An overview of SPE paper 71639: Field performance of propellant/perforating technologies to enhance placement of proppant on high-risk sand-control completions

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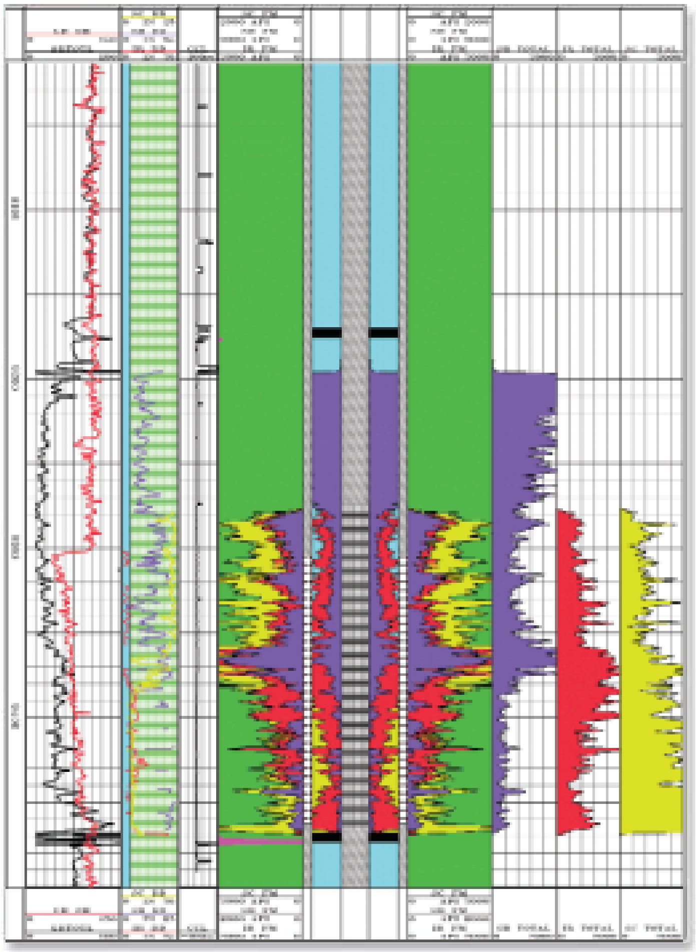
Developing new applications for the StimGun™ assembly has been a priority. Typically, a new application will increase well productivity or reduce costs. Halliburton, with customer assistance, has successfully developed a new application for improving frac-and-pack treatments that improves production, reduces costs, and increases safety. "SPE paper 71639: Field Performance of Propellant/Perforating Technologies to Enhance Placement of Proppant on High Risk Sand-Control Completions" by Kent C. Folse, Richard L. Dupont, and Catherine G. Coats, SPE, Halliburton Energy Services, Inc., David B. Nasse, Shell Offshore, Inc. presented at the 2001 SPE Annual Technical Conference in New Orleans, Louisiana, is an excellent example of the benefits for customers of assisting in the development of new applications.

Traditionally, proper frac-and-pack proppant/sand placement was difficult in unconsolidated formations with long, highly deviated, highly laminated intervals with extreme permeability variations. To ensure that the low permeability intervals accept fracturing fluids and proppant during treatment, a Gulf of Mexico operator used the StimGun™ assembly to break down the perforations prior to the fracturing treatment. The tubing-conveyed perforating jobs were completed in a balanced condition with only the lower quality intervals being stimulated with the StimGun™ assembly. Two very detailed case studies are presented in the technical paper. It was concluded that combining propellant/perforating in a balanced scenario could improve proppant placement, cost efficiency, and safety.

The entire SPE paper 71639 is included in the Appendix with due recognition to the Society of Petroleum Engineers for allowing its republication.



Spectral gamma ray log documenting improved proppant placement.

SPE 71639

Field Performance of Propellant / Perforating Technologies to Enhance Placement of Proppant on High Risk Sand-Control Completions

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Abstract

The combined use of propellants and perforating for production enhancement is not new to the petroleum industry, especially for natural completions in competent formations. When used together, the propellant is shaped in the form of a cylindrical sleeve that is positioned over a typical scalloped perforating carrier to combine the perforating and stimulation processes into one step. The perforating event is performed in either an under-balanced or balanced condition, followed immediately with the extreme over-balance or rapid-gas pulse generated from the propellant burn. This technique provides an effective method to ensure that all perforations are sufficiently broken down with the fracturing to accept either produced or injected fluids.

This paper will review a new application for the combined propellant / perforating technique that has been successfully used in unconsolidated formations in the Gulf of Mexico. The propellant / perforating technique was used to enhance the placement of proppant during frac-and-pack treatments while perforating in a balanced condition. The propellant / perforating technique was used on several formation types; i.e., long intervals, highly deviated, and highly laminated with extreme permeability contrasts, that would traditionally be deemed as high risk for proper sand placement. The propellant sleeves are positioned across the lower quality portions of the intervals with low permeability and resistivity to ensure that the perforations performed in these intervals are broken down to accept fracturing fluids and proppant during the fracturing treatment consistent with the entire treated interval.

Two case histories from a major gulf-of-Mexico operator will be presented and will discuss the steps that led this operator to use this propellant/perforating technique to overcome sand placement problems (screenouts).

In the case histories presented, it will be shown that that this technique is effective in both underbalanced and overbalanced perforating situations. With the trend in the industry to reduce cycle time, the elimination of the underbalance/surge process to ensure clean perforations and all the associated rig time in obtaining control of the well following the surge are seen as opportunities for rig-time savings. It has now been proven that combining propellant/perforating in a balanced scenario can also offer cost efficiency and safety when used as a near wellbore clean up tool for pre-frac preparation.

Introduction

Propellants have been available to the industry for many years and have been used in a variety of applications, primarily in the United States, Canada, China, and Russia. Review of the literature[1-11] reveals the variety of applications in the industry where propellants have been used along with the degrees of success attained in these applications. The concept of using the propellants in combination with the initial tubing-conveyed perforating (TCP) to enhance the placement of proppant during a frac-and-pack completion, however, is a new application for the oilfield.

The standard practice, when perforating unconsolidated formations in preparation for a frac-and-pack completion, is to perforate with a high-shot density, big-hole-shaped charge in an underbalanced well condition to surge the perforations clean. It is generally accepted that the perforating event in itself is a damaging event to the surrounding rock matrix and that underbalanced perforating serves to back flush some of this damaged or crushed formation material along with any residual perforation debris from the shaped charges. Several studies have been performed to characterize the degree of damage attributed to the perforating event,[12-15] and further research has been conducted on optimizing the degree of underbalance[16-18] to optimize perforation efficiency. The problem with having to complete relatively long perforated intervals in deviated wellbores with incompetent formations is the potential for sanding up the TCP assembly. Therefore, to mitigate the risk for having to perform a fishing job to retrieve the TCP assembly, the underbalance is usually reduced significantly or totally eliminated to perforate in a balanced condition. Elimination of this instantaneous surge following the perforation event can result in the entire interval not being treated uniformly during the frac and pack, and thus, less than optimum perforation efficiency. Studies performed by Blok et al[19] and Snider et al[20] revealed the detrimental affects that shaped charge perforators have on altering the formation characteristics and the creation of fines generated in the vicinity of the perforation tunnel. When this occurs, some type of remedial treatment such as underbalance surging of the perforations, additional back-surge trips, flow testing the interval prior to gravel packing, or post-perforating acid wash following perforating will be required ahead of the frac-and-pack operation.

This paper will discuss cases where balanced perforating has been performed and propellant sleeves positioned to selectively break down perforations during the frac and pack that might otherwise not be treated without the aid of underbalanced perforating. The candidate wells contained long, deviated intervals in excess of 100 ft with extreme permeability contrast or were highly laminated. There have been many papers published [21-25] to evaluate the factors that influence the design of a successful frac-and-pack application.

When attempting to complete these types of intervals, many operators choose to break the zone into smaller treatments to ensure effective stimulation and flow assurance. Others attempt to frac and pack the entire interval although aware of the fact that there is potential risk for a premature screen-out, leading to an unstable gravel pack with voids, especially when the higher permeability or thief zone is located in the upper portion of the interval. In this situation, it is not uncommon to run screen sections with flow tubes mounted to the exterior to allow for a circulating pack should the proppant screen out prematurely at a node located across from the higher permeability or leak-off zone. These types of formations can be effectively perforated balanced with the assistance of propellants, thus allowing performance of effective frac-and-pack treatments.

Propellant-Assisted Perforating

Propellants are defined as oxidizer materials that deflagrate as opposed to explosives that detonate. Detonation propagates a shock wave through the explosive, whereas deflagration chemically burns the material. The primary end product of the propellant burn process is the creation of high-pressure carbon dioxide gas and water vapors. The combustible gases and water vapor along with the well fluids are rapidly injected into the newly created perforations on a rate scale several orders of magnitude greater than can be achieved through conventional pumping operations. Since the wellbore fluids will be injected into the formation during the perforating process, it is, therefore, important that the selection of the wellbore fluids be considered carefully to avoid formation damage due to fluid incompatibilities.

The principle of the propellant stimulation is simple: as the perforating gun is detonated the shaped charges penetrate through the scallops causing the propellant sleeve to fracture into many smaller pieces as described by Gilliat et al.[26] **Fig. 1** illustrates a typical propellant sleeve and perforating gun configuration for a TCP application. The propellant burns as a function of pressure, temperature, and available propellant surface area exposed with the shaped charge providing the necessary ignition source. The generated gas pressure pulse is usually sufficient to overcome in situ stresses to create and extend short fractures from perforation tunnels in a cased-hole completion. It is conceptualized that all the perforations will be broken down regardless of charge phasing; however, at some point, the only fractures that will propagate are the perforations aligned with preferred stress planes. Pressure pulses ranging from 5,000 to 30,000 psi are attained within a 1 to 10 ms time regime, followed by a decay tail associated with expansion, cooling, and flow into the perforations and fractures. The loading rates and peak pressures are lower compared to explosives but significantly higher than those attained in conventional hydraulic fracturing. Peak pressures and burn characteristics of propellant tools are dependent upon wellbore diameter, geometry, perforation area, formation properties, and confining fluid compressibility.

In the past, propellant treatments were designed based on experience and field observations. The availability of a computer model and high-speed pressure recorders (as described by Schatz et al[27]) has validated this technology, greatly enhancing the understanding and reliability of propellant / stimulation techniques. Propellant-assisted TCP has been applied in many cases in either balanced or underbalanced conditions, leading to zero or slightly negative skin completion responses in most cases. Whisonant and Hall[28], Miller et al[29], and Van Batenburg et al[30] describe successful applications of propellant techniques as a pre-hydraulic fracture perforation breakdown method in competent formations.

Case Histories

Two case histories from Gulf of Mexico completions are presented to illustrate the application of using propellant-assisted perforating techniques to enhance the placement of proppant during frac-and-pack operations with balanced TCP.

Case 1. The case-1 well was a 7-5/8-in. side-track of an existing gas completion. The side-track was to be in the same zone ("I" Sand) in an adjacent fault block. The "I" sand was well characterized in the parent wellbore. (see **Table 1** for a summary of well info.) A resistivity/gamma ray log generated for the "I" sand, as shown in **Fig. 2**, reveals that the upper 40 ft of this gross interval is a high permeability (+/- 500 md) and higher resistivity sand section. The resistivity/gamma ray log shows that the remainder of the sand is highly laminated with lower quality (+/- 50 md) and resistivity pay. Based on the examination of the resistivity/gamma ray log, the completion team determined that the probability of effectively fracture treating this lower-quality sand was low unless some other remedial step was performed to ensure that these perforations would accept fracture fluids and proppant during the treatment.

The team made the decision to evaluate the effectiveness of the propellant-assisted perforating technique to provide perforation breakdown across these lower-quality sand streaks. The input parameters listed in **Table 1** were used to design the propellant-assisted perforating treatment using the computer model discussed by Schatz et al[27]. Based on computer simulation results presented in **Fig. 3**, the propellant was strategically placed across the sand streaks. **Table 2** shows the specific locations where the sleeves were positioned on the TCP gun system. It should be noted that computer simulation was used to determine the maximum pressures that would theoretically be observed at the sump packer positioned at a depth of 9,471 ft. The purpose of using simulated pressure at the sump-packer depth was to determine the length of propellant sleeve that could safely be used on the bottom gun so that the sump packer assembly would not sustain pressure damage.

The TCP assembly was run into the wellbore with a full column of seawater, and the guns were positioned on depth with a mechanical indication from the sump packer. Offset "T" sand completions had previously been TCP'd with a standard underbalance TCP assembly that included in most cases a retrievable packer, below packer safety joint, circulating valve, secondary circulating valve, underbalance valve, and pressure gauges. On this particular job, since the well was to be perforated balanced, all the retrievable test tools mentioned above were eliminated from the assembly. This generated a direct cost saving to the customer as well as a saving in rig-time costs associated with having to make-up and break-out the associated tools. After the guns were positioned on depth, a perforating bar was dropped to detonate the mechanical firing head. A clear indication of guns firing was observed at the surface with a +/- 500 psi pressure spike at the surface choke manifold. After firing the guns, the well was observed for fluid losses, which were recorded as being less than 4 bbls/hr initially. One tubing volume was reversed-out and fluid loss dropped to zero; at that point, the TCP guns were pulled out of the wellbore. Another rig-time savings was captured by use of this TCP run versus the traditional underbalanced perforating of offset wells that routinely require at least one HEC pill to be spotted to control fluid losses to the formation.

The next step in the operation was to pick-up the gravel-pack packer, washpipe and screen/blank assembly. A spectral gamma ray memory-logging tool was run in place mounted on the end of the washpipe, and the various stages of the frac job were tagged with different isotopes to determine fluid movements and proppant placement across the interval. The screen length in this case was 193 ft with a 6-gauge screen. After the packer was set, a pickle consisting of 110 gals of dope buster, 500 gals 15% Fe acid and 10 ppg $CaCl_2$ for displacement were pumped down and reversed-out to ensure clean tubulars ahead of the frac-and-pack operation. Following the pickle job, an acid job consisting of 4,000 gals of 10% Fe acid was pumped into the formation at a rate of 1 bbl\min. As shown in **Fig. 4,** no formation break back or improvement of injectivity, which would have indicated that the perforations were damaged from the balanced perforating, were shown.

Following the acid treatment, a mini-frac was pumped at an average rate of 20 bbl\min with 8,400 gals of 25 lb/Mgal of gelled fracture fluid. Mini-frac results indicated a closure pressure of approximately 4,624 psi and fluid efficiency of 18%. Based on mini-frac results, the frac job pad was increased by 12,600 gal. The main frac-and-pack treatment (shown in **Fig. 5)** was pumped at a maximum rate of 20 bbl\min with a live annulus. A total of 170,215 lbs of 50/70 sand was placed into the formation with a concentration of 1,077 lbm/ft. A net pressure increase of 775 psi was observed on the annulus, and a screen-out had to be induced by dropping the rate to 3 bbl\min with 1 bbl\min returns at the 10 ppg sand stage at the formation. A re-stress of the pack indicated the blank coverage to be 58 ft.

As the washpipe was pulled out of the screen assembly, the zone was logged with the spectral gamma ray memory tool. Examination of the log in **Fig. 6** shows that the Sc-46 (yellow) tracer used in the 1-9 ppg stage is clearly evident across all the perforations and appears to have higher concentration directly above the sump packer. The Ir-192 (red) tracer was spotted early in the 10-ppg proppant stage and is represented across the entire interval. The Sb-124 (blue) tracer was spotted late in the 10-ppg proppant stage and shows that even at the end of the treatment, the lower quality sand members are accepting the proppant.

The well was placed on production for one month, and after several choke changes were made, a stabilized rate of 30,482 $MMft^3/D$ BOPD, and 20 BWPD was achieved. (see **Fig. 7** for complete production history.) A pressure transient analysis was performed on a buildup survey that was conducted approximately one month after start-up of production on this well. Review of results in **Table 3** for the diagnostic plots presented in **Figs. 8** to**10** show a well with significant wellbore storage effects that mask any early-time linear flow that would be characteristic of fracture flow. However, at late times, a half-slope is observed on the derivative log-log plot and is matched with a finite conductivity fracture model. A rate-dependent skin factor was incorporated into the analysis technique to factor out any non-Darcy flow effects. The results of this analysis reveal a well with minimal mechanical skin effects dominated by wellbore storage and skin effects attributed to non-Darcy flow or turbulence.

Case 2. The Case 2 well is a completion in the "J" sand, which is a highly laminated oil-bearing formation as shown in **Fig. 11**. The objective of using propellant-assisted perforating in this case was to initiate good perforation breakdown across the lower-resistivity pay section from 13,270 ft to 13,300 ft. Complete well information for Case 2 is shown in **Table 4**. A computer model simulation was performed (as shown in **Fig. 12)** to evaluate the effectiveness of the propellant treatment and identify any potential hazards with this operation. The simulation predicted fractures on the order of 3 – 4 ft with a peak pressure of 19,000 psi.

The TCP assembly was run into the wellbore with a full column of seawater and positioned on depth with a mechanical indication from the sump packer. The well was perforated in a balanced condition with no fluid loss reported, and the guns were retrieved without incident. The next step was to pick up 128 ft of 5-gauge screen and run to depth. After setting the gravel pack packer, a pickle was pumped to condition the tubulars ahead of the acid and main frac treatments. An acid treatment consisting of 3,360 gal of 15% HCl was pumped at a final rate of 8 bbl\min. Review of **Fig. 13** did not show any response to the acid, and a step-rate test was conducted to determine the fracture gradient of 0.46 psi/ft. Following the acid treatment, a mini-frac was performed to determine the fluid efficiency at 24.5% and closure pressure at 5,930 psi. The main frac (as shown in **Fig. 14)** was pumped at a maximum rate of 20 bbl\min with a live annulus. A total of 67,582 lbm of 40/70 sand was placed into the formation with a concentration of 735 lbm/ft. A net pressure of 600 psi was observed on the annulus, and a screen-out had to be induced by dropping the rate to 2 bbl\min with 1.5 bbl\min returns at the 10 ppg sand stage at the formation.

The well was placed on production and achieved a stabilized rate of 1,325 BOPD, 1,497 MMft^3/D, and 7 BWPD as shown in **Fig. 15**. A buildup survey was performed approximately 3 months after commencing production of this well. Review of the buildup diagnostic plots in **Figs. 16 to 18** reveals a well test completely dominated by wellbore storage and skin effects. Without the absence of any linear flow regime associated with fracture flow, a radial flow model was assumed to estimate parameters for permeability and skin factor. The analysis results in **Table 5** indicate a completion with significant skin effects and relatively low permeability.

Discussion

The case histories presented illustrate a method for selectively breaking down perforations in preparations for frac-and-pack treatments. Although the benefits of the propellant-assisted perforating may not readily be obvious, the histories presented indicate that the need for underbalanced perforating was not required for the particular sands under study. Elimination of the need to perform underbalanced perforating can result in reduced completion cycle time by 1) reducing the number of tools in the TCP string and 2) eliminating the time spent on bottom circulating out hydrocarbons and spotting fluid-loss pills. The most obvious indication of the benefit of this technique was the evaluation of the spectral gamma ray log that was run on Case 1, which clearly shows that sand placement is attained across the entire interval where the propellant is positioned. The other benefit from using propellant-assisted perforating on sand-control completions is the additional perforation extension. Typically, most big hole perforators predict formation penetrations on the order of 3 to 6 inches into the formation. The propellant serves to break down these perforations, and in this case, the computer modeling predicts fractures extending out past 3-1/2 ft. This may become important if hole washouts are present with enlarged cement sheaths. To date, a total of four propellant-assisted perforating jobs have been performed in the "I" and "J" sands with similar results. Examination of the pressure transient analysis on these case histories shows that in order to properly evaluate these types of completions, it is necessary to perform downhole shut-in's to eliminate wellbore storage effects that mask any linear flow associated with the fractures. For future optimization of these types of jobs, it is recommended that high-speed pressure recorders be run to further validate the computer simulations. It is important to note that attempts to run the high-speed pressure recorders at the time these jobs were performed were limited by available gauge OD and the presence of a sump packer below the gun.

Conclusions

- Propellant-assisted perforating is an effective method to achieve perforation breakdown
- Selective perforation breakdown can be used to treat specific sections of perforated intervals that would not otherwise accept fluid and sand
- Selective perforation for sand placement has been validated with spectral gamma ray logs
- Balanced perforating in combination with propellants has resulted in completion efficiencies similar to those generated in offset wells shot underbalanced
- Balanced perforating reduces time spent on bottom with TCP guns by eliminating reverse-out of hydrocarbons and potential fluid loss.

Nomenclature

BHP	bottomhole pressure, psia (Kpa)
BHT	bottomhole temperature, °F (°C)
P_i	initial reservoir pressure, psia (Kpa)
P_{wf}	flowing bottomhole pressure, psia (Kpa)
k	permeability, md
C	wellbore storage constant, bbl/psi (m^3/Kpa)
S	skin factor dimensionless
ΔP_{skin}	pressure drop due to skin factor, psia (Kpa)
S'	apparent skin factor dimensionless
$\Delta P'_{skin}$	pressure drop due to apparent skin factor, psia (Kpa)
X_f	fracture half-length, ft (m)
PI	productivity index, bbl/day/psi (m^3/day/Kpa)

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SI Metric Conversion Factors

ft × 3.048* E -01 =m
in. × 2.54* E+00 =cm
psi × 6.894 757 E+00 =kPa
md × 9.869 233 E −04 =μm^2
g_n × 1.019 716 E -01 =ms^{-2}
*Conversion factor is exact

Table 1: Case 1 General Well Information

Zone	"I" Sand
Well Type	Gas
Completion Date	Aug 2000
Completion Fluid	8.6 ppg Seawater
Casing Size & Weight	7.625" 29.7#
Gun Specifications	4.625" 12 spf, 30° phased Big Hole Charges (EH = 0.8")
Top Shot (MD ft)	9,305
Bottom Shot (MD ft)	9,463
Well Angle @ Perfs	17°
Gross Pay (MD ft)	158
Net Pay (TVD ft)	119
BHP (psi)	3,195
BHT (°F)	146
Permeability (md)	585
Porosity (%)	30
Young's Modulus (E6 psi)	0.4

Table 3: Case 1 Pressure Transient Analysis	
3,016 psia @ 9,146 ft	Pi
2,730 psia @ 9,146 ft	Pwf
38,400 md-ft	kh
323 md	k
0.0341 STB/psi	C
1.65	S
4 psia	ΔPskin
124	S'
279 psia	ΔP'skin
371 ft	Xf
30,482 Mscfd	Gas Rate
320 bpd	Condensate
106.58 Mcf/day/psia	PI

Table 2: Case 1 Propellant Sleeve Placement			
Gun Number	Top Shot, ft	Bottom Shot, ft	Sleeve Length, ft
1	9,305	9,327	0
2	9,327	9,350	3
3	9,350	9,372	6
4	9,372	9,395	15
5	9,395	9,418	12
6	9,418	9,441	15
7	9,441	9,463	9

Table 4: Case 2 General Well Information

Zone	"J" Sand
Well Type	Oil
Completion Date	Nov 2000
Completion Fluid	8.6 ppg Seawater
Casing Size & Weight	7.625" 29.7#
Gun Specifications	5.125" 12 spf, 30° phased Big Hole Charges (EH = 0.8")
Top Shot (MD ft)	13,260
Bottom Shot (MD ft)	13,352
Well Angle @ Perfs	51°
Gross Pay (MD ft)	92
Net Pay (TVD ft)	45
BHP (psi)	2,957
BHT (°F)	176
Permeability (md)	100
orosity (%)	25
Young's Modulus (E6 psi)	0.6

Table 5: Case 2 Pressure Transient Analysis

Pi	3,256 psia @ 13,301 ft
Pwf	2,226 psia @ 13,301 ft
kh	3,220 md-ft
k	51 md
C	0.0152 STB/psi
S	16.4
ΔPskin	669 psia
Gas Rate	Mscfd
Oil Rate	1,325 bpd
PI	1.286 bbl/day/psia

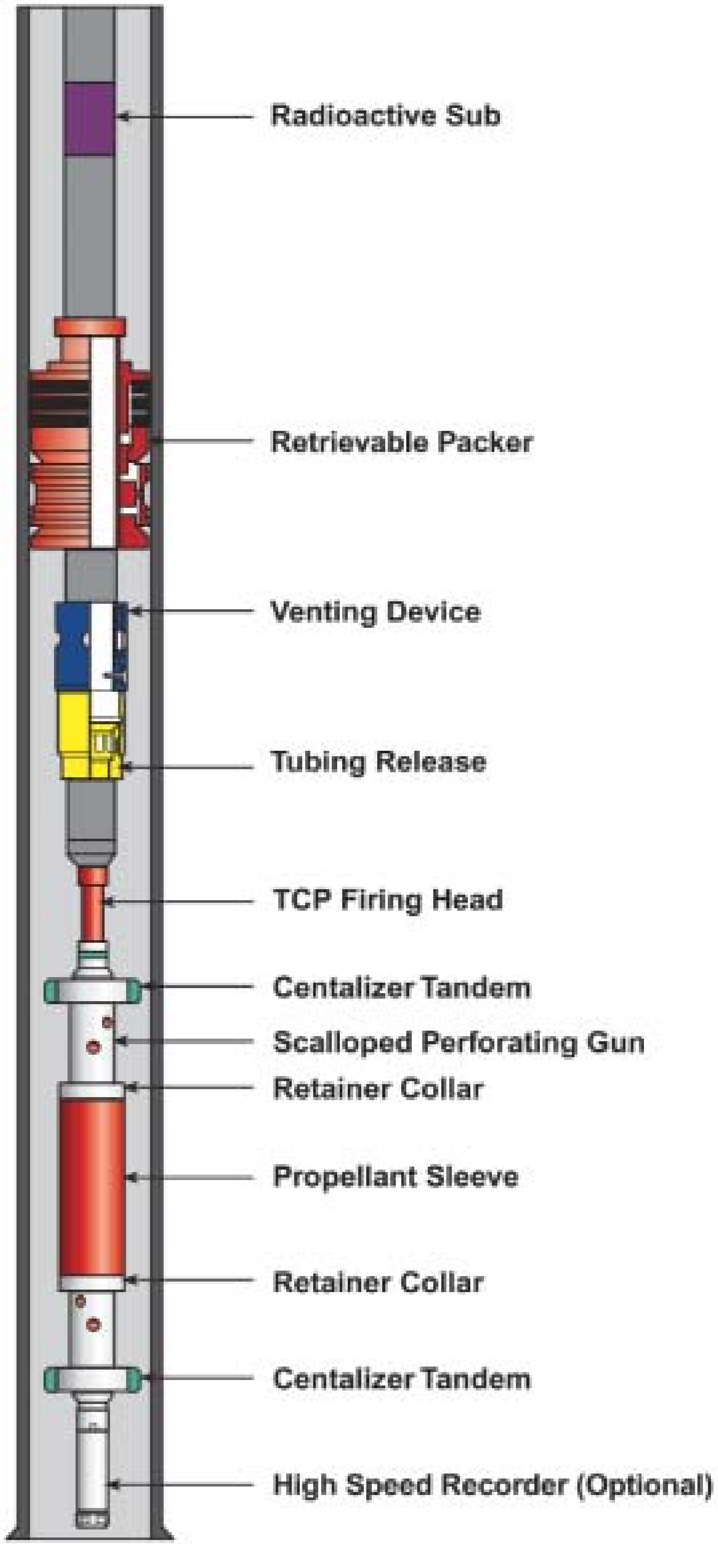

Fig. 1 — Typical propellant sleeve and perforating gun configuration for a TCP application.

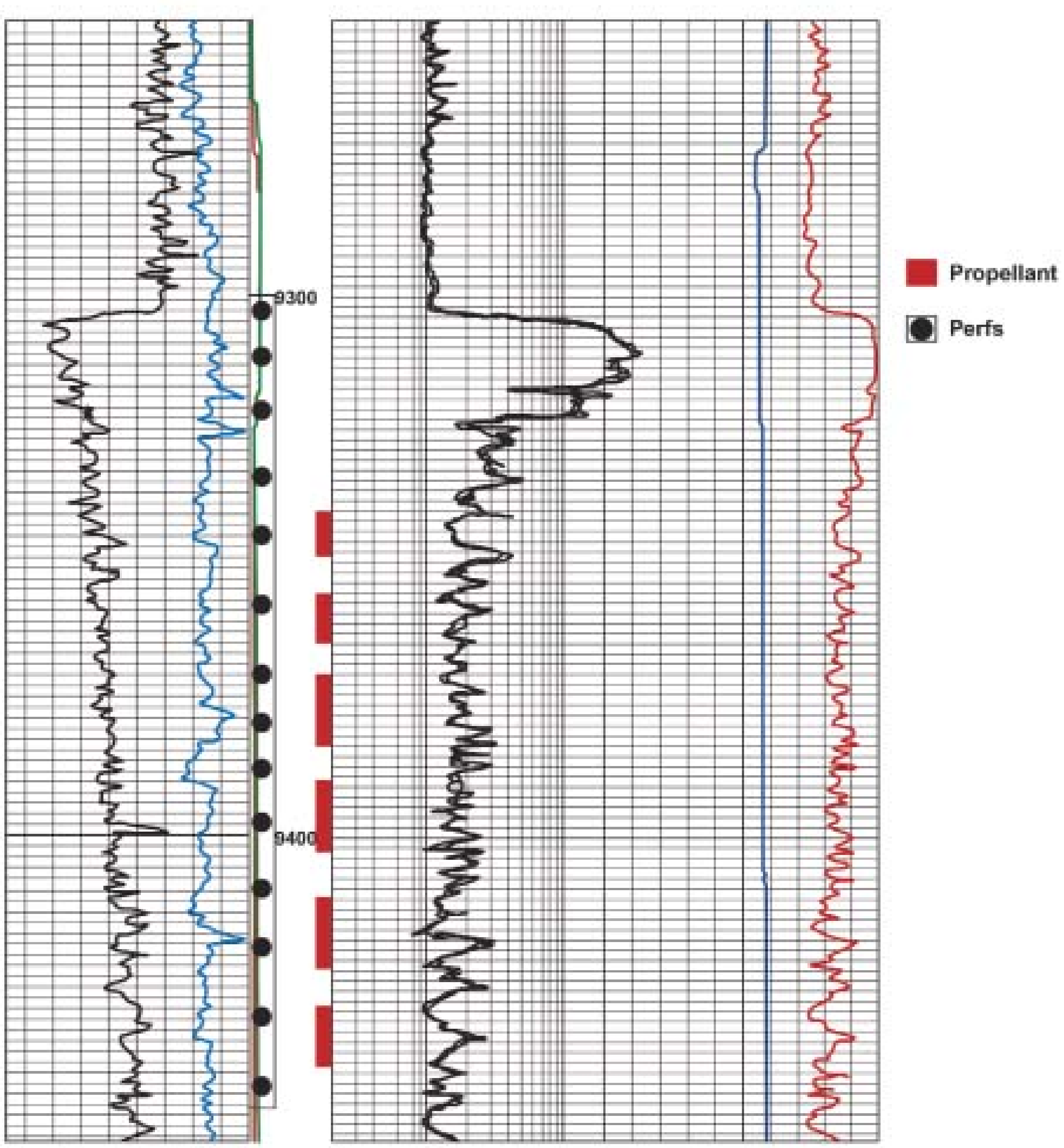

Fig. 2 — Case History 1 Resistivity/Gamma Ray Log

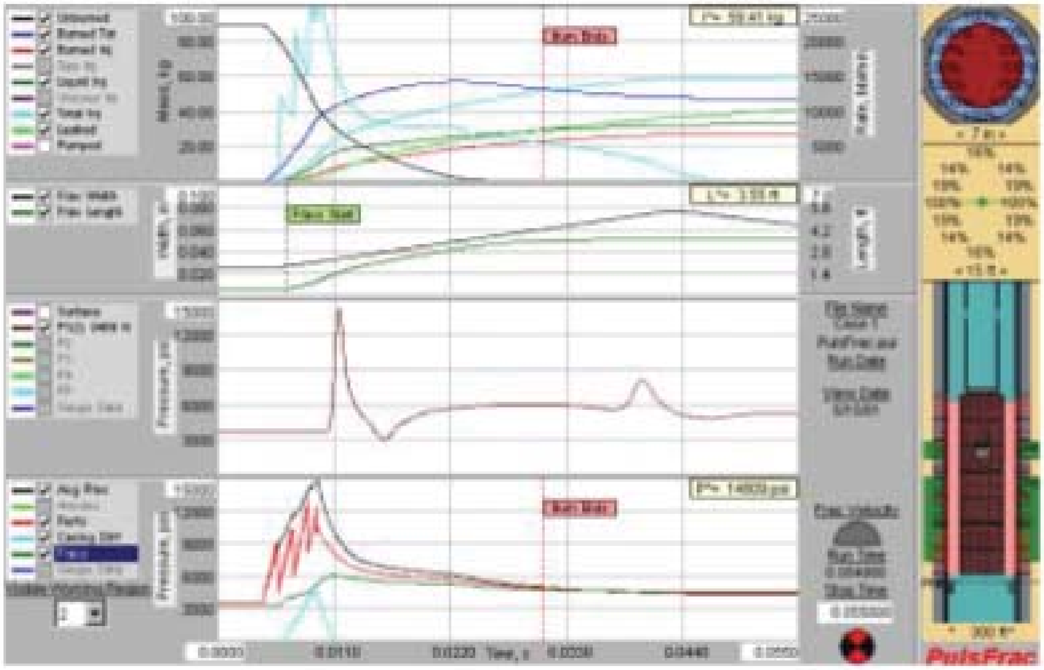

Fig. 3 — Case History 1 Computer Simulation

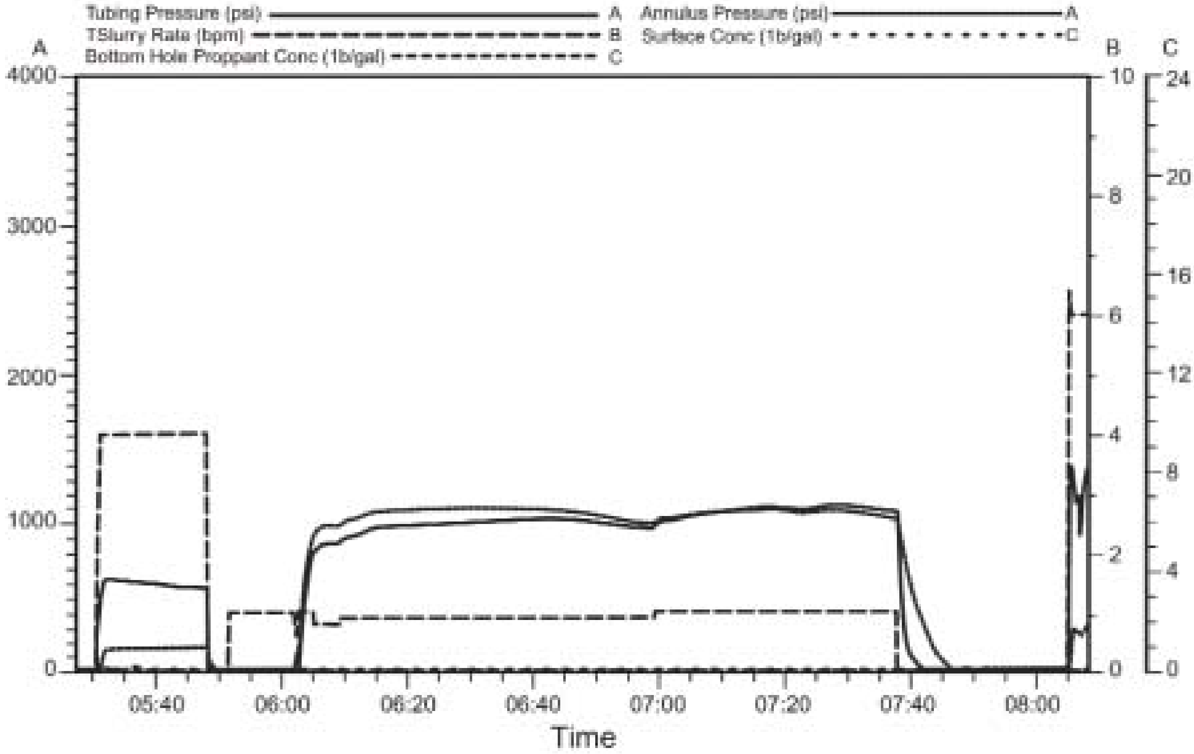

Fig. 4 — Acid Treatment for Case History 1

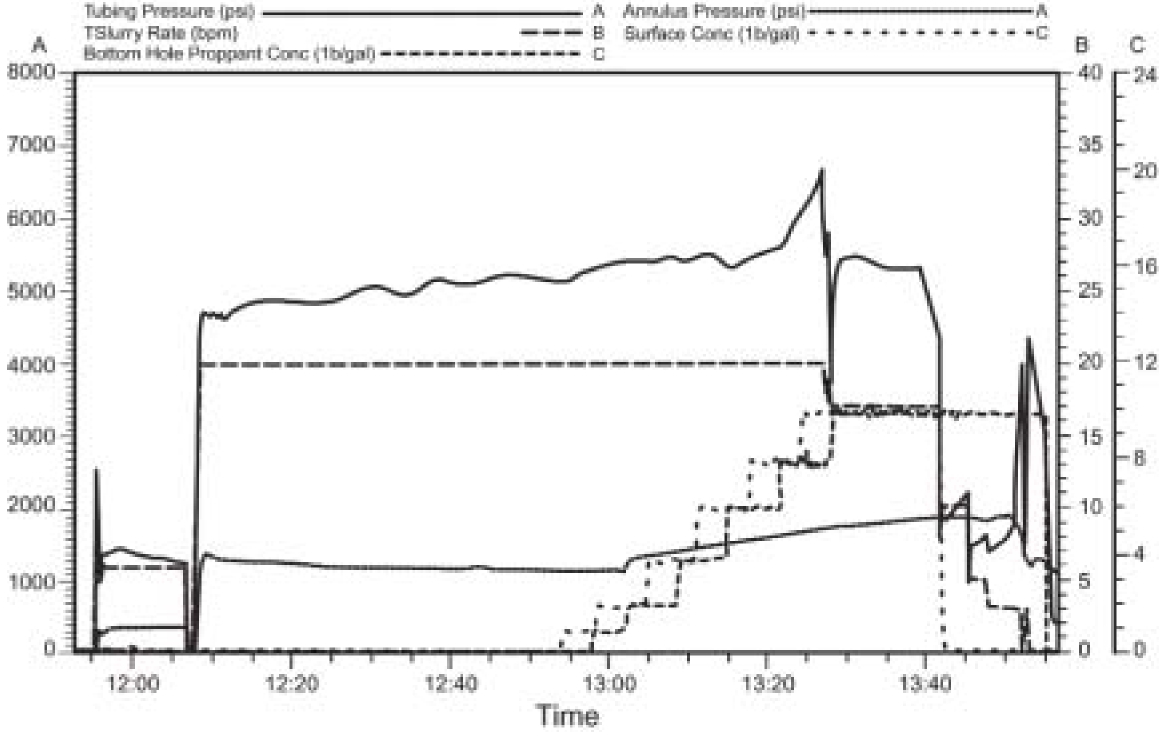

Fig. 5 — Frac-and-pack Treatment for Case History 1

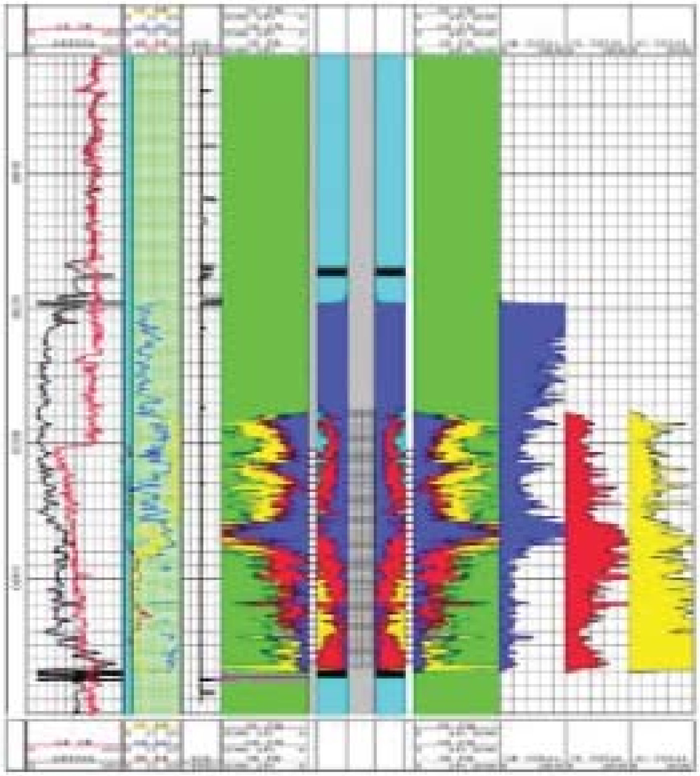

Fig. 6 — Spectral Gamma Ray Log for Case History 1

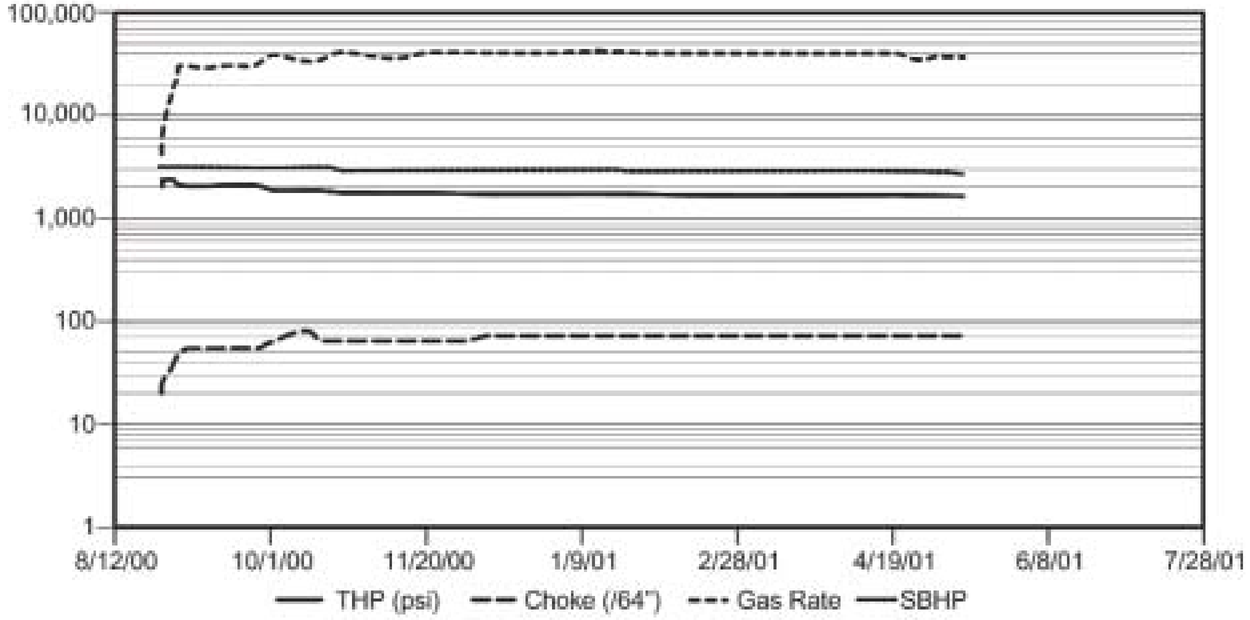

Fig. 7 — Case 1 Production History

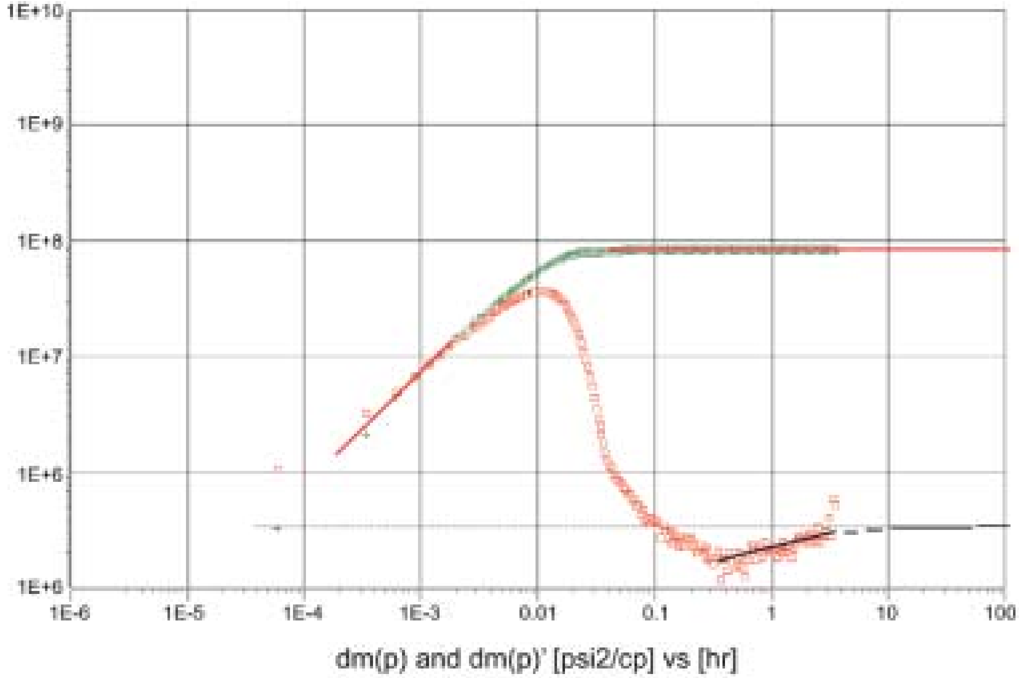

Fig. 8 — Derivative Log-Log Buildup for Case History 1

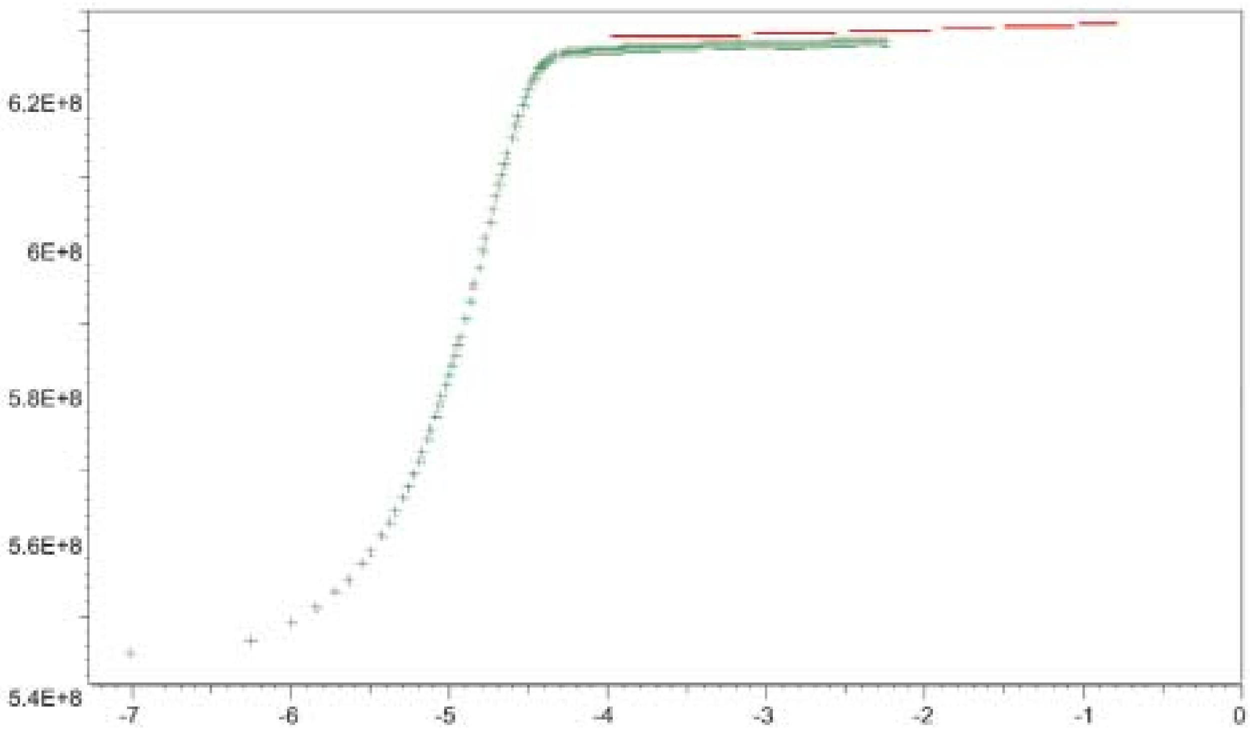

Fig. 9 — Semi-Log Buildup for Case History 1

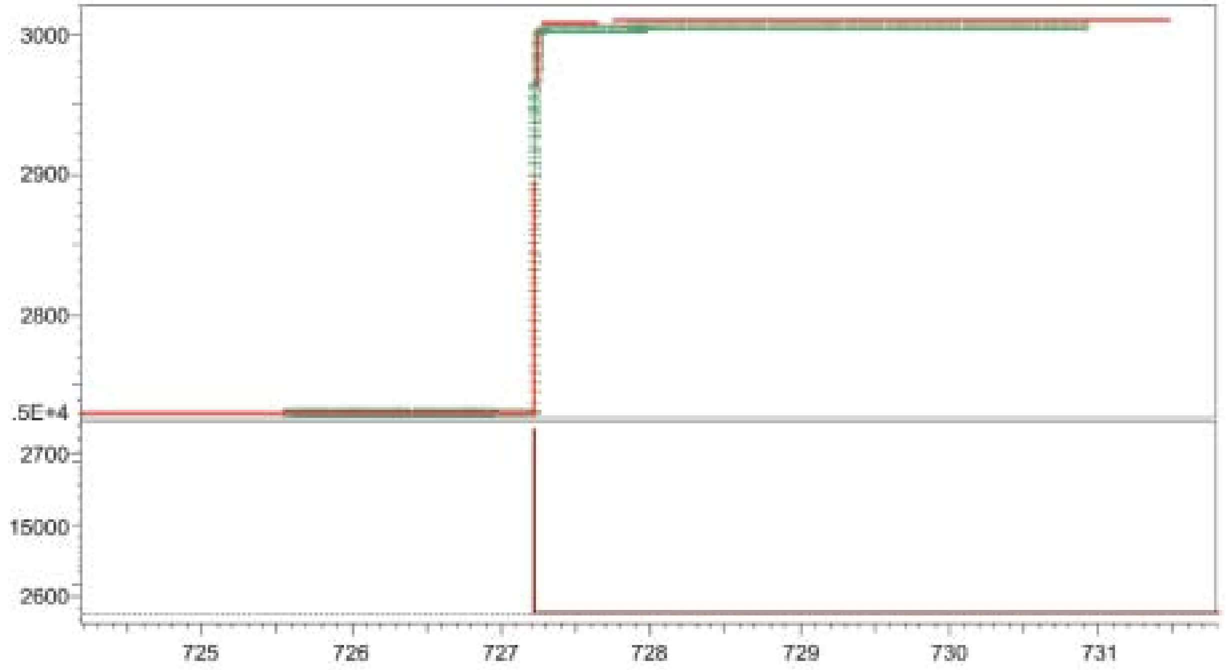

Fig. 10 — History plot drawdown/buildup for Case History 1

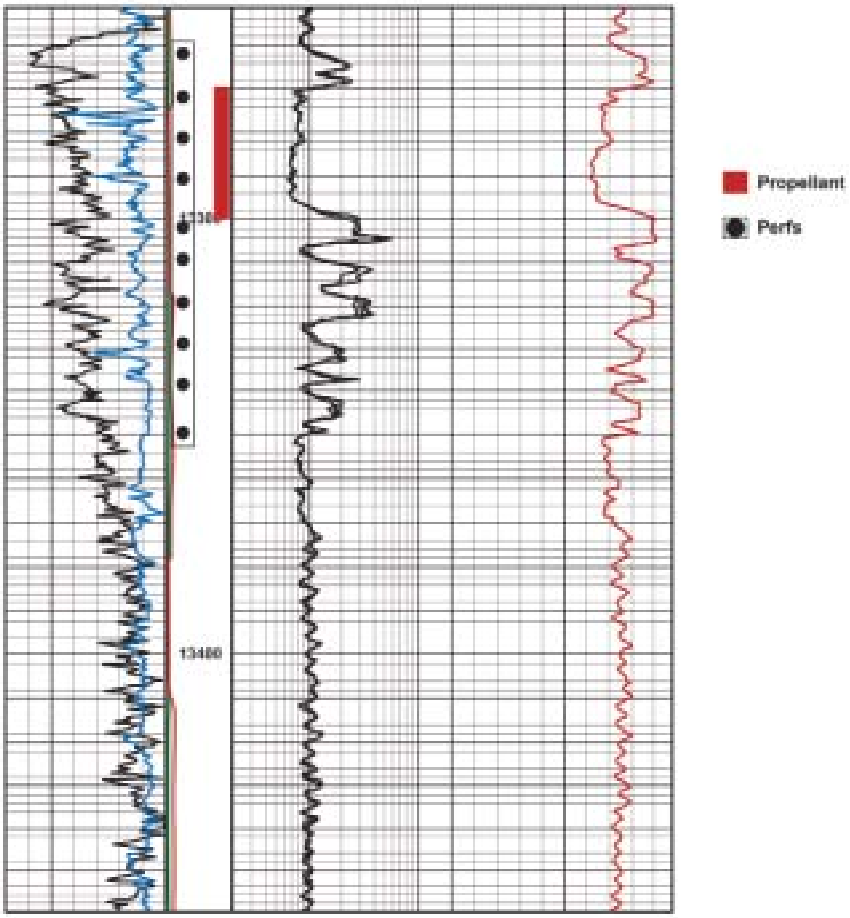

Fig. 11 — Case History 2 Resistivity/Gamma Ray Log

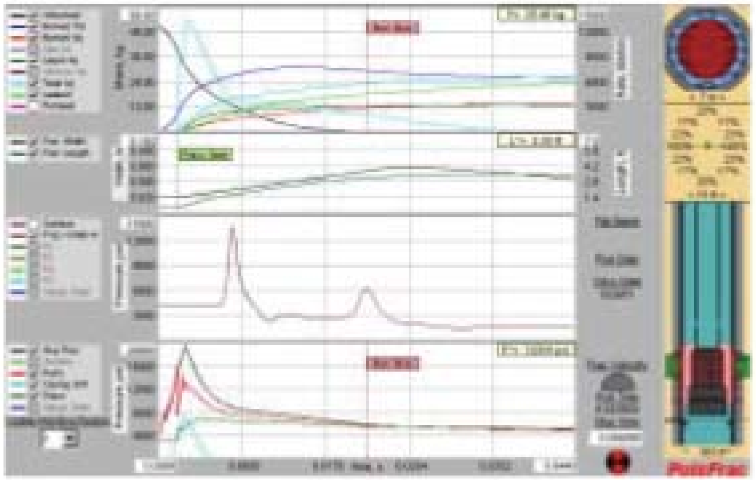

Fig. 12 — Case History 2: Computer Model Simulation

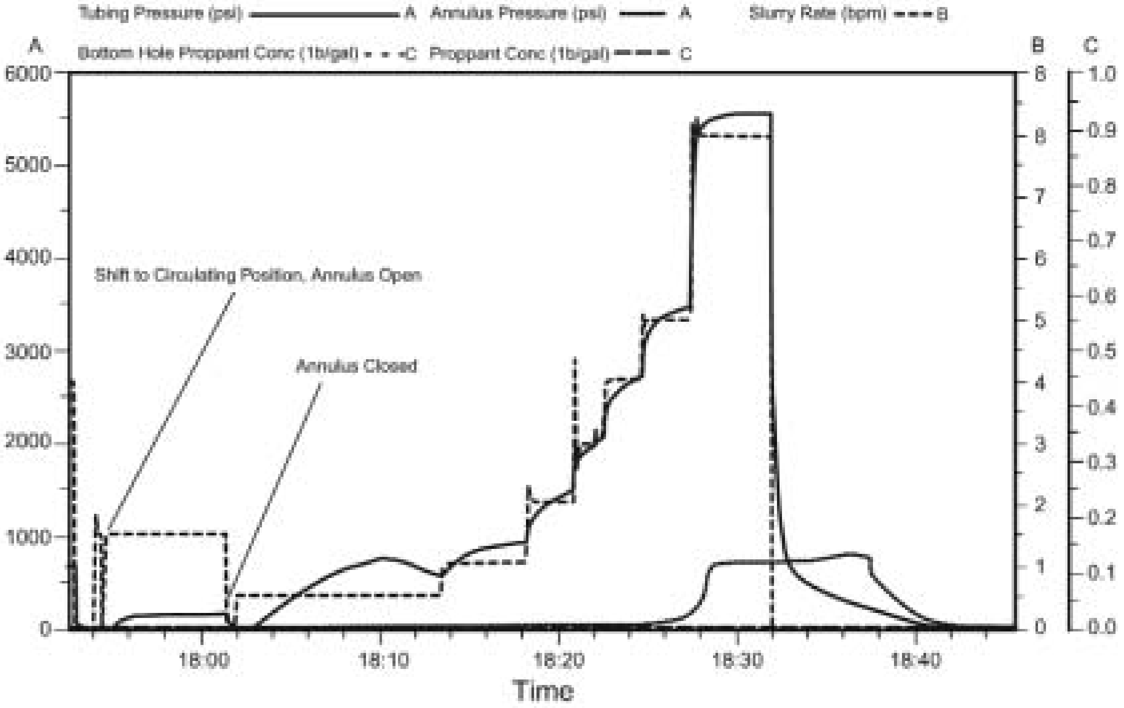

Fig. 13 — Acid Treatment for Case History 2

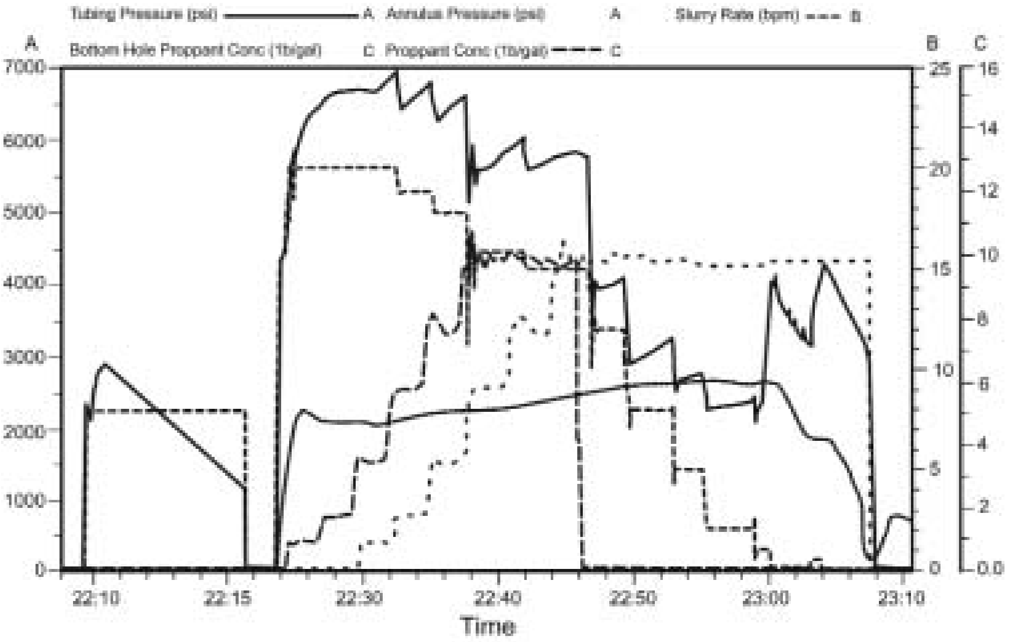

Fig. 14 — Case History 2 Well: Main Frac

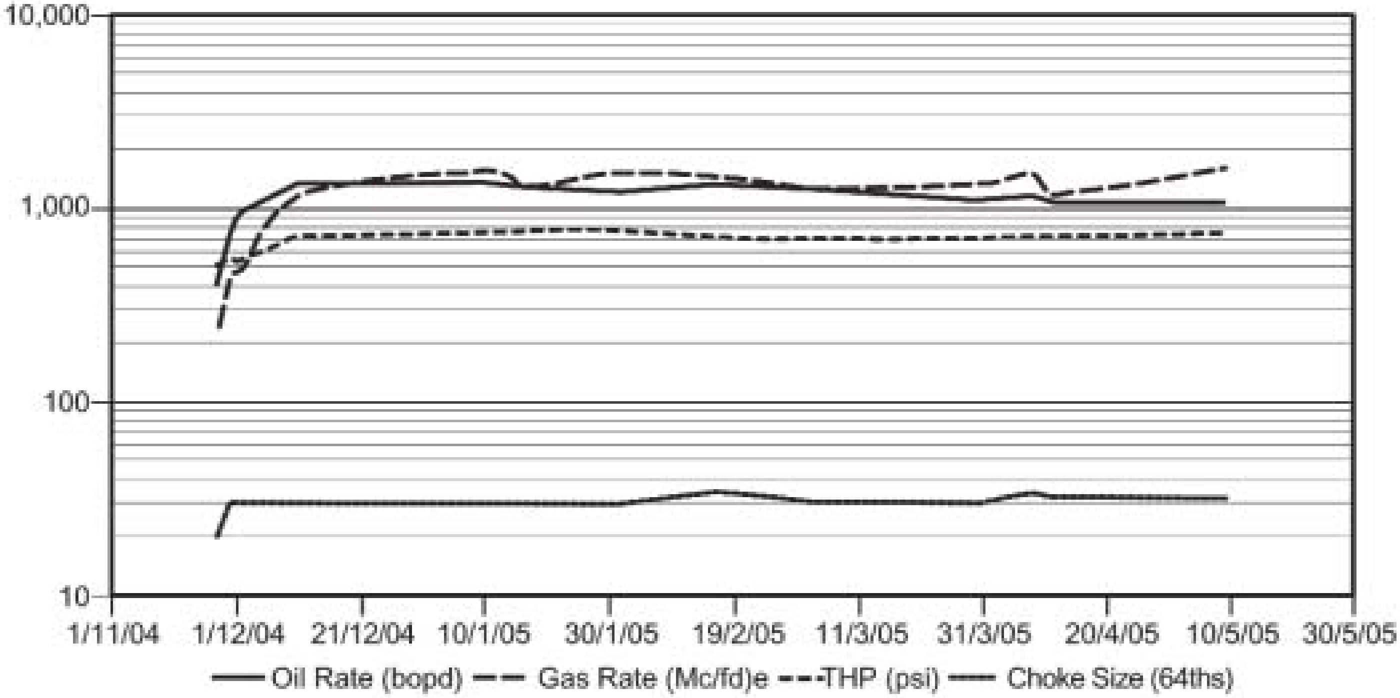

Fig. 15 — Case History 2 Production History

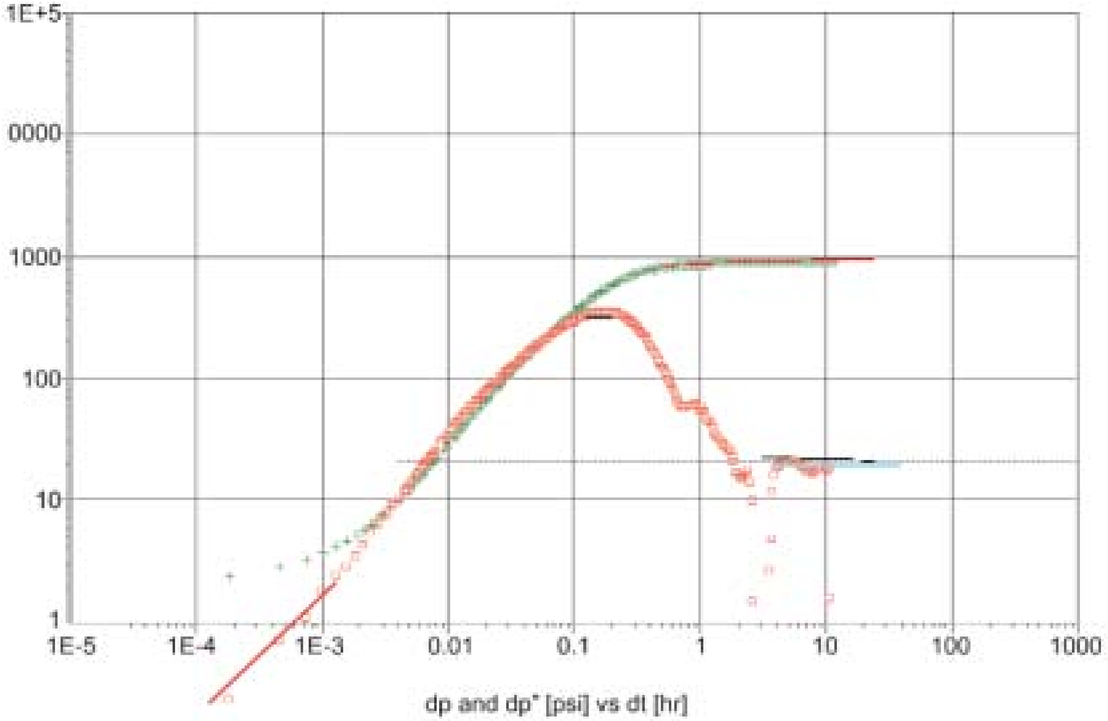

Fig. 16 — Case History 2 – Log-Log Buildup

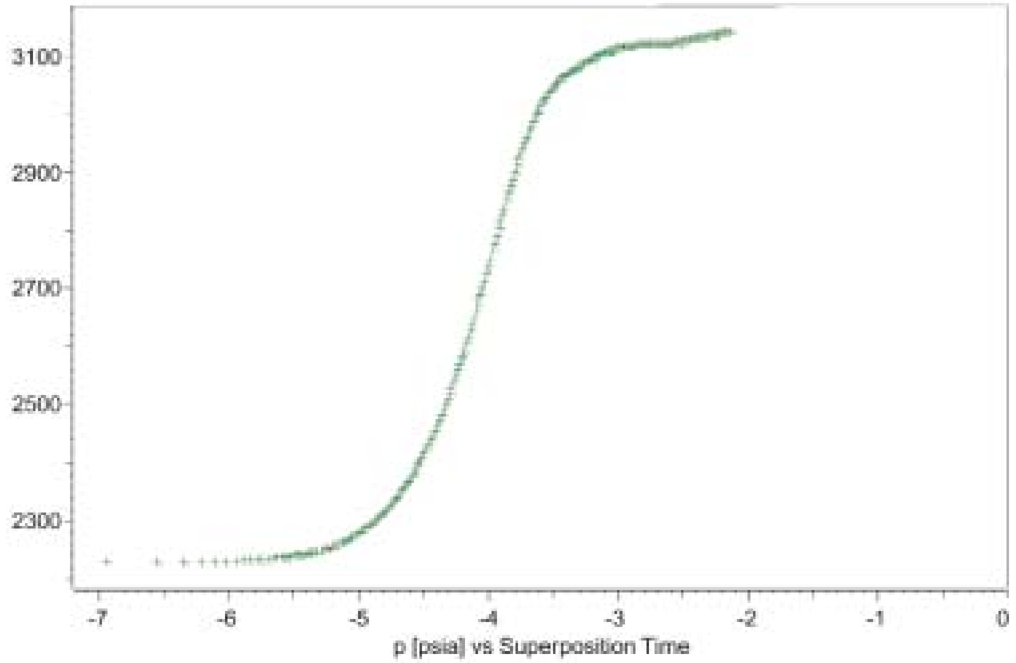

Fig. 17 — Case 2 Semi-Log Buildup

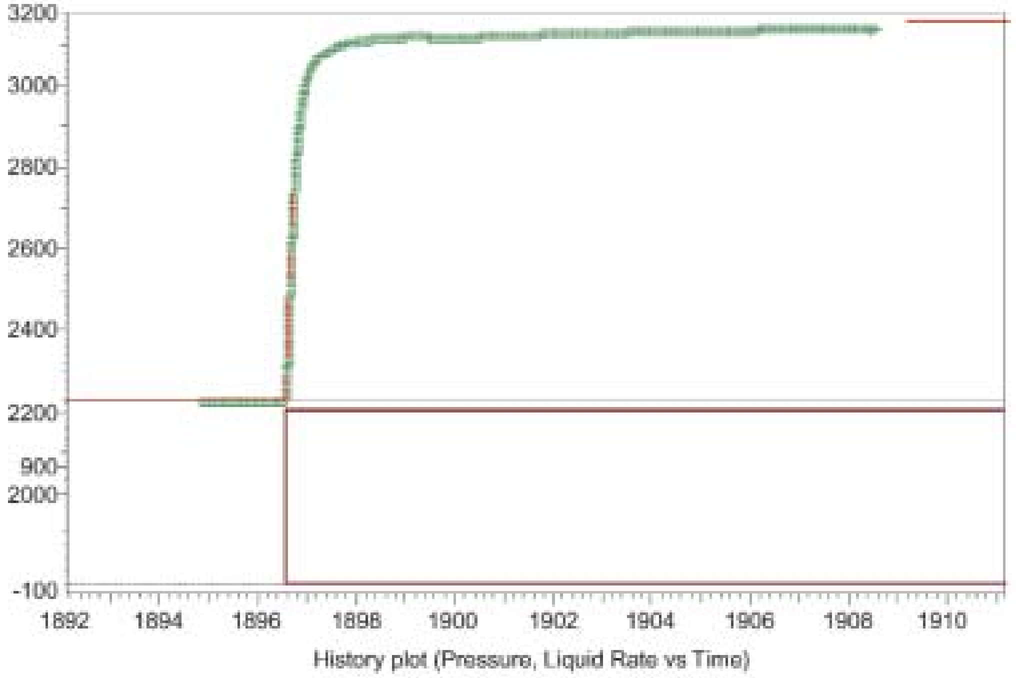

Fig. 18 — Case History Plot Drawdown/Buildup