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Successful Introduction of Next Generation - Reactive Liner Perforating Technology in Pakistan

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Abstract

Maximizing productivity from every well has always been the ultimate objective of industry experts. Connecting the wellbore with the reservoir is a key element towards meeting this challenge. In the case of perforated completions, techniques like static and dynamic underbalance are used to try and remove the crushed zone caused by the perforation process. In marginal reservoirs, poor connectivity can be the difference between a commercial discovery and a dry well.

Reactive liner perforation technology is a new technique which removes the crushed zone using a highly exothermic reaction, providing a step-change improvement in perforation geometry and performance. The reaction breaks up and expels debris to leave a clean, undamaged tunnel, even in variable or low quality rock. This process is independent of lithology and wellbore conditions. This next generation perforating technique has recently been launched in Pakistan with exceptional results.

This paper describes these successes in greater detail. When compared with offset wells with identical parameters, perforated using relatively new techniques, the superiority of the reactive technique was proven. Significant rate improvements and very low (negative in some cases) values of total skin were measured. When applied prior to hydraulic fracturing, significantly reduced initiation pressures and lower horsepower requirement added significant value through optimized fracturing treatment, reduced risk of screen-out, and reduced expenditure.

Results in-hand prove the superiority of this technology in improving well connectivity, particularly in tight gas reservoirs. The independency from rock properties and wellbore conditions are truly added advantages of the reactive liner technology. This is a technically viable and cost efficient option for ensuring operators achieves their production objectives.

Introduction

Achieving optimum well productivity depends on effective connectivity to the reservoir. Poor connectivity will not only have a detrimental effect on the well production but will increase the completion and operating cost of the well due to additional remedial treatments and interventions required to improve the well production. Poor connectivity can lead to incorrect diagnosis of the reservoir's true potential which can affect the operator decision if the well is commercially viable for production or if it is to be plugged and abandoned.

In cased and perforated completions, perforating techniques are used to provide a conduit for the inflow of hydrocarbons or injection points for injectants. Since its introduction in 1950s, shaped charge perforators have been the dominant perforating method. The shaped charges employ an explosive cavity effect coupled with a metal liner to maximize penetration. Once the main explosive is detonated, the liner collapses to form a high-velocity jet that is propelled outward at approximately 30,000 ft/sec. The shaped charge deployment simplicity is its main advantage and over the years, new developments in shaped charge perforations have allowed operators to create deeper perforation tunnels. Achieving maximum penetration depth is important as it contributes to the effective wellbore radius, however the main factor which leads to optimum well flow performance is the quality of the perforation tunnel. Shooting so deep requires a violent and damaging event, where the rock surrounding the tunnel is deformed far beyond its plastic limit and smashed rock fragments are driven into the adjacent pore throats (Bell 2009). This so called "crushed zone" is almost impermeable to flow. In addition, the compacted fill at the tip of the tunnel and debris remaining in the tunnel further contributes to inefficiency of the perforation.

Static underbalance and dynamic underbalance has been applied during perforation to satisfy the need to achieve "clean" tunnels. Unfortunately both techniques have limited applications as both depend on the rock permeability and pressure

difference that can be created. Underbalanced perforating relies on the pressure difference between formation and wellbore inducing a surge of flow to break up and remove debris from the perforation tunnels. If the reservoir pressure and/or permeability are low, or if the wellbore pressure cannot be lowered substantially, there may be insufficient driving force to break or remove the debris. In heterogeneous formations, variation in permeability will result in partial cleanup of the intervals leaving behind lower permeability sections still damaged. Dynamic underbalance techniques generate a stronger, more sustained underbalance but cannot mitigate inadequate reservoir energy, heterogeneity, or critically low formation permeability. Due to these limitations, operators normally resort to additional treatments such as perforation wash, matrix stimulation or fracturing in order to improve the well connectivity. Though, the remedial treatment is sometimes costly and is often ineffective.

In tight reservoirs which require hydraulic fracturing treatments, the need for clean perforation tunnels is critical. Damaged tunnels will result in incorrect evaluation of the true flow potential of the interval and can affect the design of the stimulation treatment. In addition, damaged tunnels will also cause elevated fracture initiation pressure, increased near wellbore pressure drop and may limit the flow rate delivered into the fracture during the treatment (Bell and Cuthill 2008). The final fracture conductivity will be badly affected due to poor quality of the perforation tunnels.

Reactive Liner Perforating Technology

A new next generation reactive liner perforating technology was introduced to the industry in late 2007. This technology delivers a step-change improvement in perforation geometry and performance. The reactive liner perforating systems uses novel liner metallurgy to create a secondary reaction in the perforation tunnel immediately after it has been formed. The reaction takes place in less than 100 microseconds. The reaction is highly exothermic, which under the confined conditions within the perforation tunnels result in the generation of a very short, sharp spike in pressure in the magnitude of 50,000 to 80,000 psi. The pressure is relieved into the wellbore causing a surge in flow, which expels debris from the tunnel. In most cases, the pressure spike is sustained long enough to initiate a small fracture at the tip of the tunnel. This cleaning effect is independent of rock properties, wellbore or formation pressures, provides greater surge flow 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. This ensures high perforating efficiency compared to conventional perforating techniques (Bell and Cuthill 2008).

Reactive liner perforating technology delivers debris-free tunnels without depending on underbalance. The result is incredible perforating efficiency, superior productivity, enhanced injectivity, and dramatic improvements in stimulation parameters and performance. In addition, the reactive liner perforating charge is compatible with existing gun technology and perforating procedures so companies do not have to change the way they handle, ship or operate perforating equipment.

Reactive liner perforators offer significant benefits to fracture stimulation operations. The clean perforation tunnels created with fractured tips are the best place to initiate matrix fracturing. By virtue of the fractured perforation tunnel tips the reactive charges deliver, fracture initiation pressures can be significantly reduced. Since fracture initiation pressure is typically the highest pressure encountered during a stimulation treatment, any improvement translates directly into a reduction in hydraulic horsepower requirements – and often into a reduction in the overall job cost. By delivering a higher percentage of clean tunnels open to receive fracturing fluid, a reduction in perforation friction is observed. Although this is a secondary effect in many fracturing operations, it can be significant when only a very short interval is perforated (i.e. very few total holes are created). As a result of the unobstructed tunnels and the fractured tunnel tips, near-wellbore pressure losses (also known as “tortuosity”) are dramatically reduced. This may be visualized as providing the fluid with an unimpaired pathway from the perforation tunnel and onto the preferred fracture plane (dictated by the prevailing stress regime). Both perforation friction and near-wellbore pressure losses can be interpreted from step-rate tests carried out ahead of the fracture stimulation treatment (Bell et al. 2009).

Since the introduction, the reactive liner perforating technology has been successfully applied worldwide, delivering spectacular results in improving well productivity and injectivity (50% greater than expectation in new well, 20 to 2,000% increase in re-perforation wells), reducing fracture initiation pressure (20 to 70% reduction), eliminating the near-wellbore pressure losses and reducing perforation friction during fracture stimulation (Bell and Clark 2009). The reactive perforating is establishing itself as the new, preferred solution for high-performance completions.

Field Applications

The reactive liner perforating technology was first introduced in Pakistan in October 2008 in Salsabil gas and condensate field. The Salsabil field is located in Safed Koh block, Pakistan, which is shown in Fig. 1. The following sections discuss the field results of this technology and share the findings and lesson learned from its applications. The reactive liner perforation was introduced successfully in two different types of applications: shoot and produce and re-perforation prior to hydraulic fracturing. Since then, reactive

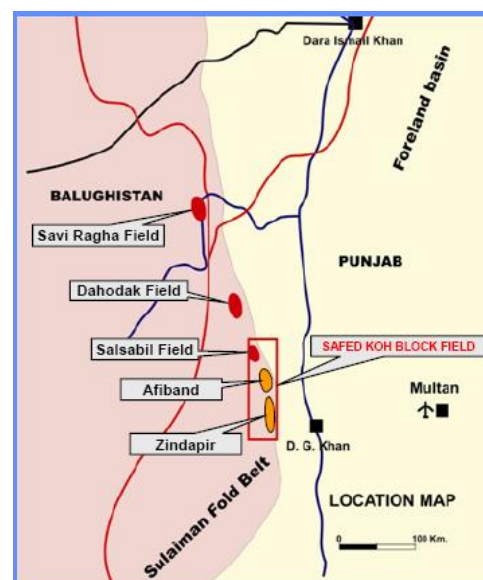


Fig.1 – Location Map, Salsabil Field, Pakistan

liner perforating has been a standard perforating techniques used by the operator for all their perforating requirements.

Case 1 – Shoot and Produce

The Salsabil field is on production since June 2007 from Lower Goru and Pab / Dunghan horizons. In early 2008, gas and condensate discovery was made from Chiltan formation through Well A. Chiltan formation is a naturally fractured carbonate reservoir. Well B was drilled and tested in late 2008 as an appraisal/development well of Chiltan discovery. It is approximately 1.1 km north of Well A. Both wells are vertical.

Well A was perforated using underbalance technique with conventional deep penetration charges. Acid stimulation with 15% hydrochloric acid at 43.5 gal/ft was then carried out after the perforation on Well A as a standard practice of the operator for carbonate reservoir. Whereas, the new Well B was perforated using overbalance shoot and pull technique with reactive liner perforating technology. It is worth mentioning that even though reactive liner perforating system is independent of wellbore conditions such as underbalance condition, it was also not operationally feasible to perform underbalanced perforation technique on Well B as the perforation intervals run across two different casing sizes. Thus, making the reactive liner perforating the best option available for Well B. Acid stimulation with 15% hydrochloric acid at 20 gal/ft was also carried out in Well B after perforating it using reactive liner perforating technology.

Cased hole drill stem testing followed by production logging survey were conducted at Well B after the perforation and stimulation. Production logging results showed that only a few sets of perforated intervals were contributing to flow. Despite that, the pressure transient analysis of the test data from drill stem testing revealed a negative 3 total skin. The match on log-log and semi-log plots are reproduced in **Fig. 2** and **Fig. 3**. The data matched with dual porosity model with constant wellbore storage and rate dependent skin. The derivative plot does not show any boundary or discontinuity. In spite of limited entry into wellbore (based from production logging survey results), no partial penetration was detected in the pressure transient analysis. It is suspected that the different contribution could either be because of different fracture intensity of layers or due to the presence of different permeability layers.

The absolute open flow potential (AOFP) of Well B was estimated to be 60 MMscf/D which was 3 times more compared to Well A of 19.5 MMscf/D.

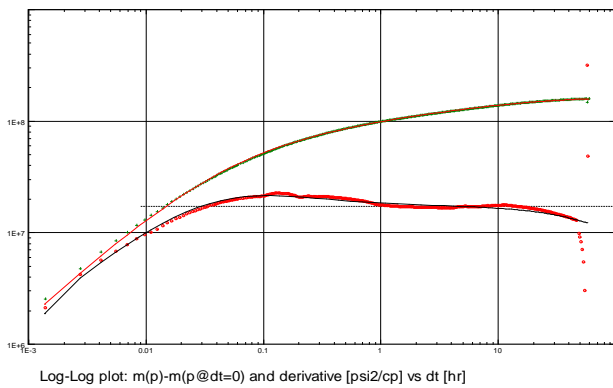


Fig. 2 – Well B (Chiltan) Log-Log Plot

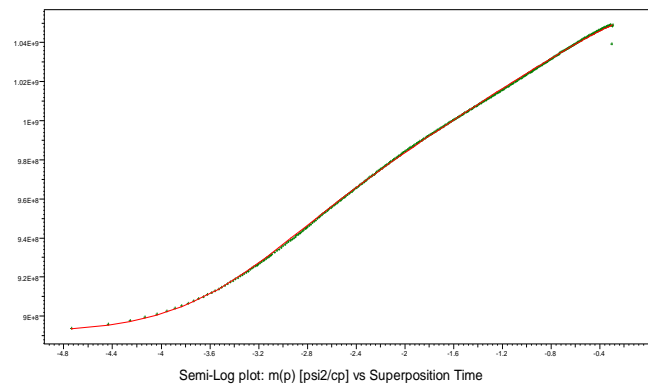


Fig. 3 – Well B (Chiltan) Semi Log-Log Plot

The log-log and semi-log plot of Well A are reproduced in **Fig. 4** and **Fig. 5** below. The pressure transient analysis of Well A indicated post-acid total skin of positive 4 as compared to negative 3 of Well B. This was despite of Well A was stimulated in bigger volume (more than double) than Well B. This result clearly shows the effectiveness of reactive liner perforating technology in achieving optimum connectivity to the reservoir.

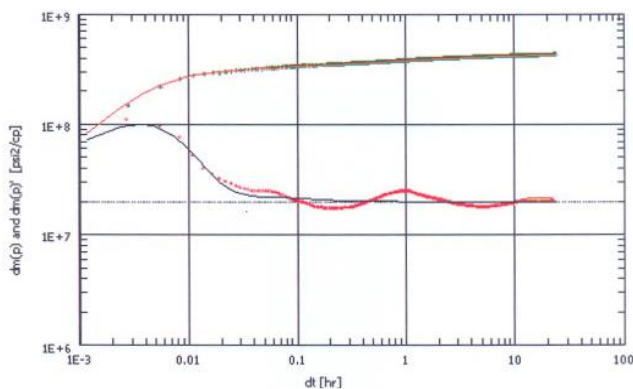


Fig. 4 – Well A (Chiltan) Log-Log Plot

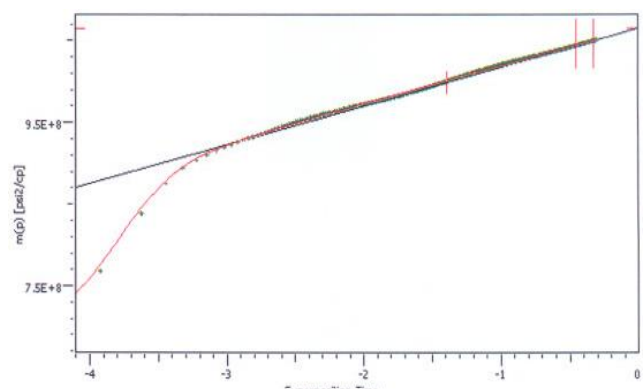


Fig. 5 – Well A (Chiltan) Semi-Log Plot

Understanding well performance and selecting appropriate candidates for reactive liner perforating technology is a critical activity. Reactive liner perforating cannot overcome massive formation damage that invades deeper than the total penetration of the perforations. Nor can reactive liner perforators guarantee productivity from intervals that failed to deliver in offset wells; an understanding of the reasons for offset well under-performance is needed before any such guarantee can be given. A much better approach to evaluating the technology is to apply it in situations for which there is considerable offset well data and where well performance is readily explicable. This facilitates the quantification of benefits ascribed to the reactive perforating technology (Bell et al. 2009). The above example of Well B shows that the reactive liner perforating technology can be successfully applied in the region to the Chilton formation.

Case 2 – Re-perforation Prior to Hydraulic Fracturing Stimulation

Well C is also located in Salsabil field. It was completed in March 2005 and producing gas and condensate from Lower Goru formation. Lower Goru Sandstone reservoir in Salsabil field is divided into three sand bodies (Upper, Middle and Lower Lobes) which are separated by shally sand. All three lobes in Salsabil field are hydrocarbon bearing and perforated in this well. Prior to completion in year 2005, the well was initially perforated overbalance with wireline using 3-1/2 in. diameter, high shot density gun loaded with 25 gram charges at density of 6 shots/ft (spf), and 72-degree phasing. After completion, additional perforations were added using wireline thru-tubing conveyance method at underbalance condition with 1-11/16 in. strip guns loaded with 8 grams charges at density of 4 spf and 0-degree phasing. The commercial gas and condensate production from Well C started on June 2007 and was produced until September 2008, when workover was carried. The objective for the workover was to increase the productivity of the well by performing hydraulic fracturing treatment in all three lobes.

Prior to the hydraulic fracturing treatments, re-perforations of the old perforation intervals were conducted through tubing conveyed perforation shoot and pull method using the new reactive liner perforating technology. The reactive shaped charge system used was 2-7/8 in. diameter with 15 grams charges at density of 6 spf and 60-degree phasing.

The injection test or step rate test was carried out with 4% potassium chloride brine prior to the main fracturing treatment to confirm the wellbore and perforations integrity. The result of the Upper lobe injection test is presented in the **Fig. 6** below. Note that the formation took the fluid with relative ease as treating pressure tend to decrease at constant pump rates. This is just as expected from reactive liner perforating system which delivers debris-free tunnels. The enhanced injectivity is due to increased open area to flow and clean debris free tunnels.

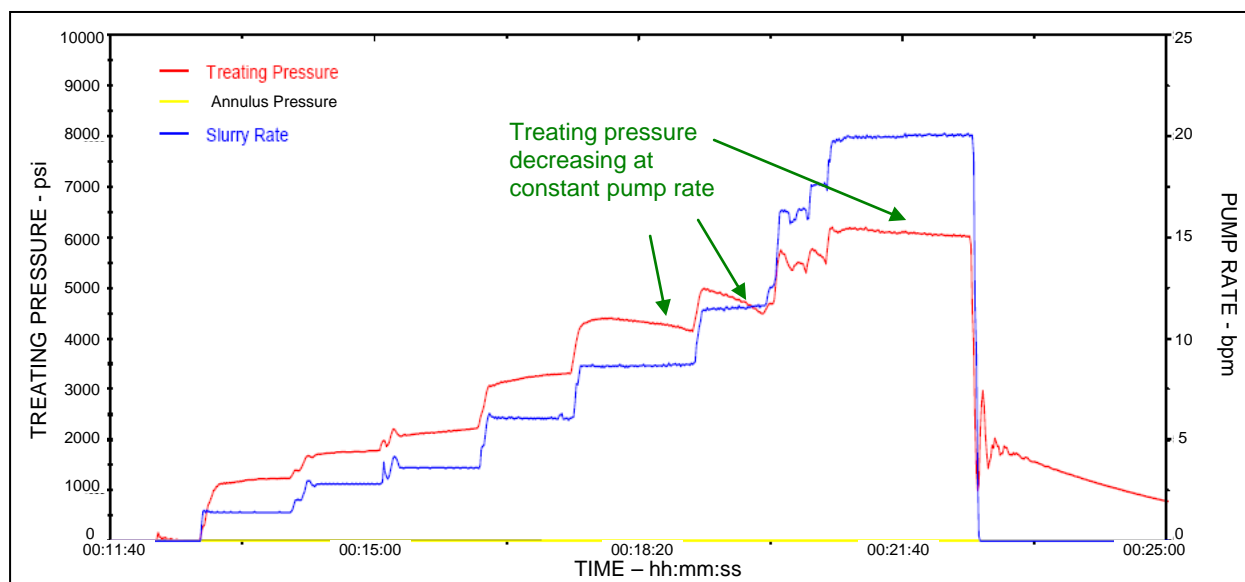


Fig. 6 – Injection plot on Well C (Upper Lobe) prior to hydraulic fracturing

The hydraulic fracturing treatment was the first treatment ever performed in Salsabil field. Therefore, it was not possible to make comparison to show how reactive liner perforating charges performed against the conventional shaped charges when applied prior to fracturing stimulation. Nevertheless, the positive pressure response during mini-frac (also known as data frac) gave the operator the confidence to proceed with the fracturing treatment as the higher perforating efficiency observed reduces the risk of potential screen-out. In addition, the fracturing treatment was further optimized after the mini-frac results so to achieve better fracture geometry.

The original hydraulic fracturing design study of Well C was conducted in 2005. The study estimated that in Upper Lobe, the expected surface injection pressure at 15 bpm would be approximately 7,000 psi, as shown in **Fig. 7** below. In the 2008 fracturing treatment, during mini-frac calibration test (using same fluid as pad fluid in the main treatment) maximum pressure

observed was close to 6,300 psi when pumped at constant rate of 20 bpm. This was 700 psi less than the design treatment pressure with higher pump rate than original design. The reactive liner perforating technology allows maximum treating rate at minimum pressure as there is more effective are available for fracturing fluid to be pump into formation.

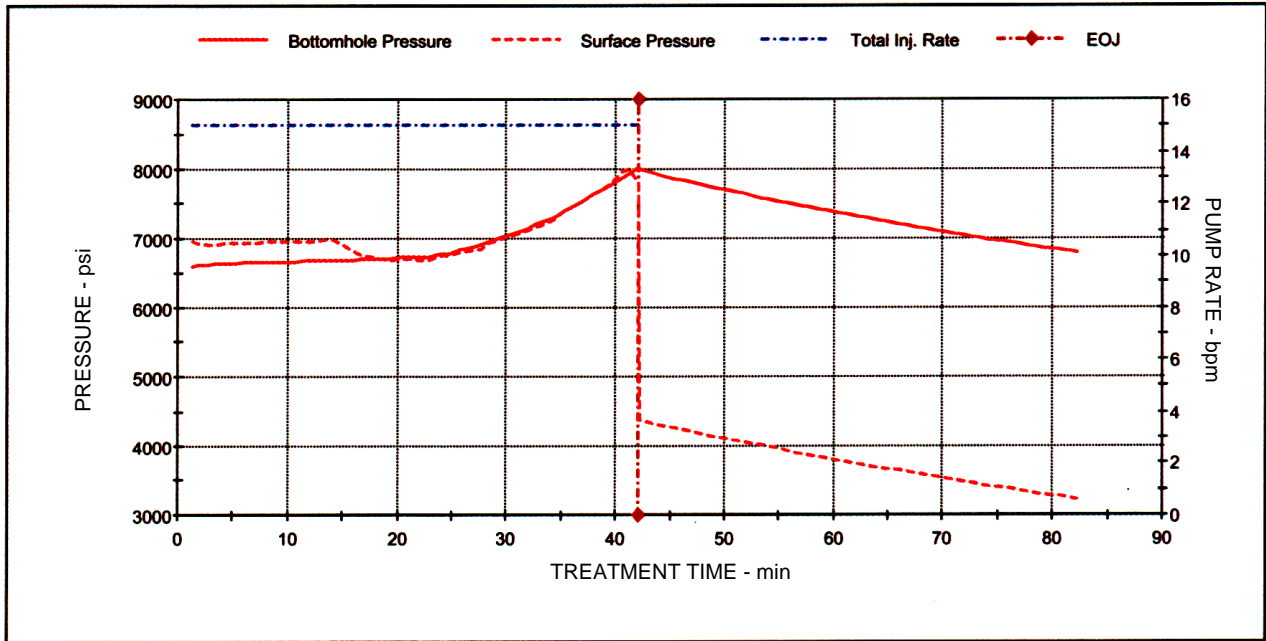


Fig. 7 – Well C (Upper Lobe) Expected Treatment Plot Based on Design Study

As a result from the reduced fracture initiation pressure observed during mini-frac, a more aggressive fracturing treatment was attempted with higher pump rate than original design to achieve better fracture geometry. A higher treatment rate of 20 bpm was carried out for the actual main fracturing treatment as the surface treating pressure would still be within the well and completion limitation. The actual treatment plot for Upper Lobe Well C fracturing is shown in Fig. 8 below. It can be seen that at 15 bpm the treatment pressure was close to 5,800 psi which was 1,200 psi lower than the anticipated design pressure, proving the advantage resulting from the reactive liner perforating technology. Similar behavior was also observed in Middle and Lower Lobes fracturing where higher treatment rate was possible due to lower fracture initiation pressure.

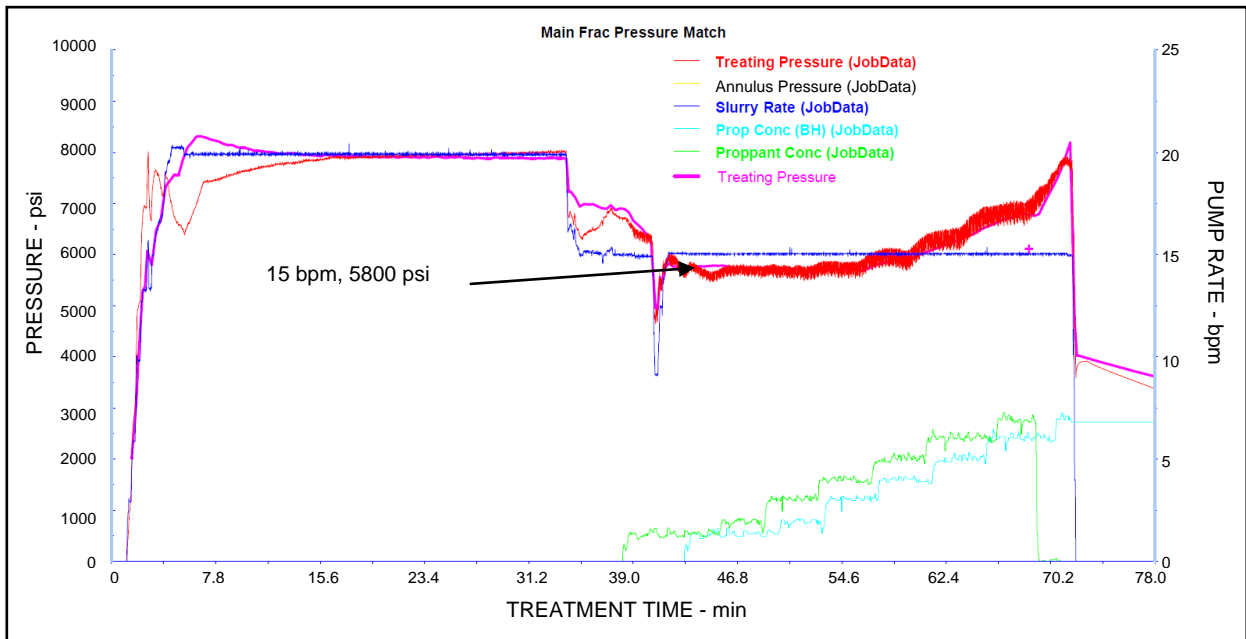


Fig. 8 – Well C (Upper Lobe) Actual Fracturing Treatment Plot (Post Re-perforation with Reactive Liner Perforating Technology)

The reduction in the formation breakdown pressure clearly demonstrated the advantage of re-perforating using reactive liner perforating technology. This will ultimately translate to potential savings from reduced horsepower requirements. Although it was not the case in Well C due to its remote location, this savings can be realized in future fracturing treatments whenever reactive liner perforating technology is utilized.

Lessons Learned and Recommendation

In the shoot and produce case history, it was observed how effective the reactive liner perforating technology when applied in fractured carbonate reservoir without the need for underbalance condition. Even when perforation is combined with a bigger volume acid stimulation treatment, the well which was perforated with reactive liner perforating technology performed better, exceeding the expectation. It is possible that the use of reactive liner perforation technology might have helped to improve the acid stimulation treatment in carbonate reservoir. This can be concluded if more of such applications are carried out to verify this behavior.

In the re-perforation prior to fracturing stimulation case, the fracturing treatment greatly benefitted from clean tunnels created with the reactive liner perforating technology where the fracturing design could be optimized to achieve better conductivity without limitation in the near wellbore.

The cost of perforating operations is generally a small fraction of the total well completion cost. In turn, it represents an even smaller fraction of total well cost. However, inadequate perforation cleanup can have a tremendous negative impact on total completion cost (due to remedial activities), total well cost (due to later intervention) and return on well construction investment (due to well under-performance). It is therefore a trivial exercise to demonstrate that incremental expenditure during the completion phase the benefit from reactive liner perforating technology will realize a significant return on investment under any circumstances that might impair conventional perforation cleanup.

Testing of reactive liner perforating technology into reservoir rock under representative conditions is extremely insightful and greatly accelerates the learning and development process. Such tests are to be encouraged whenever reactive liner perforators will be deployed under previously untested conditions, both to de-risk the field application and to promote technical learning. (Bell et al. 2009).

The main advantage of the technology is its independence from formation properties in delivering clean and efficient perforation tunnels. This widens the reactive liner perforating technology application in almost all type of perforating conditions. This is especially useful for application such as in tight gas reservoir which has been at a disadvantage with the previous perforating technology.

Conclusion

1. Reactive liner perforating technology was successfully introduced in Pakistan through its application in perforating new intervals for production and re-perforating older intervals prior to fracturing stimulation. In both cases, the results clearly show the value of the technology in delivering its promises as an established class of high-performance, deep-penetrating perforator.
2. The success stories of reactive liner perforating technology cover its application in gas and condensate reservoirs from both sandstone and carbonate formations. In addition, the technology overcame the well limitation where underbalanced perforation was not feasible.
3. Near-wellbore pressure losses during treatment or tortuosity are reduced when reactive liner perforating technology is applied prior to fracturing stimulation. 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.
4. The economic justification for deploying reactive liner perforating technology is highly compelling and extends beyond completion costs into the overall life-cycle cost of the well.

Nomenclature

<i>AOFP</i>	<i>absolute open flow potential</i>
<i>bpm</i>	<i>barrels per minute</i>
<i>EOJ</i>	<i>end of job</i>
<i>FWHP</i>	<i>flowing well head pressure</i>
<i>ft/sec</i>	<i>feet per second</i>
<i>gal/ft</i>	<i>gallon per foot</i>
<i>in</i>	<i>inch</i>
<i>km</i>	<i>kilometer</i>
<i>MMscf/D</i>	<i>million standard cubic feet per day</i>
<i>psi</i>	<i>pound per square inch</i>
<i>shots/ft</i>	<i>shots per foot</i>
<i>spf</i>	<i>shots per foot</i>

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