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Modern Concepts in Perforation Inflow Diagnostic (PID) Testing: A Safe, Green, and Cost-Effective Technique for Evaluating Pre-Frac Reservoir Parameters

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Abstract

Conventional completions and testing methods of low permeability gas reservoirs involve the cost and logistics of balanced and underbalanced perforating, next day stimulation treatment, surface production equipment, and the need for flaring during clean-up operations. In Canada, due to government regulations, operators will conduct the buildup test immediately after one or two day of clean-up operation. This practice has resulted in post-frac welltest analysis being masked by fracture fluid still present in the proppant pack and formation, resulting in misleading estimates of reservoir and fracture parameters important for production forecasting and completion evaluation.

Perforation Inflow Diagnostic, referred as PID testing, is a modern testing technique designed to deliver in a cost-effective manner valuable reservoir information such as: reservoir pressure, formation flow capacity, unstimulated gas inflow rate potential and near wellbore damage conditions prior to the fracture treatment. The advantages of PID testing are numerous: capability of accurate measurement of very low gas rates in low permeability (tight) gas wells (often reported as *too small to measure*), provides a safe testing environment, ensures secrecy and it defines itself as a green well testing procedure since it does not require flaring or venting of natural gas. PID testing is simply the surface and/or subsurface monitoring of the pressure response following **extreme underbalanced** perforating conditions, using electronic pressure recorders capable of high sampling rate. Unlike conventional testing procedures, the surface valve is closed during the entire test period and the formation fluids are produced into the closed chamber (casing and/or tubing volume). The measured pressures are converted to corresponding gas rates, based on the well-established closed

chamber theory. PID testing therefore allows the collection of pressure and rate data required to derive the in-situ matrix permeability, wellbore skin and reservoir pressure.

Introduction

In the Western Canadian Basin (WCB), drilling and completion operations are often complicated and limited due to spring thaw and restricted road access in the summer. As a result, a large number of wells are drilled and completed between the winter months of December to March. During these 4 months of high peak activity, wells are drilled, cased, perforated, stimulated, flow tested for evaluation and tied-in for commercial production. The completed intervals sometimes are suspended for up-hole potential, or abandoned due to disappointing production performance. As a cost reduction measure during the completion operations, the wellbore is filled with frac fluid prior to perforating. Although this practice can save rig time, it will make it practically impossible to differentiate a good quality reservoir response versus a poor reservoir response, immediately after perforation. Moreover, numerous operators are even foregoing the post-frac evaluation process by only conducting a single pressure measurement on the well for regulatory compliance and then placing the well immediately on production. Ideally, post-frac buildup evaluations should be performed 30 – 90 days after production to ensure proper clean-up conditions, however this practice is uneconomical due to the extended buildup durations required to achieve pseudo-radial flow conditions. Therefore, a large number of wells are completed based on historical practices or analogous offset wells. Open-hole or cased-hole logs and petrophysical analysis contribute to the identification and estimates of some reservoir parameters, providing values for net pay (h), effective porosity (Φ_{eff}), irreducible water saturation (S_w) and an indicator of permeability (k-index). Besides reservoir permeability, reservoir pressure is a key parameter in determining fluid selection and fracturing treatment size.

Additional variables such as formation reservoir heterogeneities, damage from drilling/cementing, chemical incompatibilities between completion and formation fluids, undersaturated reservoir conditions, under/over pressured reservoirs, etc affect the fluid selection during the stimulation process for low permeable gas wells. Conventional pre-frac welltesting of low permeable (tight) gas reservoirs have

limited application because frequently the wells are not able to sustain long enough measurable gas rates, or the reported gas rates are too small to measure (TSTM). On the other hand, post stimulation welltests in low permeable gas wells also pose restrictions regarding limited gas flared volumes due to environmental concerns and impractical build-up durations. Because of insufficient well cleanup and short build-ups, it was observed that permeability values determined from post-frac tests are often optimistic and therefore the well's production performance is lower than the production forecast predicted based on the welltest results.

Underbalanced perforating using wireline (E-line) or tubing conveyed (TCP) is commonly used throughout the industry to initiate production from high to moderate permeability gas wells. With the development and wide spread acceptance of underbalanced perforating, the development and analysis of downhole pressure, temperature and in-situ flow rate data during a perforating operation has evolved^{1, 2, 3}. In this paper, we will show the advantages of collecting surface and/or subsurface pressures during extreme underbalanced perforating to calculate closed chamber gas rates to obtain valuable reservoir parameters in low permeable (tight) gas wells.

Perforation Inflow Diagnostic (PID) testing analysis method is an extension (and specialization) of McKinley⁴ (afterflow-dominated pressure buildup analysis) and closed chamber drillstem testing methods developed by Lloyd Alexander⁵. Applied to deep tight gas reservoirs, the method of closed chamber (PID) testing has proven to be a very effective procedure as a pre-stimulation evaluation technique.

PID Development and Evolution

The method outlined in this paper is specifically applied to low permeable gas wells and used to analyze the period subsequently after perforating the zone of interest. Since the wellhead is shut-in during the test, this procedure presents itself as a safe, cost effective, and environmentally friendly technique that can be performed simply by using measurements of surface pressures.

As described in reference 6, PID testing for shallow gas wells can be an efficient, cost effective testing technique. The operation is rigless and only requires an evacuated wellbore with surface electronic pressure recorders. Fig 1 shows a typical wellbore schematic for shallow gas wells.

PID testing is also a safe choice for testing critical sour gas wells (Figure 2). With increasing environmental concerns of flaring sour gas wells, the tubing-conveyed perforating (TCP) assembly with packer provides a controlled and safe testing operation and is environmental friendly technique by eliminating or reducing flared volumes from sour gas wells. The technique ensures confidentiality and the elimination of unnecessary conventional surface testing hardware makes it a very cost effective procedure. Special subsurface pressure and temperature recorders are attached to the perforating drop bar and then dropped from the surface, through the tubing, to fire the perforation guns. Figure 3 shows the pressure and temperature response of tandem electronic pressure recorders dropped 3000 m from surface on a sour gas perforation test, using a TCP/packer assembly.

Testing of deep, tight gas formations is the most difficult due to impractical testing time requirements. A cost effective PID test, however, can be designed to obtain the necessary data for analysis using only 3 days of rig time (Figure 4). During day 1, the interval is perforated under extreme underbalanced conditions and the pressure response monitored to evaluate the gas inflow rate potential. Day 2, a downhole shut-in is achieved with recorders below a wireline retrievable (WR) plug in order to minimize the wellbore chamber volume. Day 3, the plug and recorders are retrieved.

Closed Chamber Theory

In low permeability gas wells, pre-frac gas rate measurements are generally too small to measure (TSTM). However, electronic surface pressure recorders are accurate and sensitive to pressure changes at high sampling frequency. In this paper, we present a testing technique and interpretation methodology on low permeability gas wells during the underbalanced perforating process. This method is particularly concerned with measuring the so-called "afterflow" pressures after perforating the well. Unlike conventional testing procedures, the surface valve is closed during the entire test period and the gas is produced into the closed chamber volume (casing and/or tubing). Figure 9 is from field example 2 showing both the pressure (left hand y-axis) and inflow gas rate (right hand y-axis) response from a typical PID test. The changing gas compressibility and the volume of the gas in the chamber account for the resistance to inflow (exerted by the gas that already occupies the wellbore chamber). As illustrated in Figure 9, the wellbore pressure increases as the reservoir continues to flow into the closed chamber (wellbore).

Closed chamber theory is based on the material balance equation,

$$q_{in} = q_{out} - \frac{dV}{dt} \quad (1)$$

which states that the fluid entering the "control volume" V (our wellbore chamber) from the reservoir (q_{in}) is equal to the amount of fluid produced at surface (q_{out}) minus a change in the volume of the gas due to changes in the chamber conditions (dV/dt). The definition of the isothermal compressibility of an ideal gas is,

$$c_w = -\frac{1}{V} \left(\frac{\partial V}{\partial p} \right) \quad (2)$$

The subscript "w" signifies the wellbore chamber. The isothermal condition assumes the average chamber temperature. Using the chain rule of calculus, we obtain the equation,

$$q_w = V_w c_w \frac{d p_w}{dt} \quad (3)$$

q_w is the flow rate in the wellbore chamber caused by the changing compressibility of the gas and the driving pressure gradient at average conditions. The product of $V_w c_w$ constitutes the so-called wellbore storage coefficient. Equation 3 then becomes the working equation for determining gas inflow rates during closed chamber conditions.

The combination of *maximum* underbalanced perforating conditions, the ability to monitor accurate surface pressures at high sampling rates and the simultaneous closed chamber gas rates provide the ability to observe a large number of rate and

pressure data points and their relationship, particularly at very early times during underbalanced perforating. Useful information such as perforation cleanup, filtrate inflow and general inflow characteristics can easily be detected.

Transient Analysis

Proper analysis of the pressure buildup response during perforation inflow testing requires that both pressure and rate be defined at certain conditions in order for an equating relationship to be developed. This is particularly true for gas since it has widely varying properties with changing pressure. We can equate this change in wellbore volume of the gas through Darcy's equation yielding,

$$q_m = q_w = -\frac{kh}{\mu} \frac{\partial p}{\partial r} \quad (4)$$

During perforation inflow tests, both pressures and flow rates are changing with time. Conventional pressure transient analyses methods require a constant rate (or constant pressure) solution in order for an analysis to be carried out. *Meunier, Wittman and Stewart*⁷ developed an equation for the infinite-acting radial flow equation for transient analysis based on Duhamel's principle (first applied by van *Everdingen and Hurst*⁸) to "normalize" pressure for variations in flow rate. This is essential in the analysis of afterflow data. The equation is,

$$p_{wD}(t_D) = \int_0^{t_D} \frac{\partial q_D(\tau)}{\partial \tau} p_{D}(t_D - \tau) d\tau + q_D(t_D)S \quad (5)$$

where t_D is dimensionless time, p_D is dimensionless pressure of the flow model, q_D is dimensionless flow rate, and S is skin factor.

The selected flow model is that of radial cylindrical flow in a homogeneous, infinite reservoir. The logarithm approximation to the solution at the wellbore is:

$$p_D(t_D) = \frac{1}{2} [\ln(t_D) + 0.80907] + S \quad (6)$$

Based on the work of *Simmons*² and *Tariq*³, and using normalized pseudo-pressures⁹, the working equation for gas then becomes,

$$p_{(pm)i} - p_{(pm)w} = \tilde{m} \left[\log_{10}(t) + \frac{\sum_0}{q_{ref}} + \frac{q(t)}{q_{ref}} S \right] \quad (7)$$

where,

$$\begin{aligned} \sum_0 = & \sum_{j=1}^{n-1} \left[\left(\frac{q_{j+1} - q_j}{t_{j+1} - t_j} \right) \left((t_n - t_j) \log_{10}(t_n - t_j) - (t_n - t_{j+1}) \log_{10}(t_n - t_{j+1}) \right) \right] \\ & + \dots + 0.434(q_{ref} - q_n) + (q_n - q_{n-1}) \log_{10}(q_n - q_{n-1}) \end{aligned} \quad (8)$$

and,

$$\tilde{m} = \alpha \frac{q_w \left(\frac{Z_R p_w}{Z_w Z_R} \right) \mu_R}{kh} \quad (9)$$

Where α is a conversion factor.

Equation 7 suggests that a plot of $p_{(pm)w}$ (normalized wellbore pressure) versus the right-hand side of equation 7 (referred to as rate convolution time function) on graph paper (Figure 10) would yield a straight line with slope \tilde{m} . The expression of the slope (equation 9) can then be rearranged to

solve for the flow capacity (kh). If the net pay (h) is known, the average permeability (k) can be obtained.

Application of the rate convolution method as presented in Equation 7 will, by definition, reduce the entire data set to a single linear trend. This is accomplished by discretizing the continually varying flow rates that occur during the closed chamber perforation inflow test.

The original idea behind this technique was presented by *Ahmed et al.*,¹ but never presented as a serious option for tight gas wells. Figure 10 is the resulting plot using surface pressure data (from field example 2 discussed later in the paper) allowing the determination of permeability and skin. As indicated by equation 7, the knowledge of skin (S) is required before the pressure data is plotted. Figure 10 therefore shows three curves representing three (3) different skin values (+5, +10, and +15). Because of the continual decrease in flow rates during the chamber fill-up, time progresses to the left. Additionally, as the "wellbore" rate becomes insignificantly low, the pressure curves converge to form a common straight line, regardless of the assumed skin value. The most correct line is the one that demonstrates the best straight-line through most of the curve (the middle curve, in this case, with a skin of +10).

Case Histories

Flow regime identification and PID diagnostic analysis is well documented for shallow, low permeability gas wells in reference 6. Therefore, in the rest of this paper, we present three field examples to demonstrate the application of the PID testing technique and emphasize the PID testing capability to provide, in a timely and cost-effective manner, reliable reservoir information.

The first example demonstrates how with routine field surface data reported during a tubing conveyed perforation, permeability can be identified to help understand the well's post-frac production behavior. The second field example is from an underpressured reservoir and the results of the PID test were validated by a post-frac buildup analysis and 12-months of production data analysis. The last field example is of a deep, tight gas well completed in central Alberta at a depth of 3100 m (10,000 ft).

Field Example 1

This example comes from a review of a number of wells in a study area in North Eastern British Columbia. The well presented in this field example was completed by a previous operator and was perforated in the Montney interval from 2763.0 – 2766.0 mKB using tubing conveyed perforating. The well was hydraulically fracture stimulated with 30 tonnes of 20/40 sand and the post-frac buildup test was evaluated by an international consulting firm. Asset team members had requested the review to address the well's poor production performance when compared to the welltest results.

The review of the completion reports stated that the surface tubing pressure increased to 950 kPa in 30-minutes after perforating the well and the early morning pressure had increased to 27400 kPa (3974 psi). As typical in most tight gas wells, when the well was opened to flow, the tubing pressure bleed-off in less than 30-minutes. The well was subsequently

shut-in and tubing surface pressures were reported for 4-hrs. The surface pressure profile is shown in Figure 5.

A best-fit curve was constructed through the surface pressure data in order to simulate a surface electronic data acquisition system response. The synthetic pressure data was then converted to downhole conditions using representative gas properties. Based on the synthetic pressure data obtained, a closed chamber analysis was conducted to determine the unstimulated gas inflow rate. Closed chamber analysis indicated a maximum gas inflow rate of $\sim 6.0 \cdot 10^3 \text{ m}^3/\text{d}$ (213 MSCF/d). Closed chamber pressure and rate profile is presented in Figure 6.

Although the buildup was wellbore storage dominated, we applied a *Modified McKinley*¹⁰ Type Curve analysis to determine matrix permeability (Figure 7). McKinley post-perforation type curve analysis is a log-log representation of the pressure ratio (wellbore pressure divided by reservoir pressure) as a function of shut-in time since perforating. It should be noted that knowing the reservoir pressure is mandatory in order to conduct the McKinley type curve analysis. The results of the analysis indicated the Montney formation permeability was in the order of 0.05 mD over the 3 m perforated interval with a flow efficiency (FE) of 1.0 (no wellbore damage). The post-frac buildup analysis reported by the independent consulting firm indicated a permeability of 0.13 mD based on 26 m of net pay and a stimulated wellbore skin of -4.3 .

We present the validation of the technique by comparing the pre-frac and post-frac permeability results with production data. The result of the production history match is illustrated in Figure 8. It can be observed that the well's production performance predicted using the initial post-frac flow and buildup analysis is optimistic. A more satisfactory production history match was obtained using the permeability calculated from the surface pressure perforation inflow data.

Field Example 2

In this field example, we demonstrate the practicality of the technique utilizing electronic surface pressure recorder data to evaluate the pressure response during an underbalanced perforation inflow test. The Notikewin formation was perforated between 895.0 – 900.0 m (2940 ft) using a 77.5 m fluid cushion. Figure 9 illustrates the pressure response and the closed chamber gas rate calculated in a gas chamber volume of 7.1 m^3 in 114.3 mm casing. The first 0.5-hr shows pressure and gas rate scatter due to gun gas, filtrate inflow and perforation clean-up. The maximum gas inflow rate was $\sim 3.5 \cdot 10^3 \text{ m}^3/\text{d}$ (124 MSCF/d). It can be observed that the gas inflow rates decline during the test, as the wellbore pressure increases, and after about 3.5 h into the test the rate of buildup pressure (dp_w/dt) diminishes considerably. The test was terminated the next day providing 15-hrs of transient pressure data. The presence of a straight line (constant skin) is established at a rate-convolution function time of 0.13 (Fig. 10), which corresponds to 2-hrs after perforating the well. The analysis of the PID data provides a formation flow capacity (kh) 13.8 mD.m with an unstimulated wellbore skin damage factor of +10.

Based on the PID test results, the stimulation treatment was increased from 10 tones to 20 tones of 20/40 sand. The re-designed treatment was pumped and the well was produced back at an initial clean-up gas rate of $35 \cdot 10^3 \text{ m}^3/\text{d}$ (1236 MSCF/d). Post-frac analysis was performed after shutting the well in for a 233 buildup test. Figure 11 is the pressure history match of the post-frac buildup, indicating a reservoir flow-capacity (kh) of 17.4 mD.m and a high conductivity fracture half-length of 61m. The post-frac test shows good agreement with the results from the surface pressure PID test. The well was tied in and daily production rates were collected for 12-months. Final verification of our technique is shown in Fig. 12. Notice the good agreement between the simulated gas rates and the actual daily production response.

Field Example 3

This field example illustrates the use of PID testing technique for a deep, tight gas well. The well is located in Central Alberta and the target horizon is a deep Lower Cretaceous formation. Bad hole conditions and lack of offset wells prevented petrophysical comparisons for bulk density and porosity calculations. The objective of the test therefore was to determine reservoir pressure and permeability for a potential hydraulically fracture treatment. The well was perforated using TCP similar to what is shown in Fig. 2. The recorder and drop bar assembly was dropped 3100 m from surface using 410 m of frac oil as cushion for the recorders and the detonator bar. Surface pressures were monitored overnight and the tubing head pressure had only increased to 1056 kPa (153 psi), indicating a very low gas inflow response. To timely meet the test objectives, a tubing plug was set in the nipple above the recorders to achieve a downhole shut-in condition. Fig. 13 illustrates the pressure response prior to and after setting the tubing plug. Fig. 14 is the corresponding closed chamber gas rate after setting the plug, indicating an unstimulated gas rate of $0.7 \cdot 10^3 \text{ m}^3/\text{d}$ (25 MSCF/d).

Reservoir pressure was obtained using the very practical Inverse Time plot (Fig. 15) as proposed by Kuchuk¹⁰. The closed chamber data was analyzed (Figure 16) and the results indicated a very low formation flow capacity (kh=0.012 mD.m) and an apparent wellbore skin of + 2.

The well was subsequently hydraulically fractured with 40 tones of 20/40 sand and following the treatment a post-frac flow and buildup test was conducted. Figure 17 shows the pressure and gas rate response during the post frac evaluation test. Gas rates were dropping off continuously throughout the 50-hr clean-up test with a final measured gas flow rate $5.9 \cdot 10^3 \text{ m}^3/\text{d}$ (209 MSCF/d). The post-frac buildup analysis as shown in Fig. 18 confirms both reservoir pressure and the low permeability as identified from the PID test. It was concluded that the well was effectively stimulated based on the resulting post-frac skin of -4.2 and that the wells long term deliverability behavior will be controlled by the formations low kh product.

Conclusions

The scope of the paper was to present the practicality of closed chamber testing for perforation inflow diagnostic (PID) testing in low (tight) permeability gas wells. From our study we present the following concluding remarks:

1. Pressure transient analysis using surface pressure data during extreme underbalanced perforating of deep dry gas reservoirs can provide key parameters for completion design such as permeability, unstimulated gas rates, wellbore skin and initial reservoir pressure.
2. Pre-frac reservoir pressure can be obtained on very low (tight) permeability formations within 1-2 days of rig time making this a cost-effective procedure.
3. Due to very tight timelines during winter operations in Western Canada, post-frac cleanup periods are limited and often provide optimistic estimates of reservoir permeability resulting in over optimistic production forecasting. In this paper, we propose the use of PID testing to achieve a better estimate of initial reservoir pressure and reasonable estimates of in-situ rock permeability, necessary for completion design studies.
4. The presented method is dependent on accurate surface pressure recorders calibrated for ambient temperature fluctuations and capable of high sampling rates (1-5 seconds). The interpretation process can be problematic when noisy pressure data is obtained.

Acknowledgement

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Nomenclature

c	=	compressibility
d	=	day
h	=	reservoir thickness
k	=	permeability
kh	=	flow capacity
\tilde{m}	=	slope on the PID plot
MSC	=	1000 standard ft ³
p	=	pressure
PID	=	Perforation Inflow Diagnostic
q	=	gas rate
r	=	radius
S	=	skin factor
t	=	time
V	=	volume
Z	=	real gas deviation factor
Δt_a	=	delta pseudo time

Greek Letters

α	=	conversion constant
μ	=	viscosity
Σ	=	sum operator
τ	=	integration variable

Subscripts

D	=	dimensionless
i	=	initial
in	=	inflow
j,n	=	indices
out	=	out flow
pn	=	normalized pseudo (pressure)
R	=	reservoir
ref	=	reference

sc	=	standard conditions
w	=	wellbore

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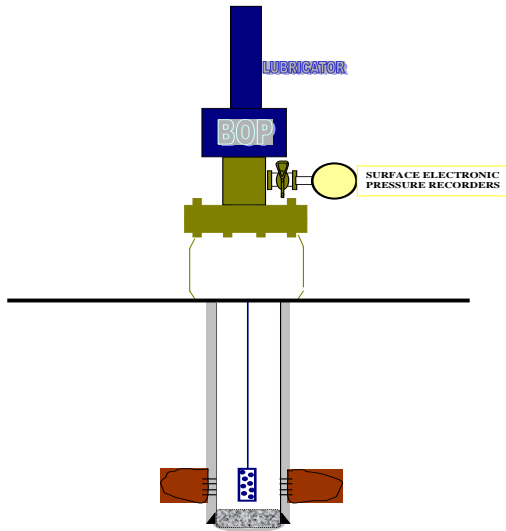


Fig 1 – Shallow Gas PID Test Configuration

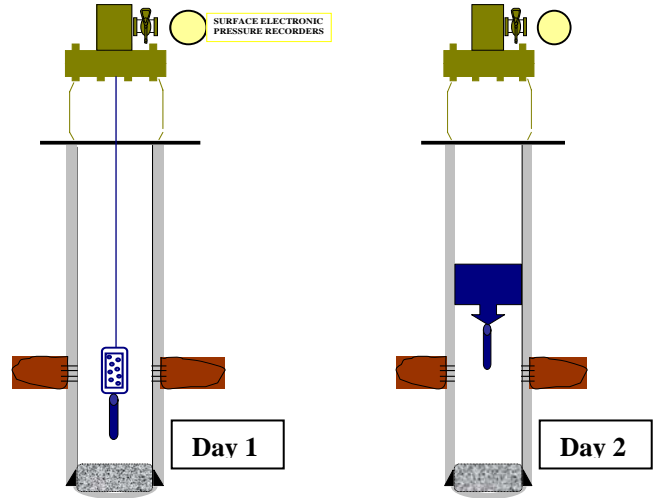


Fig 4 – Deep, Tight Gas PID Test Configuration

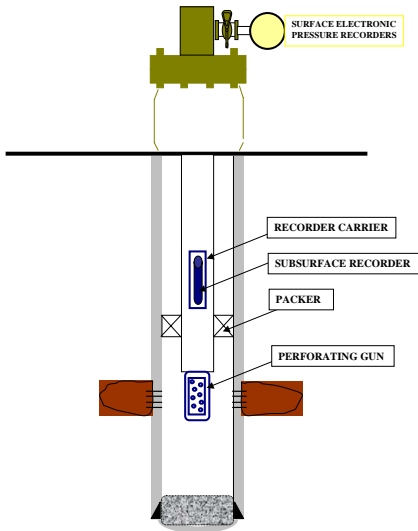


Fig 2 – Critical Sour PID Configuration

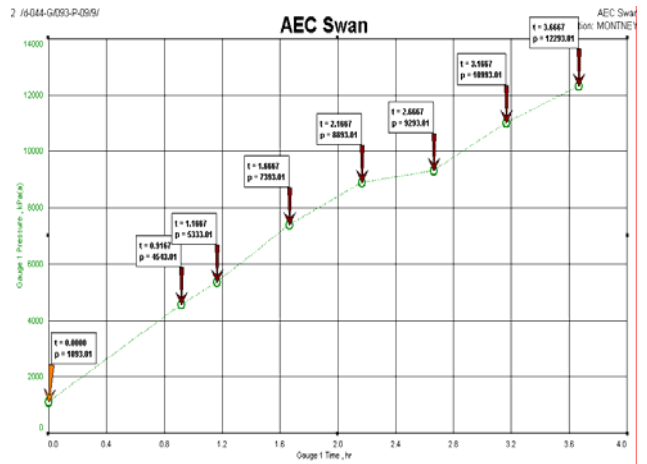


Fig 5 – Post-perf Surface Deadweight Gauge Readings

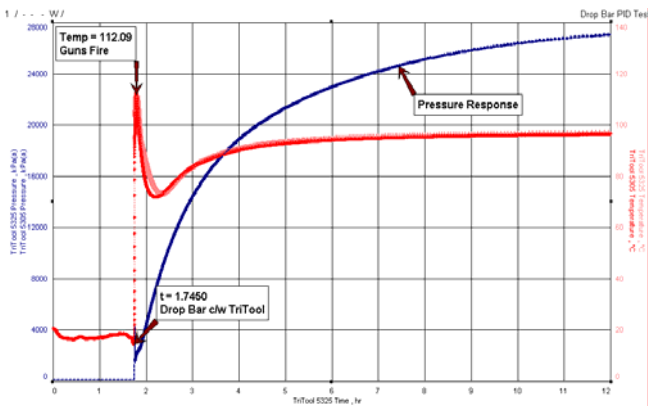


Fig 3 – Critical Sour Drop Bar PID Pressure/Temperature Data

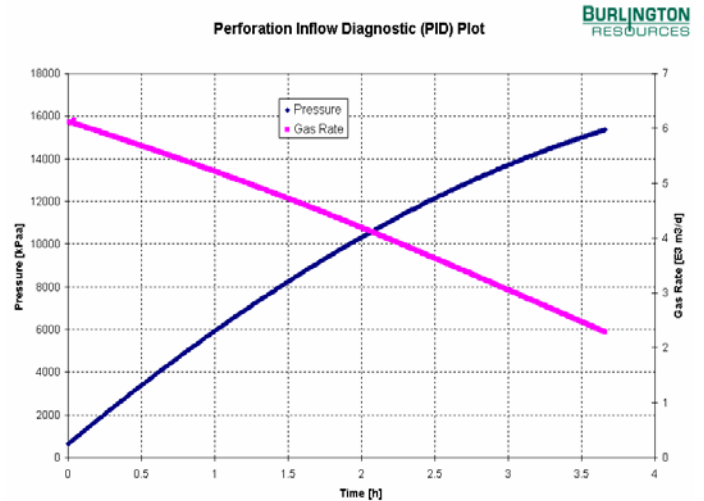


Fig 6 - Closed chamber Gas Rate Profile of Example 1

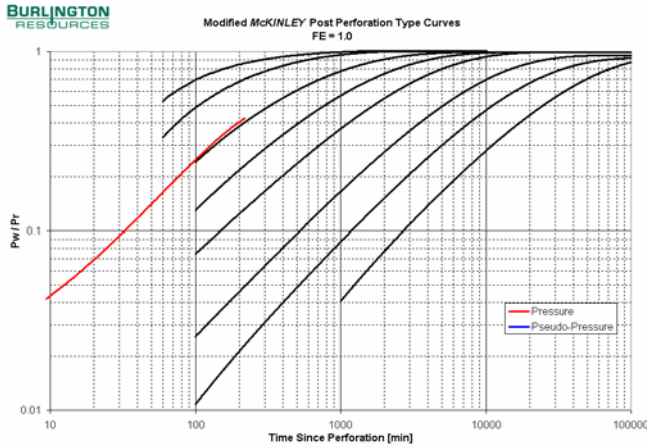


Fig 7 – Modified McKinley Type Curve Match of Example 1

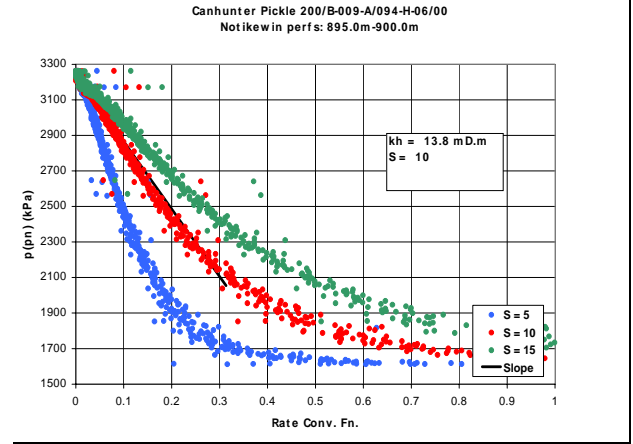


Fig 10 – PIDPro Analysis Plot of Example 2.

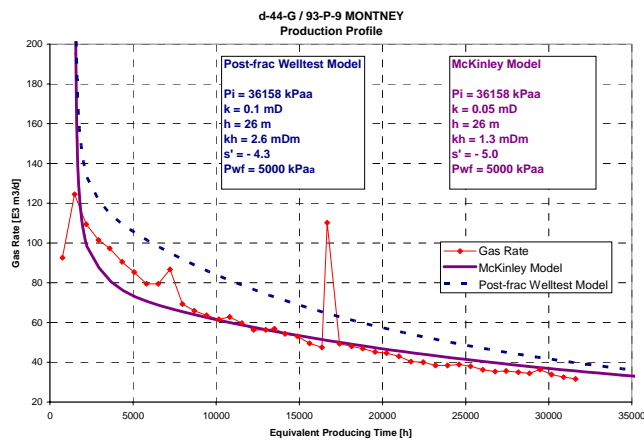


Fig. 8 – Production Data History Match for Example 1

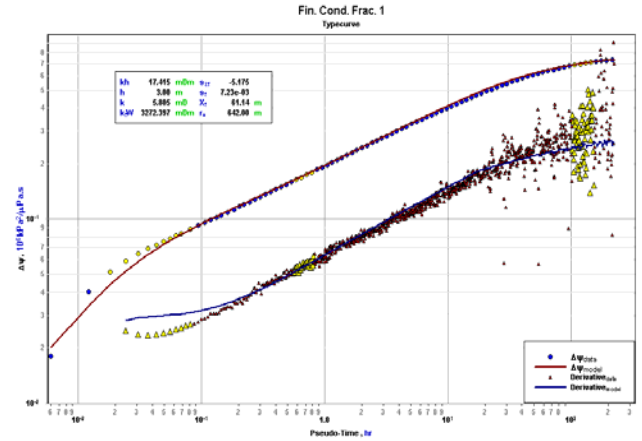


Fig. 11 - Post-frac Pressure History Match of Example 2.

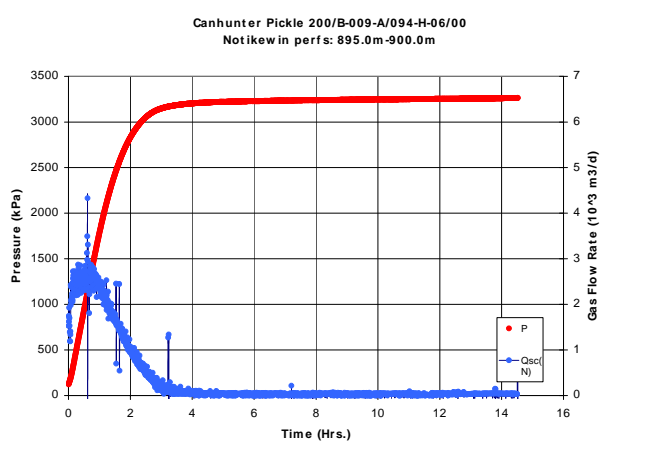


Fig. 9- Closed Chamber Gas Rate Response for Example 2.

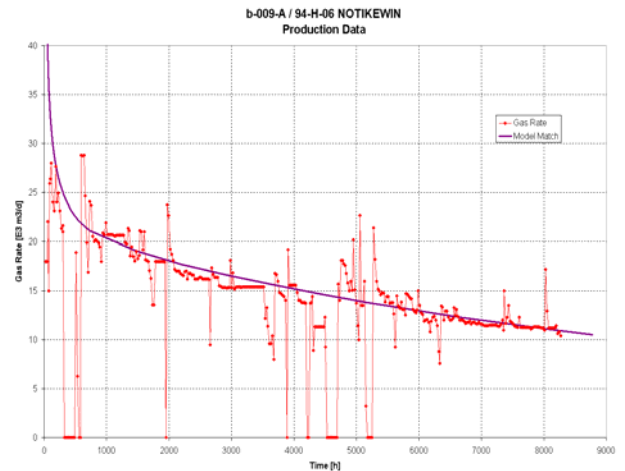


Fig. 12 – Production History Match of Example 2.

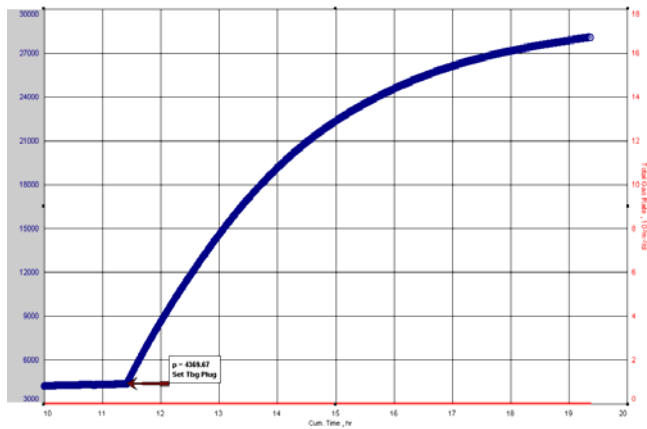


Fig 13 – Pressure Plot of Example 3.

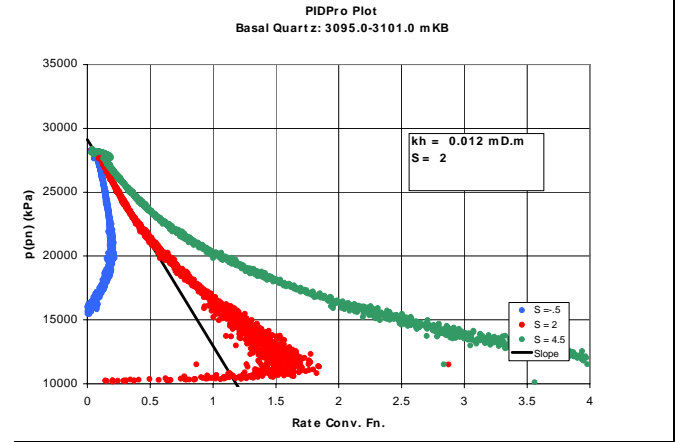


Fig 16 – PID Analysis Plot of Example 3.

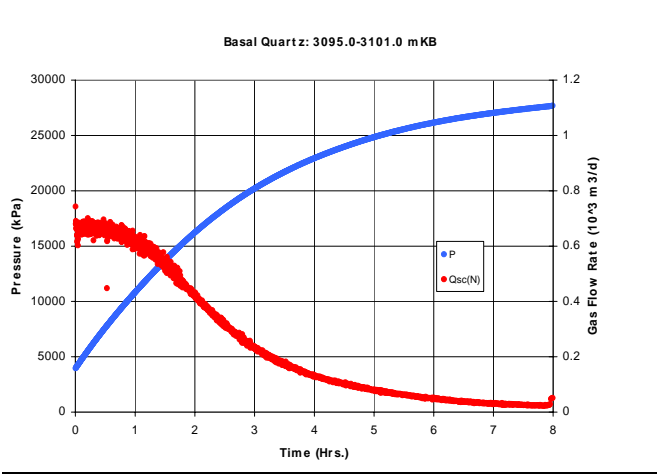


Fig 14 – Pressure – Gas Rate Plot of Example 3.

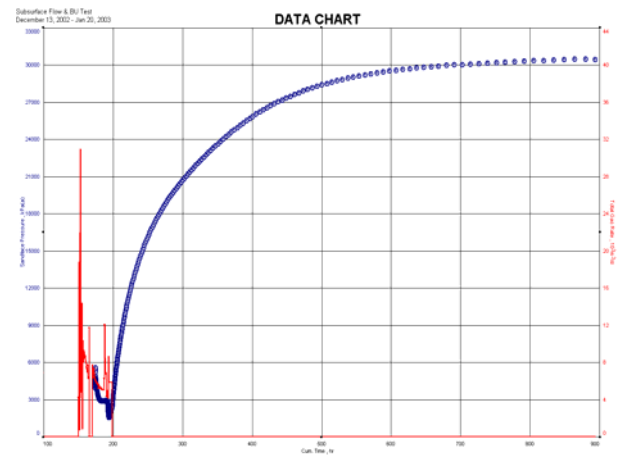


Fig 17 – Post-Frac Flow and Buildup Plot of Example 3.

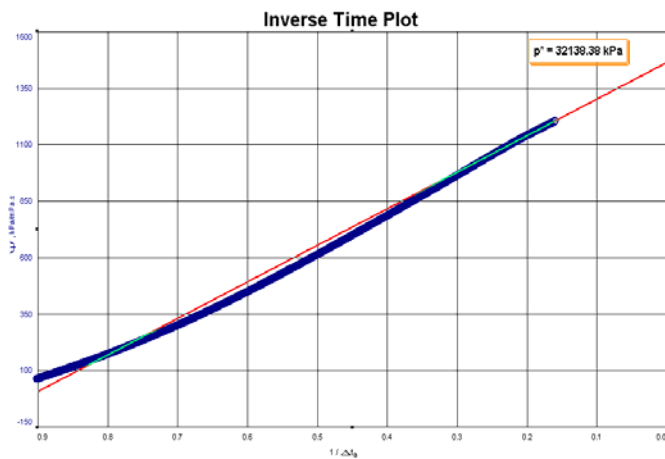


Fig 15 – Inverse Time Plot of Example 3.

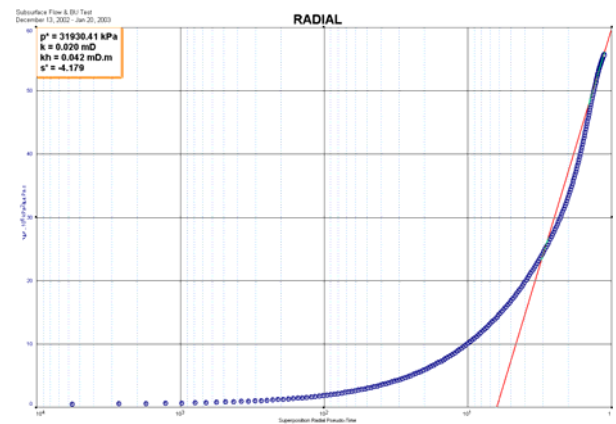


Fig 18 – Radial Analysis Plot of Example 3.