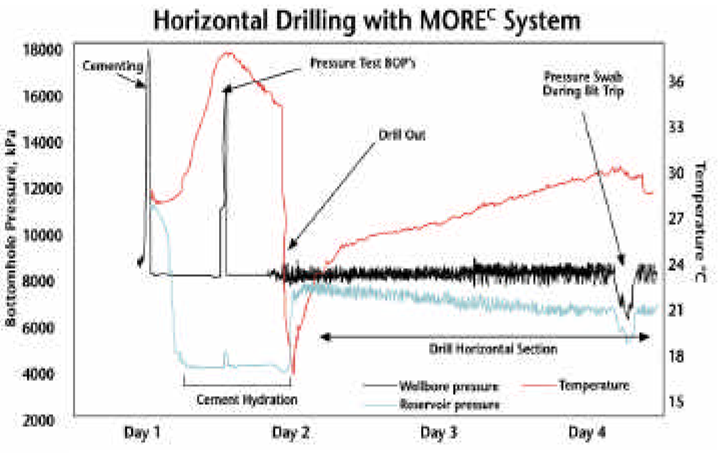

Figure #4 - Pressure and Temperature Measurement with the MORE^C System

Casing conveyed monitoring systems have been used for gas lift optimization and control in remote wells in Lake Maraicaibo, Venezuela. Continuous bottomhole pressure is utilized to control gas injection and subsequent production rates. Production rates are controlled remotely on a production platform from over 120 miles away.

Applications for standard casing conveyed tools have also included disposal well monitoring where operators want to maintain injection pressures that are close to, but not exceeding formation fracture pressure. This allows for the maximum injection rates possible without compromising the well or injection zone. Pro-active assessment of disposal zone skin migration and formation plugging from continuous monitoring of bottomhole pressure can reduce the costs associated with disposal zone workovers. Being external to the production environment, casing conveyed monitoring systems are ideal in applications where completion designs are tight or where frequent workovers are anticipated.

Beyond the initial understanding of pressure associated with drilling and well stimulation, casing conveyed tools provide continuous pressure and temperature data, which can be used for Production and Reservoir Engineering purposes for the life of the well.

MORE$^{\text{CEX}}$ (Casing Conveyed Explosive) Well Monitoring System for Reservoir Monitoring

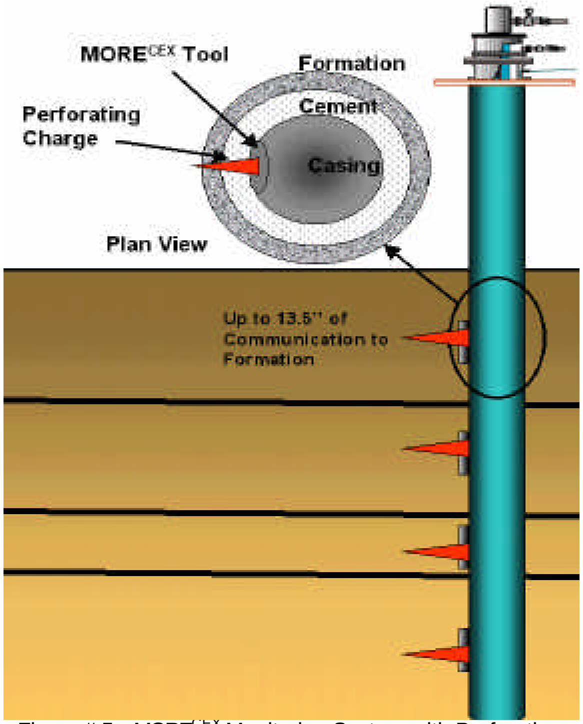

Figure # 5 - MORE$^{\text{CEX}}$ Monitoring System with Perforating Charge System

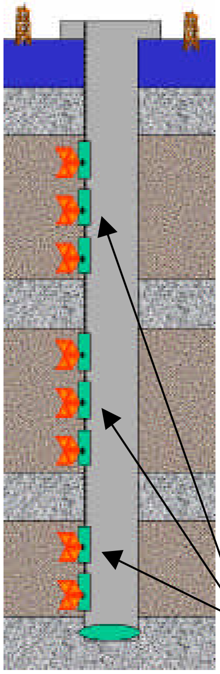

Figure #6 - Eight Pressure Measurement Points

The MORE$^{\text{CEX}}$ Monitoring System allows for the deployment of casing conveyed instrumentation equipped with a perforating charge that ensures up to 13.5'' of communication is achieved for external reservoir pressure measurement (Figure #5).

One operator utilized a MORE$^{\text{CEX}}$ System in the observation well of an enhanced oil recovery process known as "WAG" or water alternating gas injection. Three separate zones are continuously monitored using a total of eight pressure and temperature sensors (Figure #6). Understanding of reservoir transmissibility and the overall effect on oil production was evaluated long term during the WAG process.

Figure #7 shows pressure and temperature response over a one month period from eight monitoring points.

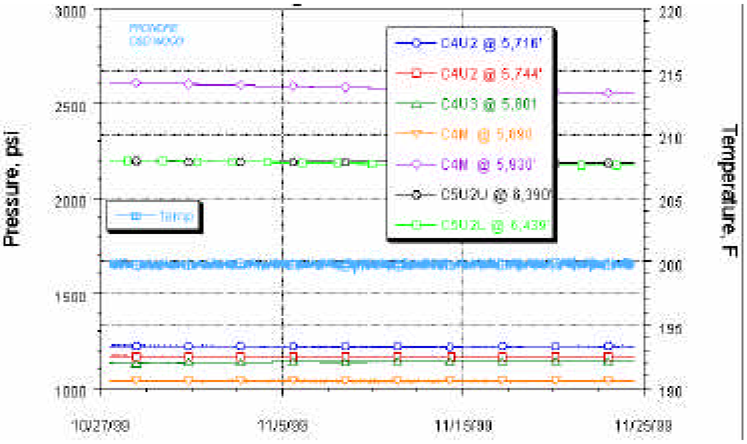

Figure # 7 – Characteristic Data Example – MORE$^{\text{CEX}}$ Tool

MORE$^{\text{T}}$ (Tubing Conveyed) Monitoring Applications

Tubing conveyed monitoring systems allow for the deployment of multiple pressure and temperature sensors anywhere along a production tubing string (Figure #8).

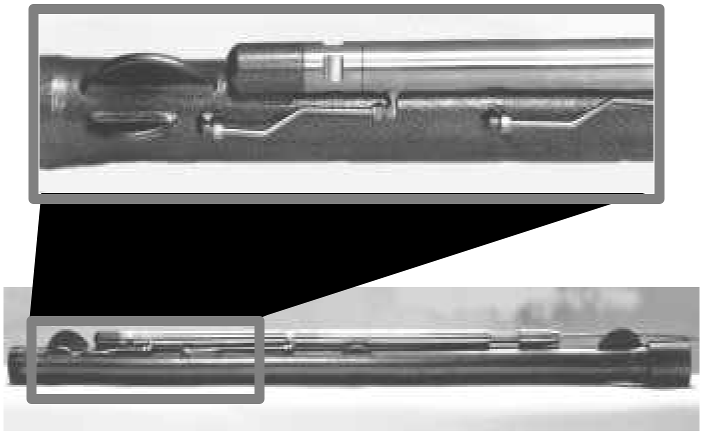

Figure #8 – MORE$^{\text{T}}$ (Tubing Conveyed) Well Monitoring System

Applications for this system have been focused primarily on production optimization, pump control, well stimulation, enhanced oil recovery and long term reservoir monitoring. Used in conjunction with downhole flow meters, tubing conveyed monitoring systems provide accurate pressure, temperature and flow data. Flow monitoring is accomplished using either differential pressure or positive displacement meters.

Optimization of Fracturing Operations

The utilization of continuous bottomhole pressure monitoring for fracturing operations provides an opportunity to design and deliver better fracs in the field. It is well known in the industry that the calculation of flowing bottomhole pressure from surface measurement is not an accurate science. Accuracy is limited by our ability to predict friction losses caused by frequent use of small tubulars and by the increasing utilization of more complex gel chemical fracture fluids. We rely on the continual evolution of software models to help predict the response of proposed fracturing programs in the field. Although improvements have been made in fracture modeling, there is no substitute to the continuous monitoring of bottomhole pressure during fracturing operations.

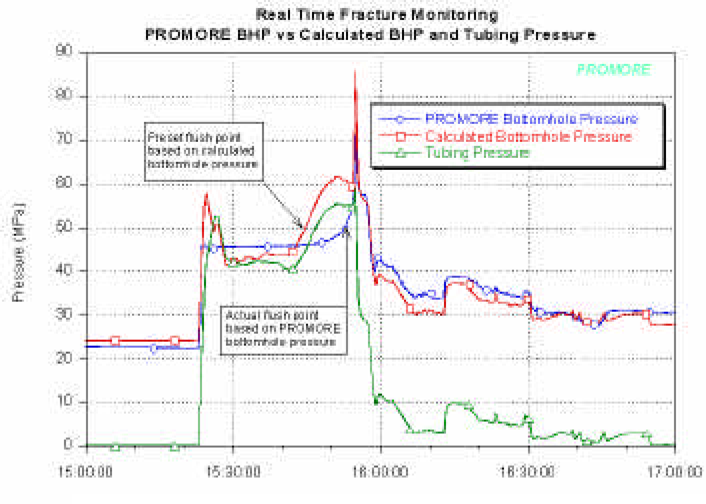

Figure #9 – Comparison of Actual vs. Calculated Bottomhole Pressure

The ability to understand bottomhole pressure and temperature during a frac allows operators to pump the correct amount of chemical and proppant into the formation, reducing the instances of tubing string sand-in or the under pumping of sand into the formation. Figure #9, shows the variance that occurs between calculated (modeled) bottomhole pressure and actual (measured) bottomhole pressure during a frac operation. In this case, this operator without access to true bottomhole pressure would have *under-pumped* the necessary amount of proppant to properly fracture the well. This of course could lead to reduced well productivity or the need to re-stimulate the well. Conversely, the “sanding-in” of frac strings is caused by *over-pumping* the necessary volume of proppant into the formation. This results in increased costs associated with sand cleanouts following the frac.

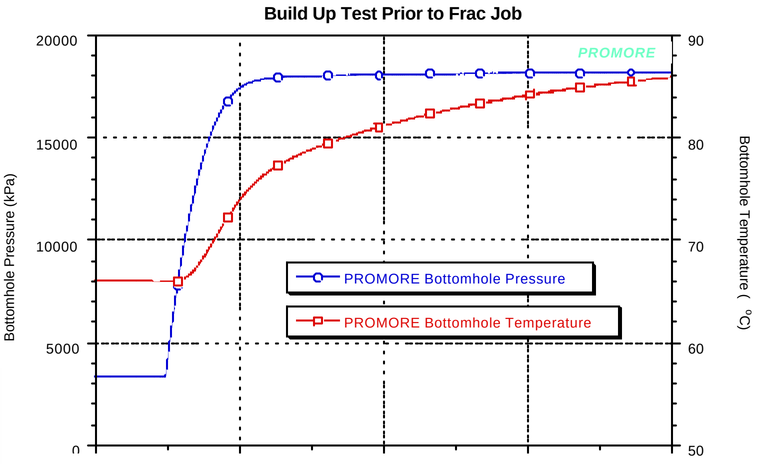

Figure #10 – Build-Up Test Prior to a Frac Job

Continuous monitoring provides accurate data that can be utilized for pre-frac design purposes (Figure #10, #11). This supports the overall goal of optimizing well fracturing effectiveness and increasing well productivity.

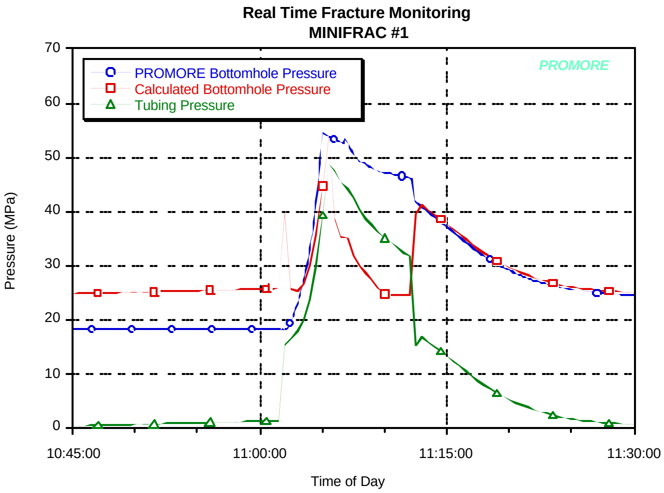

Figure #11 – Mini or Data Frac Prior to Main Frac

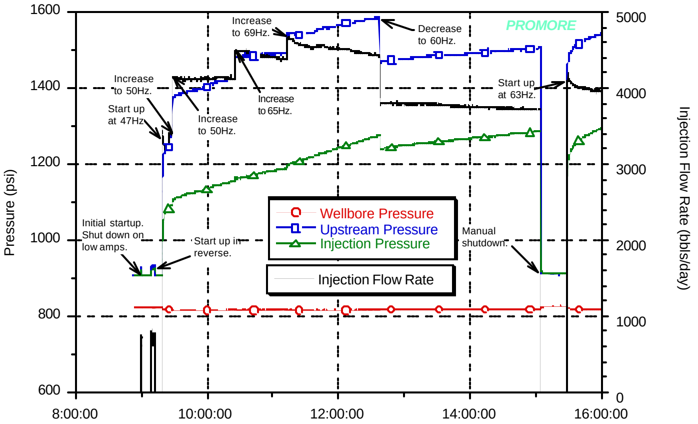

Figure #13 – Characteristic Data Response During Proper Operation of a Downhole Oil Water Separator

Downhole Oil/Water Separator Operations

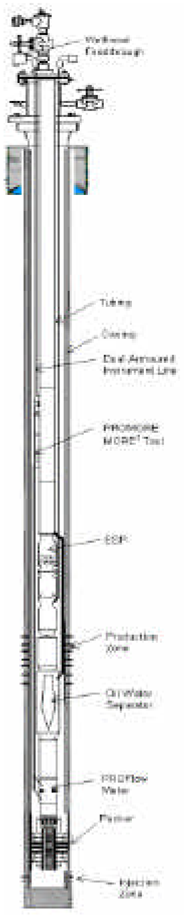

Figure #12 – Downhole Oil/Water Separation System with Continuous Monitoring

Developed in 1992 by C-FER (Centre for Engineering Research Inc.), the downhole oil water separator utilizes a hydrocyclone separator, which provides an effective means to separate oil from high water cut fluids insitu. This allows for the production of lower water cut oil to surface and for the disposal of water into a zone contained in the same well where the separation process occurred (1). Overall economics are achieved by not having to produce, treat and dispose of large volumes of water at surface, concurrent with the production of large volumes of concentrated oil.

Of the commercially available DHOWS systems today, many utilize the MORE^T System (Figure #12), which provides insitu monitoring of pumping system performance. Differential pressure is monitored across a flow restriction that is used to provide calculated flowrate, volume and flow direction during the injection process. Figure #13 shows what can be expected from the monitoring of a properly operating downhole oil water separator. The data demonstrates the relationship between pump speed, injection rate, injection pressure and wellbore pressure. The relationship although complex is critical to the operation of the downhole equipment. It is also important to understand when equipment in not operating properly as shown in Figure #14. In this example, the pump was initially started in reverse (no increasing pressure) and then the system experienced injection zone plugging, indicated by increasing pressure and reducing flow rate.

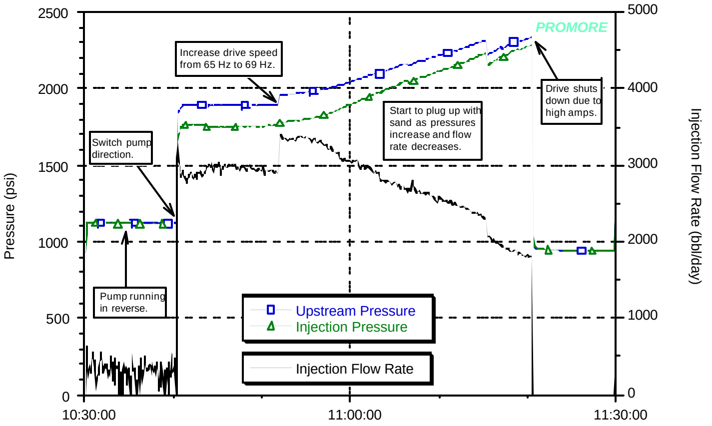

Figure #14 – Characteristic Data Response – Pumping in Reverse and Injection Zone Plugging

Injection Pressure Support Without Pipelines and Facility Costs

Localized injection support is used to provide pressure support for offsetting oil well production where pipeline and facility costs are not economic. Also known as cross flooding, water produced from a lower or upper zone is pumped into an offsetting zone in the same well thus providing pressure support (Figure #15). Pump speeds can be optimized to increase or decrease injection rate. Continuous monitoring allows operators to understand the volumetrics associated with this operation, at the same time as providing increased safety for the pumping system(s).

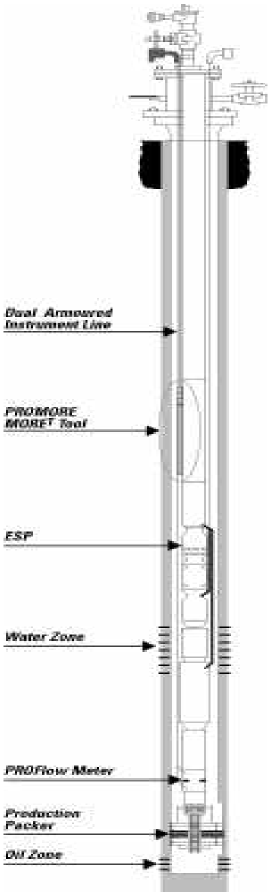

Figure #15 – Injection Pressure Support Well Monitoring System with Continuous Monitoring

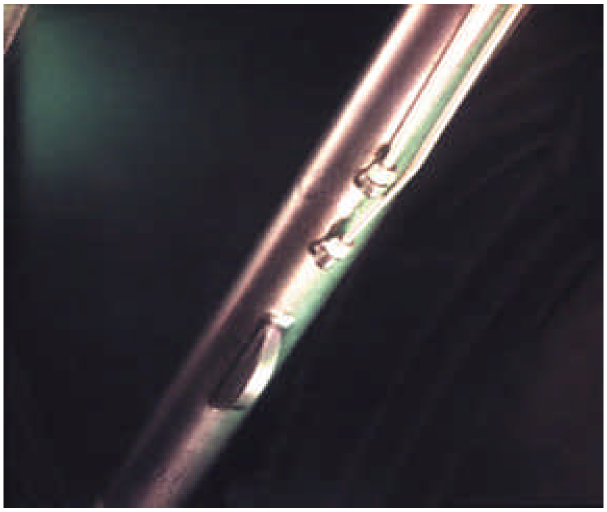

Figure #16 – PROFlow^{dp} Differential Pressure Flowmeter

Figure #17 – PROFlow ^{t} Turbine Based Flow Meter

Downhole flow monitoring in Downhole Oil/Water Separators or Injection wells is accomplished using a differential pressure flowmeter in applications where produced solids are expected (Figure #16). In applications where solids are not expected flowrate, volume and flow direction can be determined utilizing a turbine-based flow meter (Figure #17).

Optimization of Multiple Zone Tests

An operator determined that continuous monitoring of jet pump operations was an effective and efficient means to reduce workover costs and improve the understanding of multiple zone performance and jet pump operations$^{(2)}$ (Figure #18, following page). Understanding of individual zone performance is critical to determining remedial action to reduce water migration and improve well and field productivity.

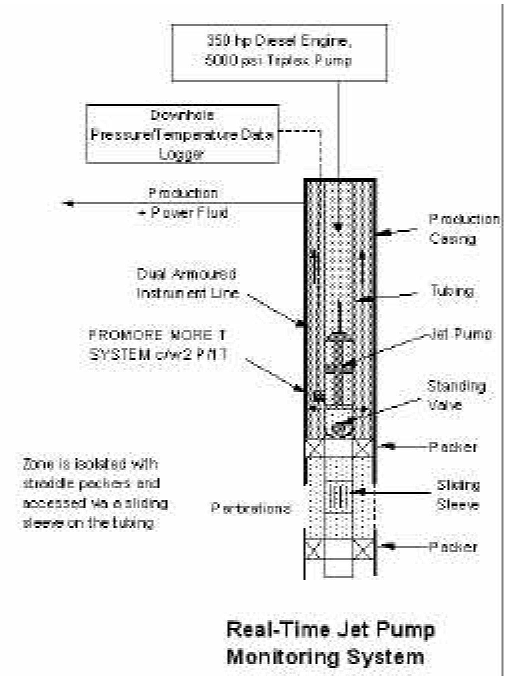

Figure #18 – Continuous Monitoring of Multiple Zone Tests

Jet pumps utilize high differential flow rates to create an annular lift capacity used to perform flow and build-up tests in multiple zones (Figure #19). Continuous monitoring provides an accurate understanding of when the zone has reached a stabilized drawdown and build-up profile. This pro-active assessment is not possible with memory-based tools and thus no opportunity exists to reduce the time and costs associated with jet pumping operations.

Preventing Sand Related Workovers Through Drawdown Control

In areas where unconsolidated sand formations exist, sand control is important. Drawdown control to reduce or eliminate sand production will extend well life and reduce associated workovers. Catastrophic failure of these sands has lead to the complete loss of wells. Bottomhole pressure has been used to control surface choke operation to reduce or eliminate sand migration.

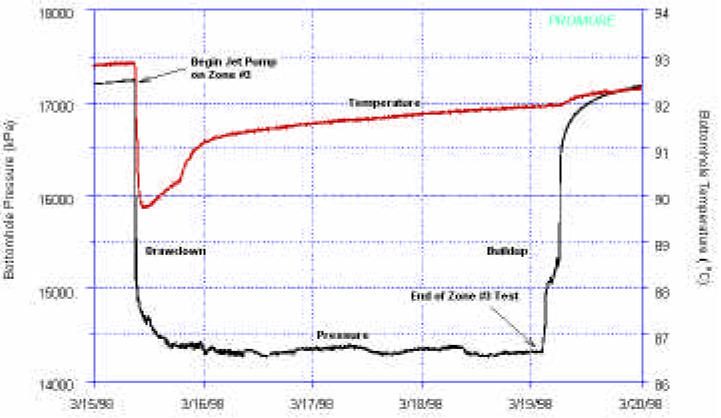

Figure #19 – Actual Client Data During Evaluation of Zonal Performance

Figure #20 shows the pressure response indicative of a catastrophic sand failure. Drawdown pressure was exceeded beyond an optimum point, resulting in a costly workover.

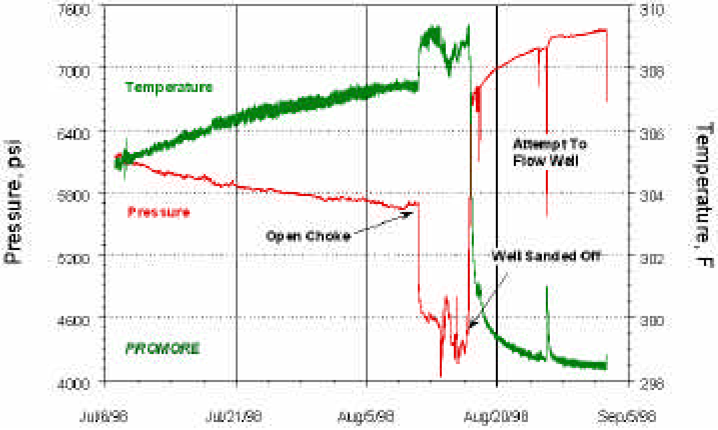

Figure #20 – Preventing Sand Related Workovers through Drawdown Control

Reservoir Development

Reservoir development has greatly benefited by the improved access to information afforded by continuous monitoring. In the following example, an operator was unsure of the commercial viability of a remote oil field and wanted to pro-actively understand its potential. Better understanding of reservoir performance was accomplished through the use of continuous monitoring systems. A comparison of the costs of continuous monitoring vs. conventional memory tools and wireline operations found continuous monitoring to be cost competitive (3). Correlation of actual data with the numerical simulator confirmed the necessity for continuous well monitoring during development of the field (Figure #21, following page). Evaluation of reservoir transmissibility dictated that reservoir drawdown must be consistent in conjunction with the monitoring and accurate control of pumping equipment.

Production Optimization

Continuous monitoring represents a significant opportunity to increase well production. As an example, an operator in Venezuela improved field productivity by over 28%, by establishing a closer link to jet pump performance and reservoir productivity(4).

Correlation of bottomhole pressure with surface measured operational parameters including pump speed, torque, efficiency and power consumption represents an opportunity to maximize well productivity and reduce operating costs. Figure #22, shows the effect of pump speed on operating costs. Increasing pump speed beyond a stabilized bottomhole pressure will cause increased power consumption, reduced pump efficiency and increase peak wear and will not result in increased oil production.

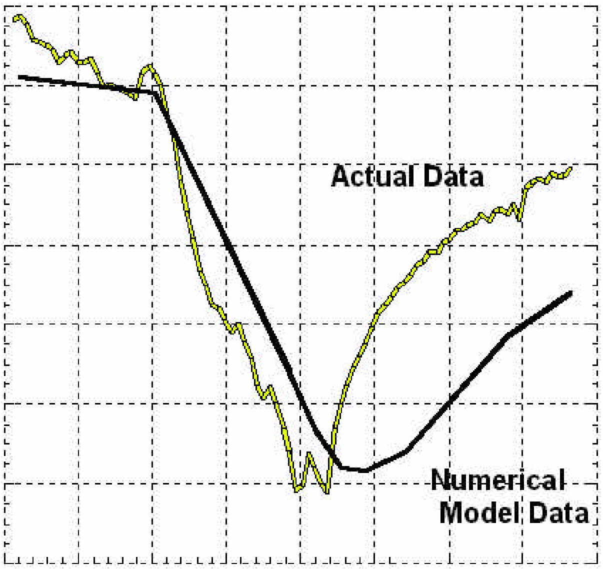

Figure #21 – Comparison of Numerical vs. Actual Data During Continuous Well Monitoring

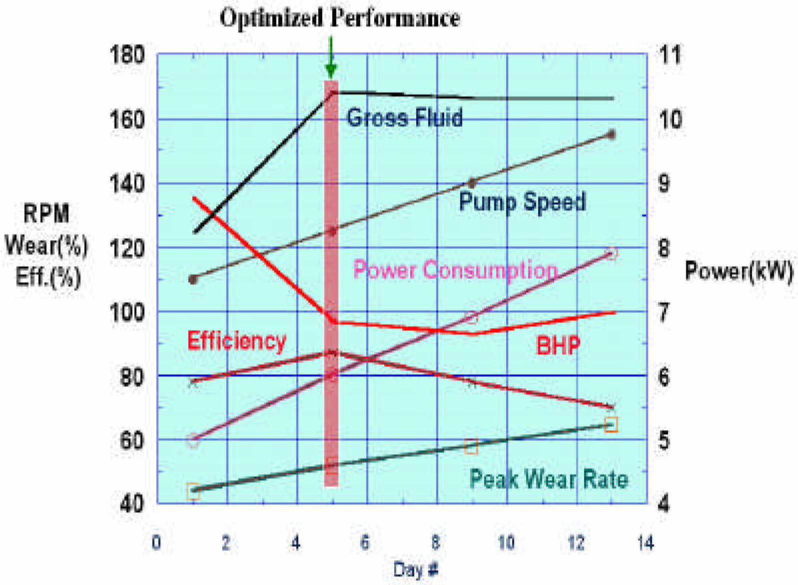

Figure #22 – Production Optimization Using Continuous Monitoring of Bottomhole Pressure

Figure #23 shows the characteristic response of a pump that is automatically controlled based on bottomhole pressure. Increasing bottomhole pressure will cause the pump to speed up, effectively capturing incremental oil production. Conversely, decreasing pressure will cause the pump to slow down when inflow is reducing or has completely stopped. This results in the most effective means to safely operate pumping wells.

Characteristic Response of a Pump Controlled on BHP

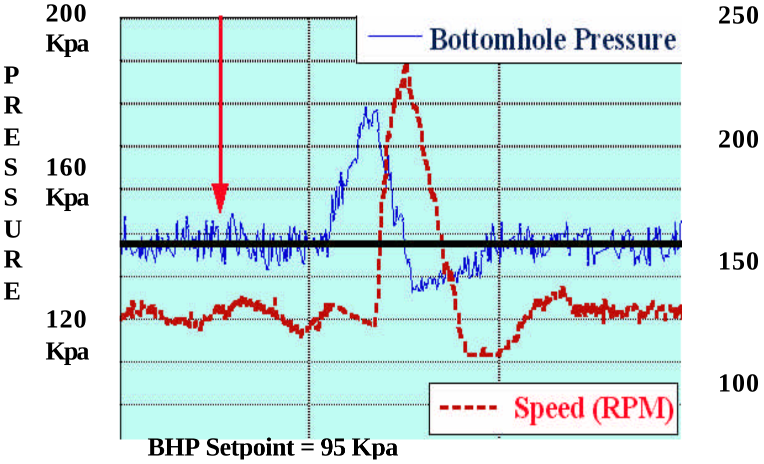

Figure #23 – Incremental Oil Production Resulting from Automatic Pump Speed Control

Use of acoustic fluid measurement equipment is common to establish fluid levels in pumping wells. The resultant fluid level indicated by these devices is used to manually adjust pump speeds. Figure #24 confirms a common measurement error that occurs with acoustic fluid level equipment. Without continuous monitoring, this Operator would have believed 7 joints of fluid existed in the well when in fact the well was already in a pumped off condition as indicated by the bottomhole pressure. This problem is especially compounded in heavy oil, slanted or horizontal wells or those with high gas oil ratios.

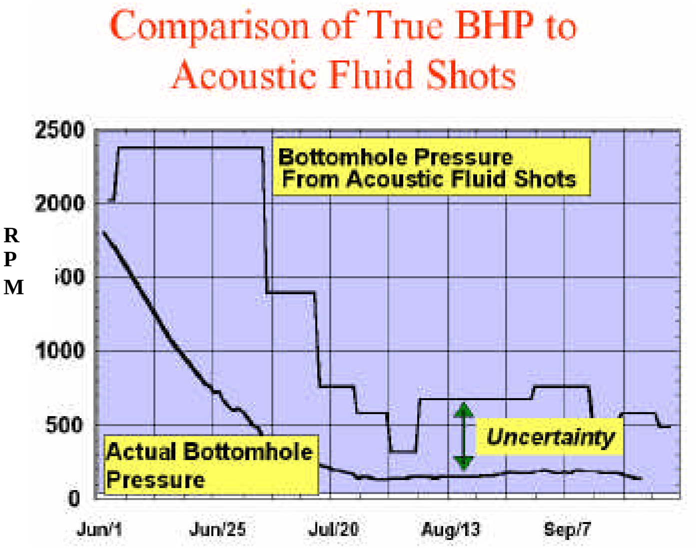

Figure #24 – Comparison of True BHP to Acoustic Fluid Shots

Reservoir Surveillance

Continuous well monitoring supports a more pro-active approach to managing reservoirs towards the ultimate goal of improving the recovery of hydrocarbons. Access to continuous pressure, temperature and flow data allows reservoir Engineers to better understand overall reservoir condition and take a more pro-active approach to managing the resource.

Improved data access has resulted in the modification of drilling fluid programs to reduce skin and subsequent formation damage on a more pro-active basis(5). Reservoir characterization and modeling also becomes more efficient through better access to continuous data. This has resulted in new understanding regarding the potential to drill wells in more productive areas of the reservoir vs. less productive ones(6). Improved characterization provides the potential to drill less wells while increasing reservoir recovery. Continuous monitoring provides better knowledge of pressure response or interference between wells, which can support a more cohesive approach to field development.

The use of continuous monitoring in support of Reservoir Engineering in offshore environments is justified by the higher risks associated with field development and the opportunity to realize higher field production. Monitoring in offshore environments has provided a number of benefits, including early assessment of water migration or other production problems and more accurate determination of boundaries, faults and other reservoir heterogeneities. Early detection of these factors confirmed by continuous monitoring, has resulted in pro-active adjustments to field development strategies. This results in improved cost management and better leverage towards improving reservoir recovery.

Summary

Continuous measurement of bottomhole pressure, temperature and flow represents a considerable opportunity to maximize well productivity and reduce operating costs. Those companies that have been early adopters of well monitoring technologies have benefited. Although the industry has been primarily focused on continuous monitoring in higher producing commonly offshore environments, many Operators are starting to realize the benefits of monitoring in lower producing areas. As presented in this paper, continuous monitoring with either casing or tubing conveyed systems, has been related to the understanding of real-time pressures associated with drilling, well stimulation, enhanced oil recovery, production optimization and Reservoir Engineering.

Whether the need is to reduce operational problems and increase the efficiency of well fracturing or utilize injection support schemes, downhole oil water separators or optimize well tests, continuous monitoring plays a valuable role. It is hoped that this paper provides a forum for Operators to continue to pursue the application of continuous monitoring in lower producing reservoirs.

Tim Conn graduated from the Southern Alberta Institute of Technology (SAIT) in 1982 and has held various technical research positions with Shell Canada Ltd. and Technifluids. His background in downhole instrumentation started in 1989, when he joined an industry leader in the development of electronic instrumentation for well testing purposes. He has written articles on downhole electronic pressure and temperature measurement, horizontal well monitoring systems and high temperature well monitoring for SAGD applications.

Tim's technical background, coupled with his experience in marketing and sales lead to his current position as Manager of Marketing for PROMORE Engineering Inc. In this role, Tim is responsible for PROMORE's global marketing efforts.

Terry Moffatt is a Professional Engineer, a member of APEGGA (Association of Professional Engineers Geologists and Geophysisists), CIM (Petroleum Society Canadian Institute of Mining), CHOA (Canadian Heavy Oil Association) and SPE (Society of Petroleum Engineers), with a degree in Mechanical Engineering and a Diploma in Petroleum Technology. He has an excellent understanding of the "grass roots" of the oil and gas industry, having worked in Drilling, Production, and Refining sectors. Terry started his career in the industry over twenty years ago as a roughneck on the drilling rigs and later became involved in optimizing drilling and production operations, and plant and refinery processes. He worked several years as a Research Engineer where he played a key role in several projects involving extensive reviews of field operating practices and implementation of production optimization techniques.

While working as a Research Engineer, Terry recognized the lack of quality data to support critical engineering decisions related to production optimization and reservoir management. This prompted the formation of PROMORE Engineering Inc., a company dedicated to the design and installation of real-time well monitoring systems.

Terry currently holds the position of President of the company and spends the majority of his time guiding the growth of PROMORE on a global basis. PROMORE is a technology company dedicated to the design, manufacture and installation of real-time monitoring systems for continuous reservoir monitoring and production optimization.

We would like to thank the contributions of the following individuals towards the information contained in this paper:

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(2)Tom Negenman, Anderson Exploration Ltd.
(3)Wes Siemens, Hans Jonasson, Wascana Energy Ltd. (a Canadian Occidental Company)
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