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Next-Generation Perforating System Enhances the Testing and Treatment of Fracture Stimulated Wells in Canada

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Abstract

Ineffective perforation can adversely affect the completion of fracture stimulated wells in several ways. If the interval is to be tested prior to fracturing, a clean connection to the formation is required to facilitate meaningful data acquisition. Excessive perforation damage can mask true formation potential and lead to incorrect diagnosis and decision making. Inadequate perforations can result in significant fracture tortuosity, increasing formation breakdown pressure – occasionally beyond the capacity of surface equipment or design rating of the well. Finally, limited entry perforation – a common technique for diverting a treatment across multiple fracture initiation points – demands that as many perforations as possible are open and can accept treatment fluids. Low perforating efficiency and variations in perforation cleanup associated with heterogeneous formations can cause uneven treatment distribution and suboptimal completion.

Traditional methods for achieving clean perforations depend on creating a pressure gradient between formation and wellbore to induce flow and remove debris from the perforation tunnels - this can be difficult to accomplish, especially in low-pressure reservoirs. Underbalance cleanup favors intervals with higher flow potential – typically those with greater permeability - and may result in low perforation efficiency in poor or variable quality zones. Operators of wells requiring fracture stimulation are therefore faced with a significant challenge to find reliable, cost-effective perforating methods.

A new class of reactive shaped charges has recently been introduced that generates a powerful secondary effect within each perforation tunnel immediately after it is formed. The reaction supercharges each tunnel, causing a surge of flow into the wellbore that removes all compacted debris and the near-tunnel crushed zone that would otherwise impair flow performance. Since this effect is independent of rock properties and wellbore conditions, a very high percentage of clean tunnels can be obtained across the entire interval without necessarily perforating in an underbalanced condition.

This paper describes the new charge technology in greater detail and reports on its successful deployment in more than a dozen wells for different operators in Canada. Specific examples are used to illustrate how the system facilitates pre-frac evaluation, fracture initiation and limited entry fracture stimulation.

Introduction

Shaped charge perforators are the dominant method used to create a flow path between formations of interest and the wellbore in a cased and perforated completion. The vast majority of perforated completions depend on the use of shaped charges because of the relative speed and simplicity of their deployment compared to alternatives, such as mechanical penetrators or hydro-abrasive jetting tools. However, despite these advantages shaped charges provide an imperfect solution.

Shaped charges are formed by compressing high explosive powder within a metal case using a conical or parabolic metal liner, as depicted in **Figure 1**. When the explosive is detonated, the symmetry of the charge causes the metal liner to collapse along its axis into a narrow, focused jet of fast moving metal particles (**Figures 2A-2C**). When the charge is positioned perpendicular to the wellbore casing, the jet penetrates the casing, and the surrounding cement sheath and formation rock (**Figures 2D-2E**). This is a displacement mechanism where the steel, cement and rock are pushed aside by the jet[1], a process that continues until the speed of the jet falls below some critical velocity and cannot penetrate further[2]. The effectiveness of this perforation tunnel is determined by both its geometry and quality.

Tunnel Geometry and Quality. The distance the tunnel extends into the surrounding formation, commonly referred to as the total penetration, is a function of the explosive weight of the shaped charge; the size, weight, and grade of the casing; the prevailing formation strength; and the effective stress acting on the formation at the time of perforating.

Effective penetration is some fraction of the total penetration that contributes to the inflow or outflow of fluids. This is determined by the amount of compacted debris left in the tunnel after the perforating event is completed. Effective penetration may vary significantly from perforation to perforation, and there is currently no means of measuring it in the borehole. The effective penetration determines the effective wellbore radius, r_w, an important term in the Darcy equation for radial inflow:

$$q = \frac{2\pi kh(p_e - p_w)}{\mu\left[\ln\left(\frac{r_e}{r_w}\right) + S\right]} \tag{1}$$

Where:

q = Flowrate
k = Permeability
h = Reservoir height
p_e = Pressure at the reservoir boundary
p_w = Pressure at the wellbore
μ = Fluid viscosity
r_e = Radius of the reservoir boundary
r_w = Radius of the wellbore
S = Skin factor

Effective penetration becomes even more significant when near-wellbore formation damage has occurred during the drilling and completion process, for example resulting from mud filtrate invasion. If the effective penetration is less than the depth of invasion, fluid flow may be seriously impaired.

A further impairment to flow is caused during the perforating process when fractured sand grains, cement particles, metal particles from the disintegrating liner, and other fine debris are displaced by the jet and compacted into the pore throats of the surrounding rock. This zone, commonly referred to as the crushed zone, is typically of the order one-quarter inch thick and has been shown to have permeability one-tenth or less that of the undamaged rock[3]. The crushed zone forms a major component of perforation skin unless it can be removed during the perforation event or some subsequent operation.

Other factors contributing to the overall effectiveness of the tunnel as a flow conduit are: casing entry hole diameter (a function of shaped charge design and casing size, weight and grade); tunnel diameter (also a function of shaped charge design, rock strength and effective stress); tunnel fill (although loose fill is generally highly permeable and may be ignored), and the presence of any cracks or fractures extending into the formation from the tunnel wall.

Attempts at Achieving a High-Quality Perforation. Various approaches are taken to optimize the geometry and quality of the tunnel, either through remedial operations during or after the perforating event or through modification of the perforating system configuration.

Underbalance perforating is the most common optimization technique, whereby the hydrostatic pressure in the wellbore is reduced prior to perforating to create a pressure difference between the formation and wellbore. As the tunnel is created, this pressure difference induces flow from the formation towards the wellbore. Given sufficient pressure difference and formation permeability, enough flow velocity can be generated to destabilize the crushed zone and convey the plugging material into the wellbore. Some, or all, of the compacted fill may also be removed from the tunnel tip.

Dynamic underbalance techniques take advantage of the pressure difference existing between the perforating carrier (sealed at atmospheric pressure) and the wellbore (hydrostatic pressure) at the time of detonation. As a result of this pressure difference, wellbore fluid surges into the gun immediately after detonation, causing a locally sustained pressure drop in the wellbore across the perforated interval. This tends to induce a greater surge of flow from the newly-formed perforations than static underbalance alone, thereby enhancing the degree of crushed zone and compacted fill removal[4].

Unfortunately, both static and dynamic underbalance techniques are sensitive to formation permeability and the amount of pressure difference that can be created. When the formation permeability or reservoir pressure is too low, insufficient flow can be induced and tunnel cleanup is limited. Permeability contrasts within the perforated interval can result in cleanup being limited to only the zones of better permeability from which significant surge flow is obtained, eliminating the underbalance before tunnels in poorer zones have the opportunity to clean up.

In cases where below-expectation well performance is attributed to poor perforation cleanup, operators must either resort to more complex and costly techniques – such as acid stimulation, coiled-tubing deployed jetting tools, or fracture stimulation – or accept a suboptimal connection between the wellbore and the formation.

Effect of Suboptimal Perforations on Pre-Stimulation Testing. In low-cost operating environments the need to apply secondary cleanup techniques after perforating may significantly impact the economic viability of a well. Where hydraulic fracturing is necessary in order to obtain economic flow rates, some impairment to unstimulated inflow potential may not be of consequence. However, it is often desirable to measure the unstimulated productivity of an interval in order to estimate its likely productivity after stimulation, to design the stimulation itself appropriately, or even to determine whether the zone is worth stimulating or not.

Damaged perforation tunnels will cause the flow rate measured during a pre-stimulation test to be unrepresentative of the true flow potential of the interval. Since tunnel geometry and quality created in the wellbore cannot currently be measured, the operator must assume or infer the degree of damage based on past experience, rules of thumb, and (rarely) on laboratory experiments carried out under representative conditions. This uncertainty compromises both the ability of the operator to make sound stimulation design decisions and any subsequent evaluation of stimulation treatment success.

Consequences During Fracture Stimulation. Fracture stimulation involves raising the wellbore pressure to the point at which the surrounding rock fails resulting in the creation of a fracture. This is typically carried out by pumping fluids into the well at high rates and pressures (hydraulic fracturing) or by igniting gas-generating material within the wellbore adjacent to the perforated interval (propellant fracturing). Hydraulic fracturing typically results in fractures extending tens to hundreds of feet from the wellbore – depending on the amount of fluid pumped above the fracture propagation pressure. Propellant techniques generate fractures extending five to twenty feet from the wellbore, and are generally used to overcome near-wellbore damage or in situations where larger fracture treatments risk extending into a water-bearing interval.

Perforations play a critical role in any stimulation treatment because they form the only connection between the wellbore and formation. However, arriving at an optimum perforation design can be difficult because essentially all perforated completions are damaged. The residue from the perforating charge plugs the end of the perforation tunnel and the rock surrounding the perforation tunnel is pulverized and compacted by the explosive shock of the perforating event. The perforating event is so fast that the associated rock deformation and compaction exceed the elastic limit of the rock and result in permanent plastic deformation. Along with changes in porosity and permeability, the in-situ stress in the plastically deformed rock is also substantially changed, forming a stress cage extending several inches beyond the actual dimensions of the tunnel[5].

The compacted zones around the perforation can be so highly stressed that the pressure required to initiate a fracture is significantly greater than the measured fracture gradient of the unaltered rock[6]. In extreme cases the altered rock cannot be broken down before surface equipment limitations are reached. When breakdown is possible, the induced fracture will try to follow a path of lower stress, through unaltered rock, resulting in increased near-wellbore pressure drop, commonly known as tortuosity.

Severe pressure losses may limit the flow rate that can be delivered into the fracture with the available pump capacity and completion constraints. This will limit the size of the fracture that can be created and may result in the operation being terminated prematurely to avoid screen-out (a situation where proppant added to a hydraulic fracture treatment in order to hold open the fracture can no longer be transported into the formation and fills the wellbore, requiring expensive remediation). Final fractured well productivity will also be damaged as a result of the low conductivity channel established at the wellbore.

Limited Entry Stimulation. In situations where several intervals in the same well require stimulation and it is advantageous to perform such stimulations in one operation, treatment fluids must be distributed across the different intervals in order for each to be stimulated effectively. This process is called treatment diversion and is critical to achieving optimum productivity as a result of the stimulation treatment.

Limited entry perforation is a popular diversion method because of its relative simplicity and low cost compared to alternatives such as ball sealers and self-diverting treatment fluids. The technique involves perforating a carefully calculated number of holes across each interval in order to restrict the flow rate that can enter each zone. This theoretically ensures that the total flow rate is distributed in proportion to the number of holes created in each zone. In reality, the perforations will not all clean up equally and will therefore take fluid at different rates.

Poor or inconsistent cleanup will mean that the effective number of perforations is less than the actual number of shots. This may vary from interval to interval, depending on formation properties and their influence on tunnel cleanup, causing the actual distribution of treatment fluid to deviate from the theoretical design. In severe cases, some zones may not be stimulated at all.

Opportunity for Enhanced Perforation Cleanup. Each of the scenarios described above provides an opportunity for enhanced perforation cleanup, preferably achieved as part of the primary perforating operation and not by introducing additional operational complexity or cost. If clean perforation tunnels can be reliably delivered irrespective of formation properties and without requiring the application of a large pressure difference, pre-stimulation testing will yield a more accurate measure of the intervals production potential, fracture stimulation treatments will be completed without reaching equipment pressure limitations or risk of screen-out, and limited entry perforation will become a more reliable method for multi-zone stimulation treatment diversion.

New Shaped Charge Technology

A new class of shaped charge has recently been introduced that uses novel liner metallurgy to create a secondary reaction in the perforation tunnel immediately after it has been formed (**Figure 2F**). The reaction takes place in less than 100 microseconds and can therefore be considered part of the perforating event.

The reaction is highly exothermic, which under the confined conditions within the perforation tunnel results in the generation of a very short, sharp spike in pressure. The magnitude of this super-charging effect has been measured in the 50,000-80,000 psi range during laboratory experiments carried out by the manufacturer. The energy released per unit mass of reactive material is of the same order as that released by TNT, although the total energy released per tunnel is relatively low because only a fraction of the shaped charge liner is composed of reactive material.

Relief of this pressure into the wellbore (being the path of least resistance) causes a surge in flow, which expels debris from the tunnel (**Figure 2G**). Laboratory experiments under representative conditions (carried out in compliance with API recommended practices for perforator evaluation[7]) indicate that all compacted fill is removed from the tunnel tip and the entire crushed zone is removed from the tunnel wall. Furthermore, in most cases, the pressure spike is sustained long enough for a small fracture to initiate at the tip of the tunnel (**Figure 2H**). This is of significant benefit during subsequent stimulation operations. **Figure 3** shows tunnels created during single shot perforation experiments using natural rock targets under conditions representative of the downhole environment. **Figure 3A** shows a classical tunnel created with a conventional charge and **Figure 3B** shows a tunnel created with the new class of reactive shaped charge.

The cleaning effect introduced by this class of charge offers a significant advantage over conventional products and addresses many of the challenges described in the introduction. This cleaning effect is independent of the formation properties, provides a driving force at least one order of magnitude greater than conventional underbalance (in excess of 50,000 psi versus typically less than 5,000 psi), and takes place in each tunnel independent of the others.

Methodology

Although the geometry and quality of tunnels created with the new perforating charge have been extensively tested and compared to conventional technology in the laboratory, benefits prior to and during fracture stimulation can only be assessed during actual well operations. The new charge has been deployed by numerous operators across North America and in other regions of the world. This paper focuses on examples from Western Canada, where the technology has been evaluated in fields with significant numbers of existing wells for comparison purposes.

The primary method for characterising the near-wellbore region in order to compare the efficacy of the new and conventional perforating systems is a step-down test, carried out during a mini-frac (also known as a data frac) prior to the main stimulation treatment. The mini-frac is used to obtain a direct measurement of formation properties such as the breakdown gradient and fluid leak-off coefficient, so that the treatment design can be fine-tuned prior to execution.

The step-down test involves pumping a constant fluid into the well at several distinct rates while measuring pump pressure. By combining this information with the other parameters calculated as a result of the mini-frac, near-wellbore pressure losses, perforation friction, and the number of open perforations can each be estimated[8]. Equation 2 is used to predict perforation friction pressure as a function of rate, the number of perforations taking fluid, the diameter of each perforation (obtained from manufacturers' surface tests), and the discharge coefficient. The discharge coefficient may be estimated from the perforation diameter, assuming a round perforation, or measured empirically during tests at surface.

$$P_{pf} = \frac{1.975 q^2 \rho_f}{C_D^2 N_p^2 d_p^4} \qquad (2)$$

Where:

P_{pf} = Perforation friction pressure (in psi)
q = Total pump rate
ρ_f = Slurry density
C_D = Perforation discharge coefficient
N_p = Number of open perforations
d_p = Perforation diameter

Predicted pump pressure is plotted against measured pump pressure at each of the test rates. Since the other variables are essentially constant, the number of open perforations and the discharge coefficient can be iteratively adjusted until a good match is obtained between predicted and measured values.

Comparison of these results between wells perforated with the new shaped charge and wells perforated with a conventional system will indicate whether the cleaning effect delivered by the new charge is of material benefit under field conditions.

Results

Wells perforated with the new reactive charges across five different formations were analyzed in terms of fracture initiation pressure, near-wellbore pressure losses during fracture stimulation, and treating power requirements.

The first analysis presented features two wells typical of the overall dataset, one perforated with a conventional system and one perforated with the reactive system. Differences in each of the parameters of interest are examined, based on step-rate data gathered during mini fracs (which were only performed on selected wells in the total population). The second analysis compares treating power requirement across a population of wells, a subset of which were perforated with the reactive system.

Step-Rate Test Results. This example features two wells completed at a depth of approximately 2,500 m in the Rock Creek sandstone formation in West Pembina. Wells in this area are typically perforated and hydraulically fractured. Problems are occasionally encountered with excessive breakdown pressures.

In this example, Well A was perforated using a 3 m long, 3.3/8 inch (86 mm) diameter, expendable hollow steel carrier loaded with regular 23 gram, deep penetrating charges at a density of 9 shots/meter, and 60-degree phasing. Well B was perforated with 4.5m of 3.3/8 inch (86mm) diameter guns distributed across a gross interval of 35 m, loaded with the new reactive shaped charges at a density of 6 shots per meter, and 120-degree phasing. The total number of shots in each case was 27.

Table 1 shows the formation breakdown pressure, breakdown gradient, and fracture propagation gradient. The data indicate that although Well B exhibited a much higher fracture gradient (24.2 kPa/m versus 18.2 kPa/m), the breakdown gradient was actually less than that measured in Well A (26.9 kPa/m versus 28.0 kPa/m).

Figure 4 shows total near-wellbore pressure losses calculated from the step-rate test. At a typical treating rate of 2.5 m^3/min, Well B (new charge) experiences only 2,800 kPa pressure loss compared to 11,000 kPa in Well A (conventional charge). **Figures 5** and **6** show the calculated pressure losses due to tortuosity (near-wellbore pressure loss) and perforation friction. Perforating with the new charge almost eliminated tortuosity (<200 kPa at 2.5m^3/min versus 4,300 kPa with the conventional charge) and significantly reduced the perforation friction (2,600 kPa at 2.5 m^3/min versus 6,700 kPa). The calculated number of open perforations is 5.2 for the regular charge (19.3% efficiency) and 7.4 for the new charge (27.4%).

Since step-rate test interpretation involves iterative matching of a model to the field data, the results are dependent on the quality of data gathered and subject to a certain amount of engineering judgment. However, consistent application of the same methodology has confirmed similar results across multiple pairs of wells in the region and elsewhere.

Treating Power Analysis. To further examine the impact of perforating with the new charges on hydraulic fracture treatment, an analysis has been conducted of treating power requirements against treating rate in the Cadomin formation. **Figure 7** shows a crossplot of treating power against rate for the fifteen wells studied. Those wells perforated with the new charge clearly fall on the low side of the overall dataset, confirming our hypothesis that cleaner tunnels allow treatment at reduced pressure loss, and therefore use less hydraulic horsepower.

Furthermore, the average breakdown pressure gradient was reduced by 41% (from 14.3 kPa/m for wells perforated with conventional charges to 8.4 kPa/m for wells perforated with the new charges) and the average treating gradient was reduced by 19% (from 16.2 kPa/m with conventional charges to 13.2 kPa/m with new charges).

These benefits translate directly into value for the operator, who is able to reduce pumping costs for a given treatment.

Conclusions and Significance to Industry

Perforating with the recently introduced reactive perforators significantly reduces near-wellbore pressure effects observed during fracture stimulation.

The difference between measured formation breakdown gradient and fracture gradient (which affects the surface pressure required to initiate the fracture) is significantly reduced. This minimizes the risk of being unable to initiate the fracture due to surface equipment pressure limitations, reduces the stress placed on surface equipment operating at high pressure (lower maintenance costs), and may allow operators to mobilize fewer hydraulic horsepower to location (lower operational costs).

Near-wellbore pressure losses during treatment (also known as tortuosity) are reduced to negligible levels. In combination with greater open area to flow as a result of higher perforating efficiency, this facilitates placing the fracture treatment as designed and reduces the risk of screen-out. The increased number of open perforations in contact with the fracture should also lead to improved productivity.

The benefits of increased perforation efficiency (holes open and taking fluid) and predictable pressure losses are particularly significant where limited entry perforating is used as the diversion technique for simultaneously stimulation multiple zones.

The ability to place a very high percentage of fractures as designed – and to apply more aggressive fracture designs once sufficient comfort has been gained with the new system – leads to greater overall well productivity.

Further work is ongoing to evaluate the efficacy of the new perforating charge to a wider range of lithologies, reservoir properties, and pressure/stress regimes. The results of this work will be reported in a future paper.

Nomenclature

kPa = KiloPascal
m = Meter
m^3 = Cubic meter
min = Minute
psi = Pounds per square inch

Acknowledgements

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Tables

Table 1 – Comparison of Critical Fracturing Parameters

Property	**Well A** **(Conventional Charge)**	**Well B** **(New Charge)**
Bottom hole breakdown pressure	72,000 kPa	63,500 kPa
Breakdown gradient	28.0 kPa/m	26.9 kPa/m
Frac gradient	18.2 kPa/m	24.2 kPa/m
Incremental breakdown gradient	9.8 kPa/m	2.7 kPa/m
Open Holes / Total Shots	5.2 of 27	7.4 of 27
Perforating Efficiency	19.3%	27.4%

Figures

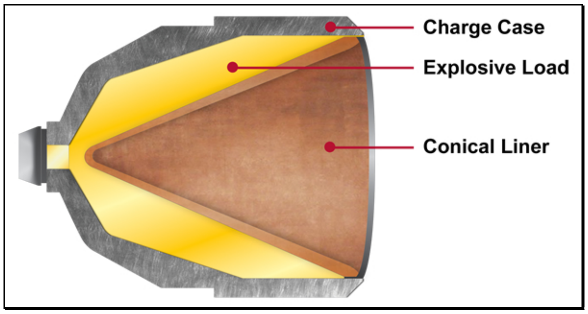

Figure 1 – Cross-Section through a Shaped Charge

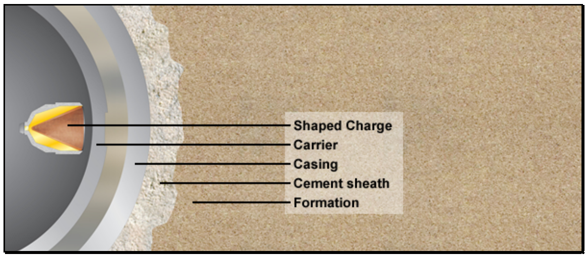

Figure 2A – Prior to Perforating System Initiation

Figure 2B – Shaped Charge Detonating

Figure 2C – Jet Penetrating Carrier Wall

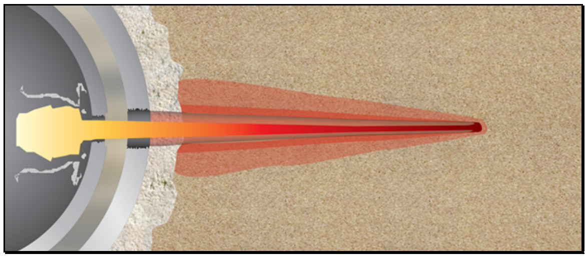

Figure 2D – Jet Penetrating Casing, Cement & Formation

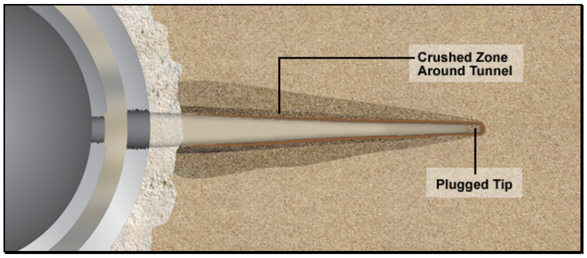

Figure 2E – Conventional Tunnel with Crushed Zone

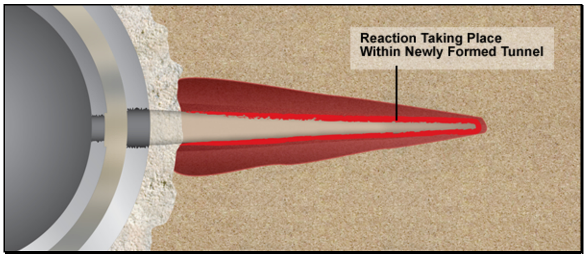

Figure 2F – New Charge Creates Reaction in Tunnel

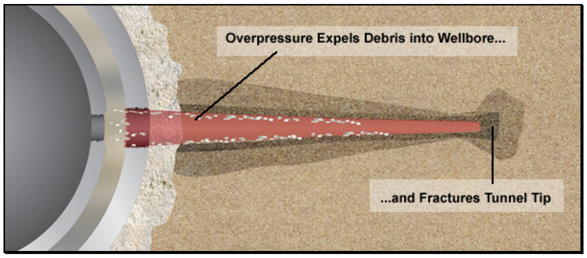

Figure 2G – Over-pressure Expels Debris and Fractures Tip

Figure 2H – New Debris-Free Tunnel with Fractured Tip

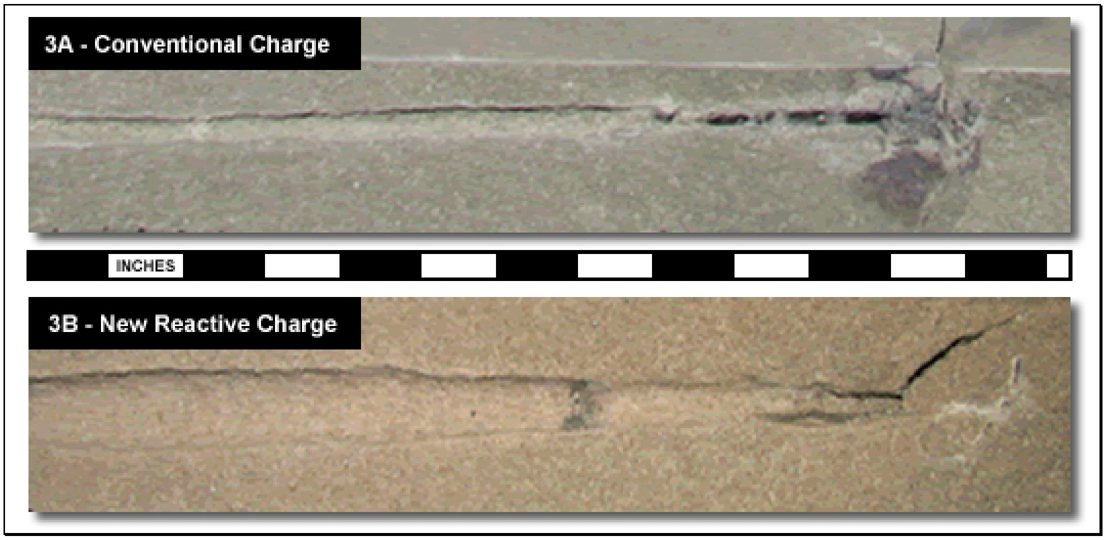

Figure 3 – Comparison of Tunnels Created with Conventional and New Charge Types

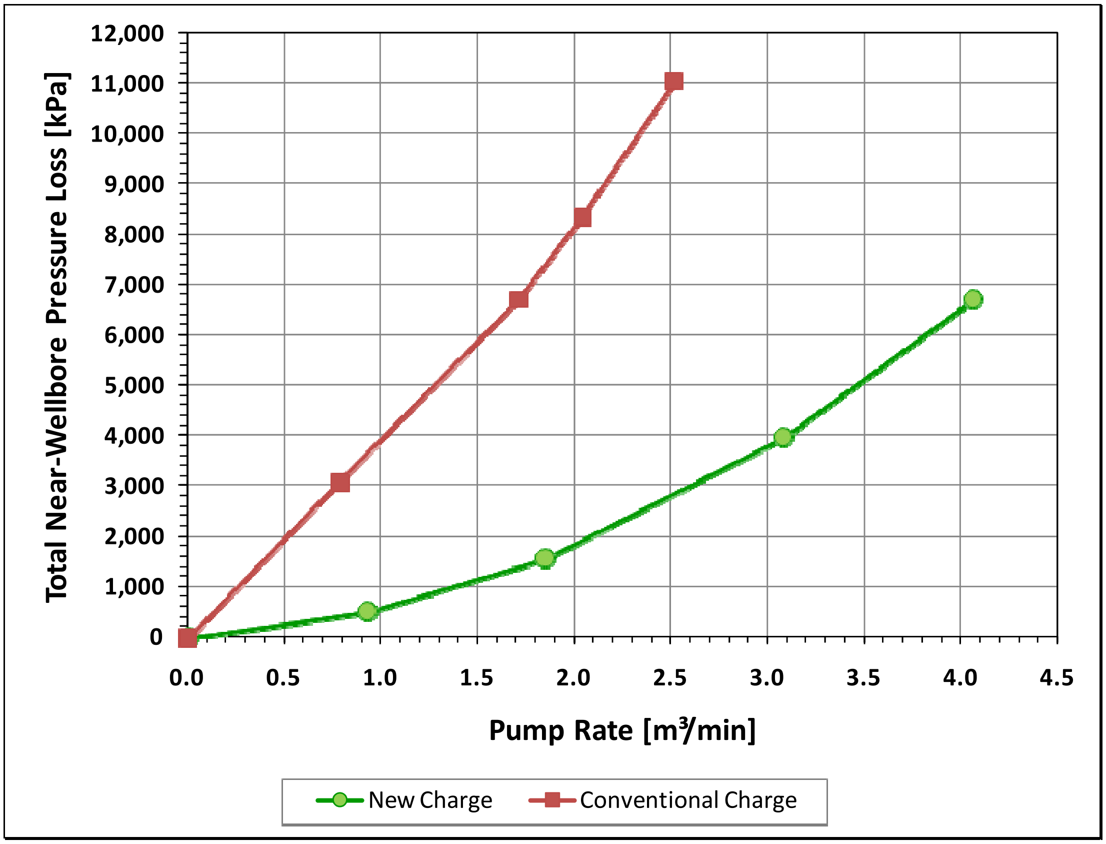

Figure 4 – Comparison of Total Near-Wellbore Pressure Losses

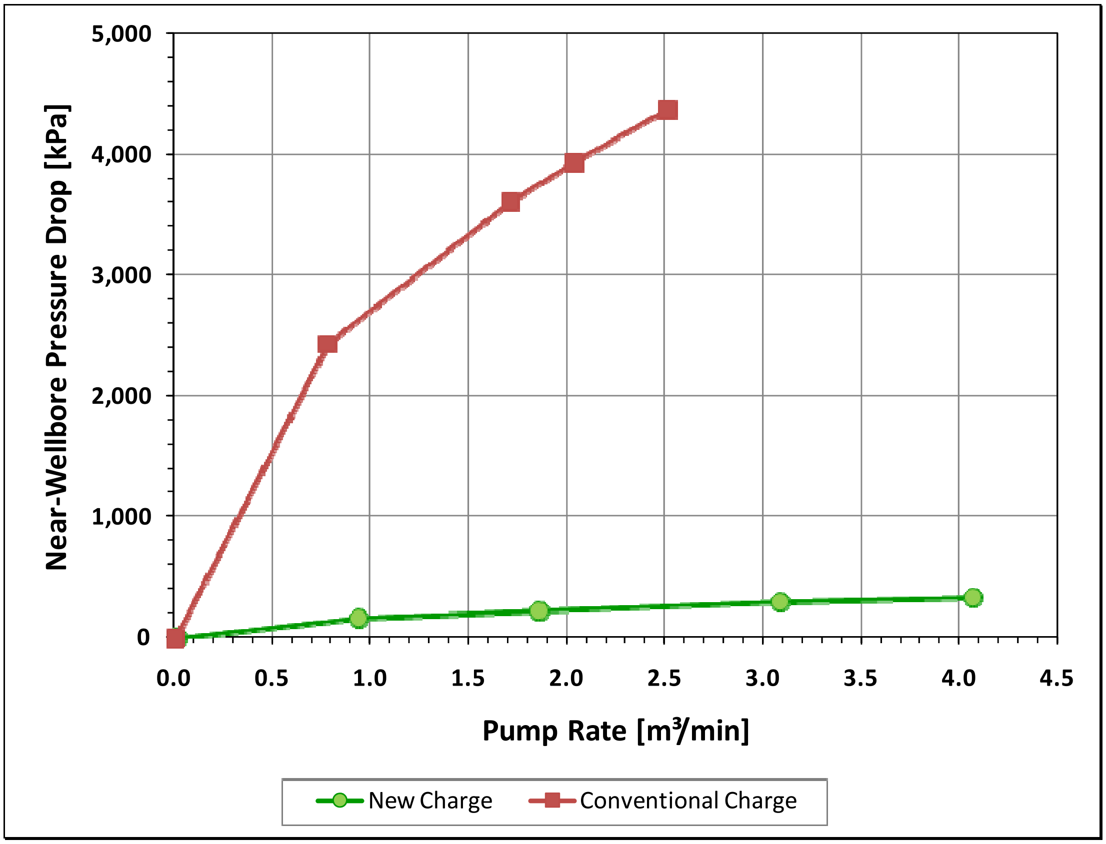

Figure 5 – Comparison of Near-Wellbore Pressure Drop (Tortuosity)

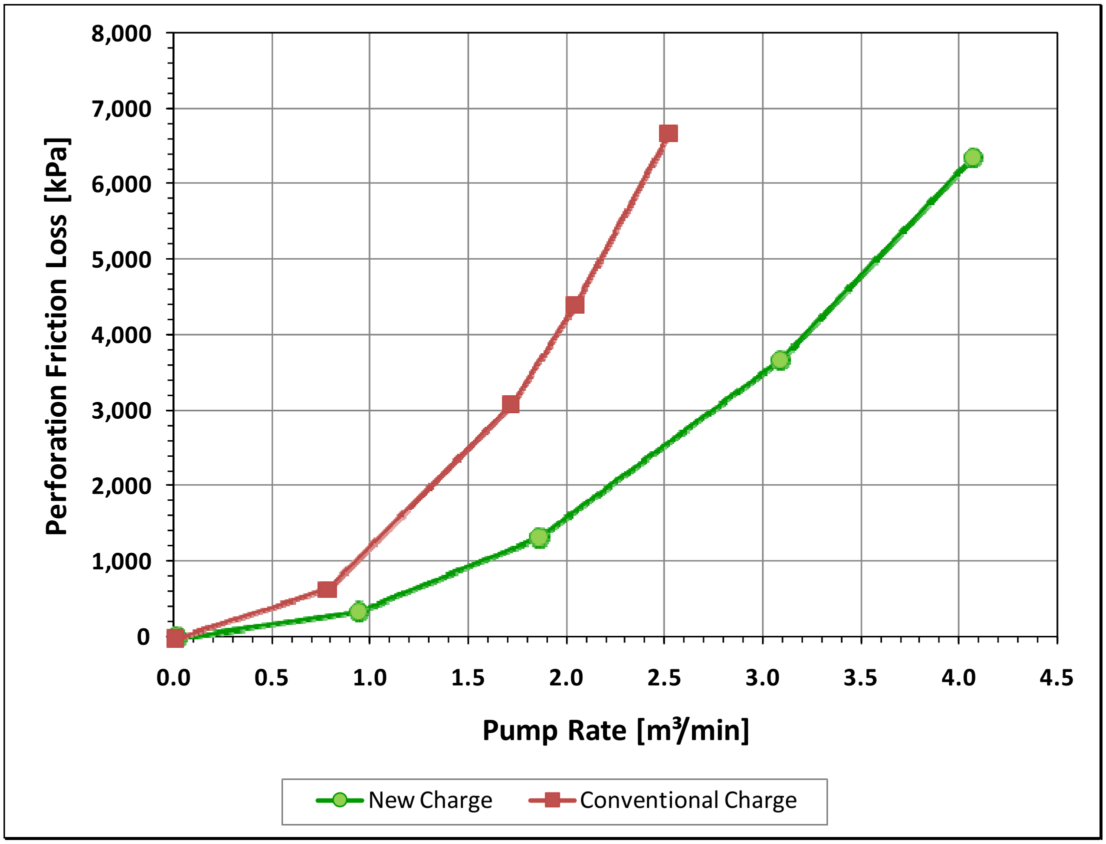

Figure 6 – Comparison of Perforation Friction Losses

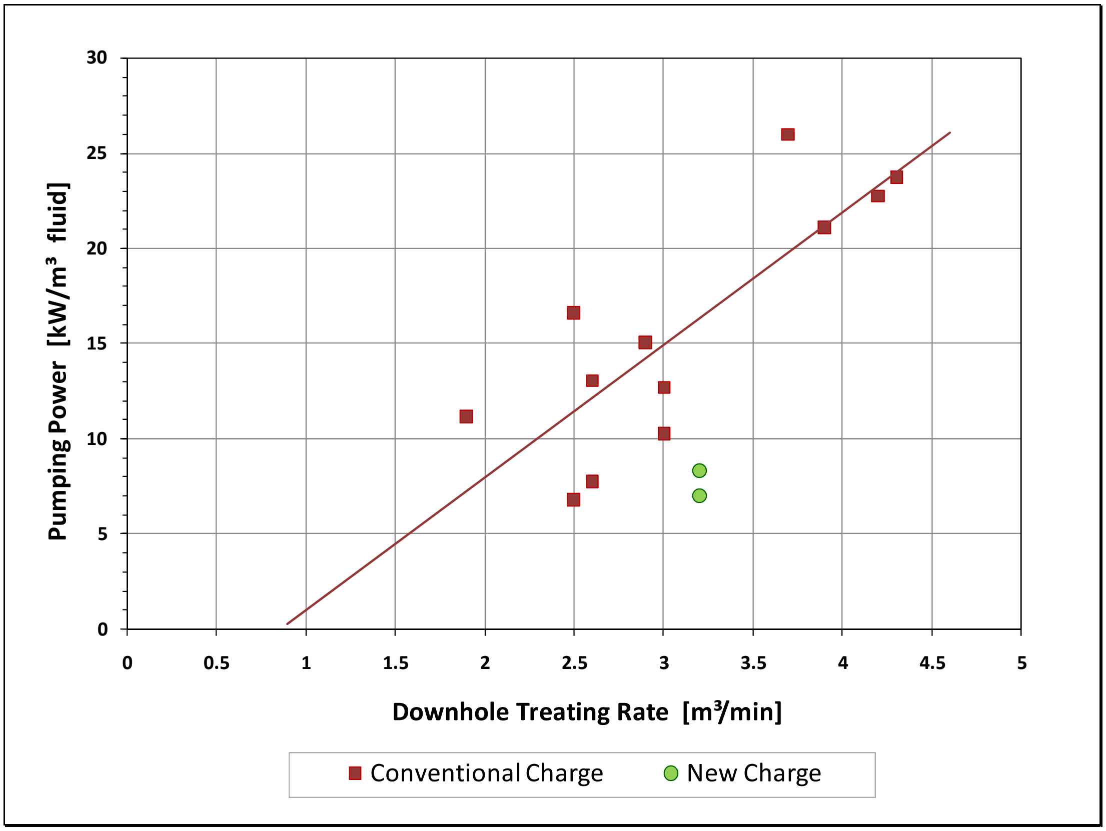

Figure 7 – Comparison of Pumping Power Requirements