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Gas Well Productivity Enhancement through Re-Perforation

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Abstract

The productivity of the perforated wells is controlled by several perforating parameters; perforation length, perforation diameter, degree of the damage around the perforation tunnels, shot density, and perforation phasing angle. In a new well, once the well is perforated and the production is tested, the well is then killed and completed. Even with the used of non-aggressive kill fluid and non-damaging completion fluid, some degree of formation and perforations damages are induced during well killing and completion operations. Reduction of well productivity post completion compared to pre-completion is often observed.

The well productivity can be restored by stimulation treatment which is commonly successful practice in carbonate oil reservoirs but this option can be complicated when it comes to sandstone and gas reservoirs. Production enhancement through matrix stimulation on sandstone and gas wells has much lower success rate. This option is even more difficult in cases where reservoir information is limited. Restoring the gas well productivity to the initial pre-completion condition is challenging and most gas wells unable to deliver the expected production.

This paper describes a case history of a gas well in sandstone reservoir, where productivity falls dramatically after completion. Proper investigations were carried out through well test evaluations and comparisons to pre-completion tests which showed high degree of formation and perforation damages. Potential root causes from completion activities which contributed to the damages were identified. Several productivity enhancement options were evaluated in order to restore the well productivity. Re-perforation option was selected as the best option with lowest risk to induced further damage to the formation as well as being the most economical option available. Re-perforation was carried out on the same interval as the original perforations using reactive liner perforating technology. Reactive liner perforating technology was used as it is independent of rock properties and wellbore conditions. The technology also has successful track record especially in tight sandstone reservoirs. Post re-perforation well tests indicated significant production rates improvement as a result from successful re-perforation. In addition, the paper summarizes the key learning's that will assist operators when attempting to enhance gas well productivity through re-perforation.

Introduction

Productivity of a well mainly depends upon the degree of connectivity to the zone of interest. In cased hole completions, the critical link between the reservoir and the wellbore which has significant effect on the well productive potential and ultimate recoverable reserves, is the perforation. Despite its importance to the well productivity, perforation is just a transitional phase between well construction and well completion which is often under evaluated or neglected almost entirely in a well design.

Once the drilling phase is completed, the well is perforated and the well production is tested to evaluate the well potential. Then, the well is killed and completed before it is put to production. It is common to find that the well productivity is reduced in post-completion compared to pre-completion. Further production enhancement attempt is required in order to regain the well potential as observed prior to completion. Systematic and proper interpretation techniques are needed to perform proper investigation to determine the main cause of the reduction in productivity. Based on the evaluation results, suitable production enhancement technique which is economically viable can be chosen to bring back the well productivity to its optimum.

Skin Induced During Drilling & Completion

During drilling and completion, the permeability of the formation near the wellbore is often altered. This altered zone of permeability is called the damage zone. The invasion by drilling fluids, dispersion of clays, presence of mudcake and cement, and presence of saturation of gas around the wellbore are some of the factors responsible for reduction in the permeability. The

skin factor determined from a well test analysis reflects any near wellbore mechanical or physical phenomena that restrict flow into the wellbore. Most common causes of such restrictions in addition to damage are due to the partial penetration of the well into the formation, limited perforation, plugging of perforation, or turbulence. It is important to recognize the main cause in order to select a proper treatment to maximize the production.

In completion stage, kill fluid and completion fluid invade the formation through the perforation tunnels. This is the main cause for reduced well productivity post-completion compared to pre-completion. Even with the use of non-aggressive kill fluid and non-damaging completion fluid, some degree of formation and perforations damages are still induced which cause a large pressure drop around the wellbore and result in lower production. By evaluating the well production before and after the completion, increase in total skin during post completion production can be observed.

Production Enhancement Methods

There are several production enhancement methods that are used to recover the pre-completion production potential or even to enhance the productivity further. The type of method that suitable for each application depends on the formation properties, type of damage sustained by the formation and the economical justification of such production enhancement method. The most common production enhancement methods are matrix stimulation, hydraulic fracturing and re-perforation.

Matrix Stimulation

Matrix stimulation treatment is the most common option to remove damaged induced to formation by drilling fluid, kill fluid and completion fluid. By evaluating the properties of the damaging fluid introduced to the formation, suitable stimulation fluid can be used to dissolve the damaging material from the formation. The type of stimulation fluid used has to be compatible with the formation lithology so that no further damage can be induced through this treatment. Matrix stimulation treatment is so successful in carbonate formation that it has been adapted as part of the well drilling and workover programs where stimulation treatment is done prior to handing over the well for production. Matrix stimulation in carbonate formation not only recovers the well pre-completion potential by cleaning the perforation tunnels and dissolving the induced completion fluid material but also able to enhance the well productivity further as the stimulation fluid creates new channels and wormholes to improve well connectivity. In sandstone formation, the success of matrix stimulation treatment is low and sometime the treatment can even deteriorate the well productivity further. Matrix stimulation in sandstone formation depends heavily on the formation lithology and the type of damage suspected. Even with lithology obtained from core samples and formation logs, the degree of uncertainty is still there especially in long heterogenous zones. The success of matrix stimulation in gas reservoir is even less than oil reservoir in sandstone formation.

Hydraulic Fracturing

Hydraulic fracturing is often considered on tight sandstone reservoirs to enhance the well productivity. Hydraulic fracturing design requires detailed information on the reservoir which is not always easily available. This method should not be attempted if lack of reservoir information to avoid treatment failure or even further complications such as increasing water or sand production. Hydraulic fracturing is very costly so decision to use this option should be made by evaluating the potential gain in production versus the expenditure resulting from the treatment. In some tight gas sandstone reservoir, hydraulic fracturing can not be executed due to high fracture initiation pressure that is limited by the well completion.

Re-perforation

The re-perforation option is the simplest and can be the most economical option for production enhancement. In situation where lack of reservoir information or in cases where uncertainties in the damaging material induced in the formation, re-perforation option is the best option as it has the lowest risk to induce further damage to formation. This is especially true in sandstone formations. In tight gas formation where pressure limitation of the completion preventing the use of hydraulic fracturing treatment, re-perforation is the only option left. In any case, proper design of the perforation method is a must. The type of gun and charges, gun sizes, conveyance method for perforation and need for underbalance are some of design considerations that have to be addressed in order to deliver effective perforation tunnels.

Case Study

This paper describes the use of re-perforation as production enhancement method on a gas well sandstone reservoir. The well associated with this study is Saqib 1A which is an exploration well

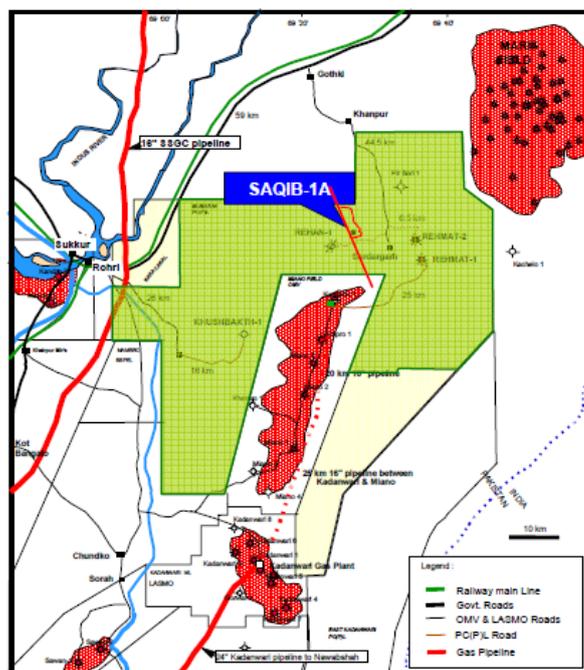


Fig. 1 – Field location map

located in Sukkur District, Sindh Province (refer to **Fig. 1**). The zone of interest is Lower Goru Sand K-55. The Saqib Field K-55 sandstone reservoir is part of the clastic shallow marine deposition on the western margin of the Indian sub-continent during early cretaceous time.

The well was originally perforated through tubing conveyed perforation method using 4-1/2 in. diameter, high shot density gun with HNS charges at density of 12 shots/ft (spf). Once perforated, Lower Goru Upper Sand K-55 formation was tested through drill stem testing (DST). The well was tested at various choke sizes with gas production ranging from 13.39 MMscf/D (choke size 32/64 in.) to maximum flow of 25.15 MMscf/D (choke size 80/64 in.) with 53 STB/D of condensate, 91 STB/D of water and 0.6 gal/min of fine sand at flowing wellhead pressure (FWHP) of 1,044 psi. Well test analysis based on the production data were carried out and the results are summarized in **Table 1**. **Fig. 2** to **Fig. 5** shows the interpretations plots for the well test analysis carried out during pre-completion stage.

P_i at Gauge Depth Psi	kh md.ft	k md	Skin	AOFP MMscf/D
4,885.5	2,220	84.4	2	126

Table 1 – Test Interpretation Results of Pre-Completion

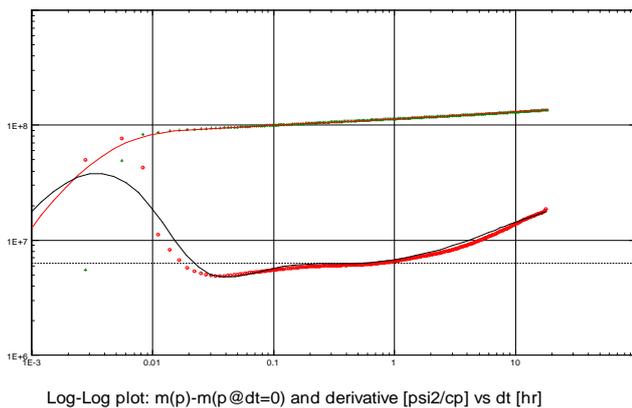


Fig. 2 – Log-log plot (Pre-Completion)

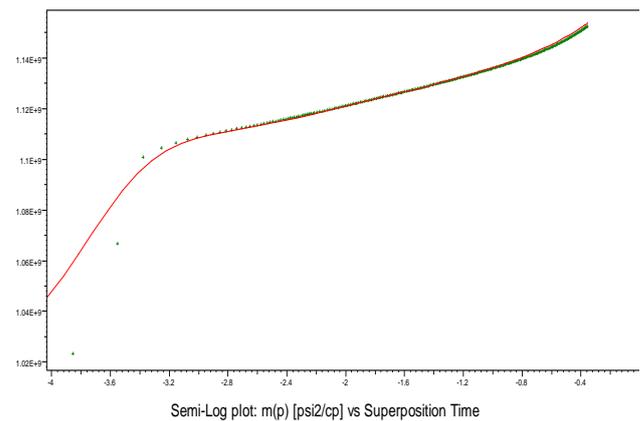


Fig. 3 – Semi log plot (Pre-Completion)

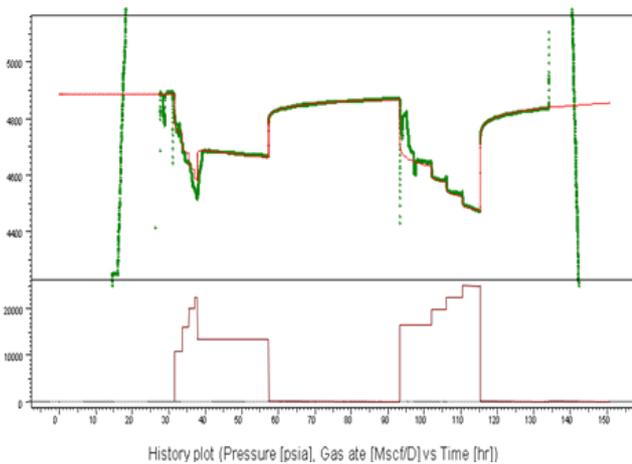


Fig. 4 – History match plot (Pre-Completion)

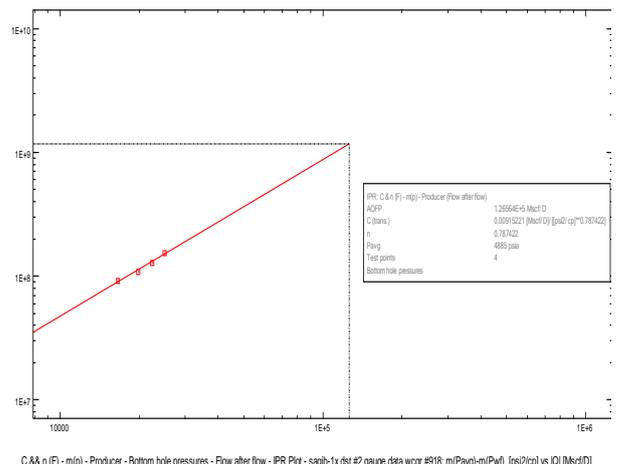


Fig. 5 – AOFP plot (Pre-Completion)

After executing the DST, Saqib 1A was killed and completed. A build up test was then executed through surface well testing. The post-completion well test data were analysed and summarized in **Table 2**. **Fig. 6** to **Fig. 9** shows the interpretations plots for the well test analysis carried out during post-completion stage.

P_i at Gauge Depth <i>psi</i>	kh <i>md.ft</i>	k <i>md</i>	Skin	AOFP <i>MMscf/D</i>
4,786	2,180	83	46	32

Table 2 – Test Interpretation Results of Post-Completion

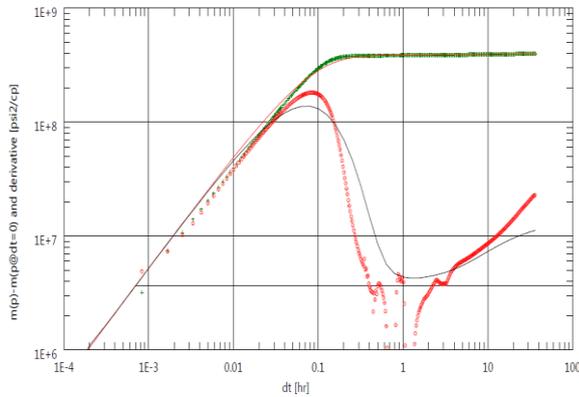


Fig. 6 – Log-log plot (Post-Completion)

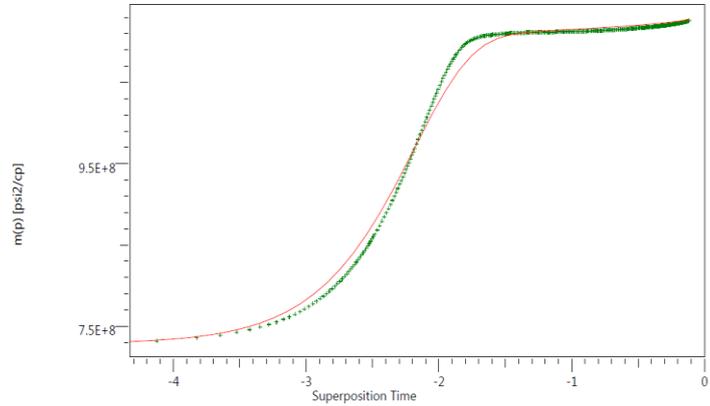


Fig. 7 – Semi log plot (Post-Completion)

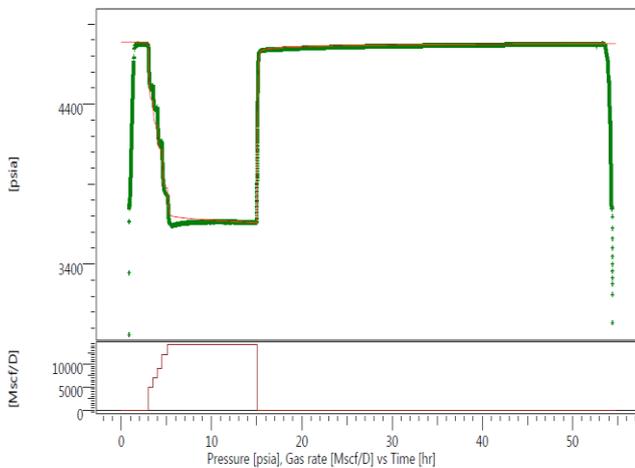


Fig. 8 – History match plot (Post-Completion)

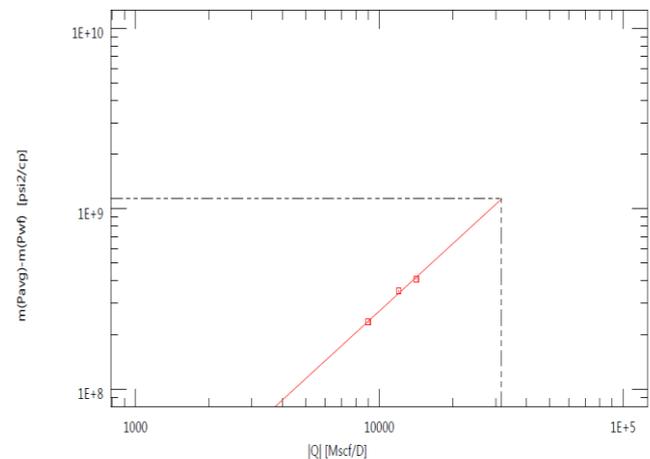


Fig. 9 – AOFP plot (Post-Completion)

Diagnostics of the Problem

The well test results shown in **Table 1** and **Table 2** indicated skin increased from +2 to +45. The absolute open flow potential (AOFP) decreased to 32 MMScf/D from 126 MMScf/D. This was significant production impairment that occurred during the killing and completion operation. It was suspected that the main causes for formation damage were the kill fluid and the completion fluid. Presence of solids from the fluid or its incompatibility with some lithology of the formation could have induced damage to the formation. The solids and insoluble particles created from incompatible reactions between rock and fluid could have obstructed the perforation tunnels by plugging the pore throats and the tunnels with debris and compacted the tunnel tips with fills. The overbalance condition in the wellbore during killing and completion operations could also contribute to the increase in skin. Higher pressure in the wellbore than the formation resulting in fluid invasion into the formation through the perforations (refer **Fig. 10** and **Fig. 11**).

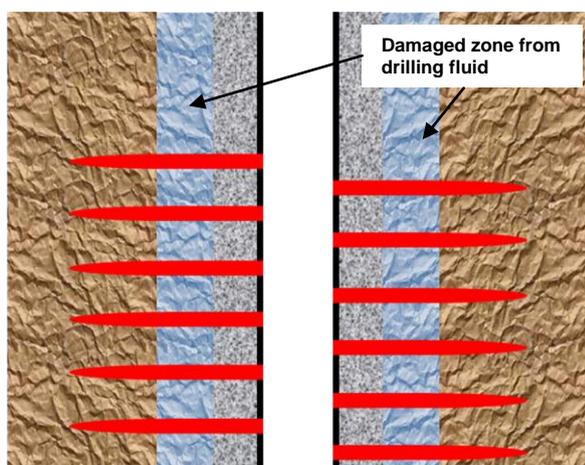


Fig. 10 – Initial perforations during testing

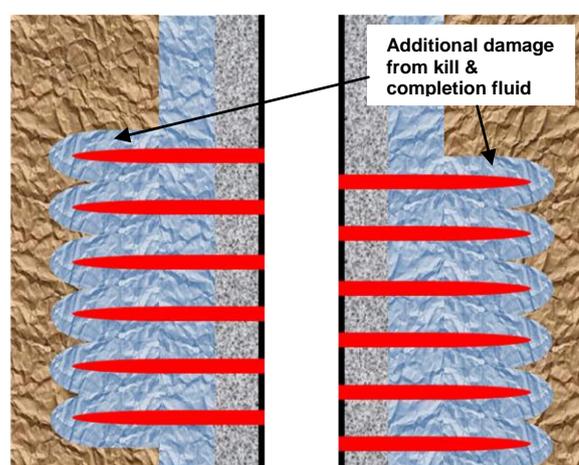


Fig. 11 – Initial perforations after killing the well

Strategic Decision of Re-Perforations

If the well formation is limestone, the remedial step to reduce the skin would have been to perform matrix stimulation. Since the formation is sandstone, performing matrix stimulation required more considerations. Since this was an exploratory well, there was not adjacent well with history of matrix stimulation treatment. The lithology information of the formation was limited and uncertain. Considering limited information on the formation available to perform the stimulation treatment, design the right stimulation fluid was difficult. The risk of damaging the formation further is high considering low success rate of sandstone matrix stimulation in Pakistan. Incompatible stimulation fluid creates precipitations which cause further reduction in the productivity.

The hydraulic fracturing option was costly and required information on the formation which was unavailable. This option was considered as the last resort if everything else failed.

Re-perforation option was considered the most suitable option as it was not only simple but also fast and economical. Nevertheless, it was important to properly design the perforation operation itself so that the best possible result can be obtained. Since the well had been completed, the only quick and economical conveyance method to perforate was through wireline. The optimum gun size for the well 7 in. liner was 4-1/2 in. diameter but the size of the completion string limited the size of gun that can be used. Maximum gun size that can be safely used was 2-7/8 in. Unfortunately with a smaller gun size a less penetration depth would be accomplished. It was critical to achieve as much penetration as possible in formation damaged well so that to increase the chance of bypassing the near wellbore damage zone.

The explosive impact during the perforation could also create crushed zones in the perforation tunnels through physical crushing or compaction of the rock. In order to achieve maximum connectivity of the perforation tunnels, it is important to achieve clean tunnels by reducing the crushed zones as minimum as possible. Conventional perforation technique combined with underbalance condition or perforating using dynamic underbalance to achieve clean tunnels effect was not possible in Saqib 1A scenario as multiple wireline perforation runs were required. Reactive liner perforating technology was introduced to overcome all these limitations.

Reactive Liner Perforating Technology

The reactive liner perforating technology is the most versatile perforating technology that can deliver high perforating efficiency compared to conventional perforating techniques. Reactive liner perforating technology delivers debris-free tunnels independent of rock properties, wellbore or formation pressures and without dependency on underbalance condition. In most cases, the pressure spike created from its highly exothermic reactions is sustained long enough to initiate a small fracture at the tip of the tunnel (Bell and Cuthill 2008). The result is incredible perforating efficiency, superior productivity and enhanced injectivity. Since its introduction, the reactive liner perforating technology has proven to be a very successful perforating technique for production enhancement especially in sandstone reservoirs. In tight sandstone gas well, re-perforation with reactive liner perforating technology will help to reduce the perforation friction and tortuosity, which will allow lower fracture initiation pressure for hydraulic fracturing treatment if required (Bell et al. 2009). Reactive liner perforating technology had proven track record in both sandstone and carbonate wells in Pakistan (Qayyum et al. 2009). It was then decided to attempt the re-perforation by using the reactive liner perforating technology.

Re-Perforation Results

The original perforations were re-perforated with reactive shaped charge system of 2-7/8 in. diameter with 15 grams charges at density of 6 spf and 60-degree phasing. Surface well test analysis was carried out after the re-perforation to evaluate

the well performance. The results from the post re-perforation were compared with post-completion production as shown in **Table 3**.

	Choke Size (%)	FWHP psi	FWHT °F	Gas Rate MMscf/D	Condensate Rate STB/D	Water Rate B/D
Post Completion	37	2,710	192	14.31	114	85
Post Re-perforation	37	3,220	195	17.26	150	95
Post Re-perforation	41	3,084	208	20.50	195	110

Table 3 – Saqib-1A Production Comparison

Production Evaluation

Since the post re-perforation build up test was carried out by recording well surface parameters, Nodal Analysis was used to estimate the skin post re-perforation. Inflow performance relationship (IPR) with varying skin from 0 to 55 were correlated and compared with the available well test data. Outflow performance relationship (OPR) with varying FWHP from 2,000 to 3,400 psi were generated and used to reconfirm the correct model with the well test data. Comparing both IPR and OPR with post-completion production verified that the Nodal Analysis correlations were correct. As shown in **Fig. 12**, total skin had reduced from 45 to 10 whereas AOFP had increased from 32 to 82 MMscf/D as shown in **Fig. 13**.

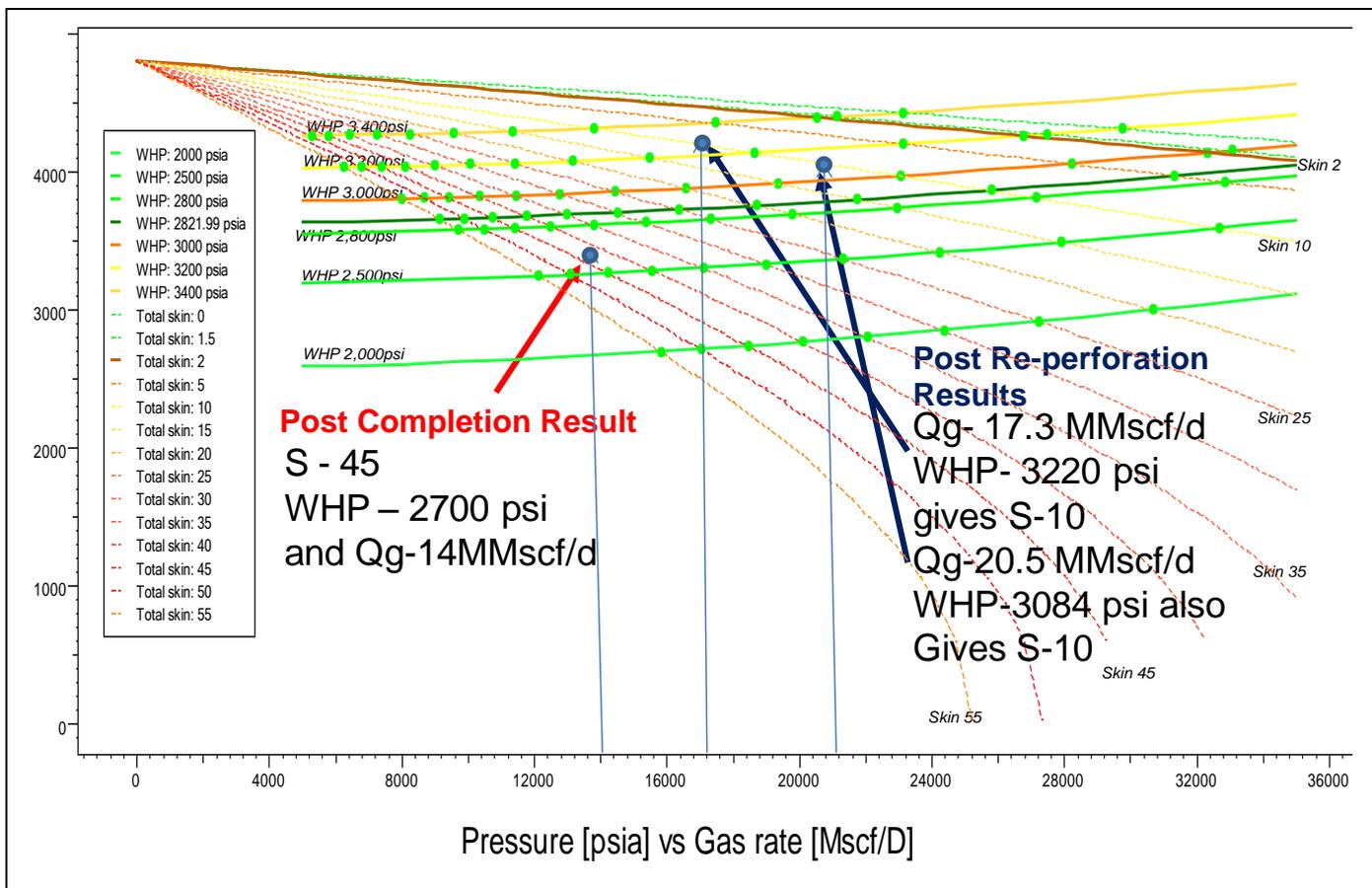


Fig. 12 – Nodal analysis

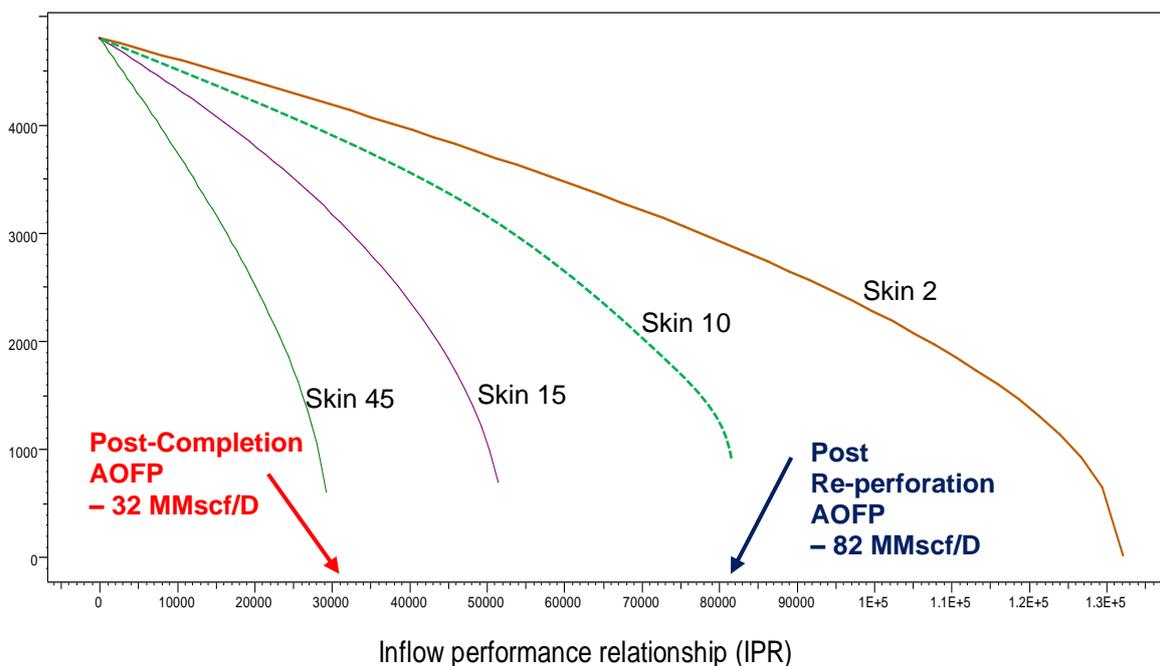


Fig. 13 – AOFP with Skin 45, 15, 10 and 2

The improvement in the well productivity after the re-perforation was significant. It was suspected that, the reactive liner perforating technology had performed as it promised by delivering clean tunnels and fractured tips which connect to the reservoir and bypassed the damage created by completion (see Fig. 14).

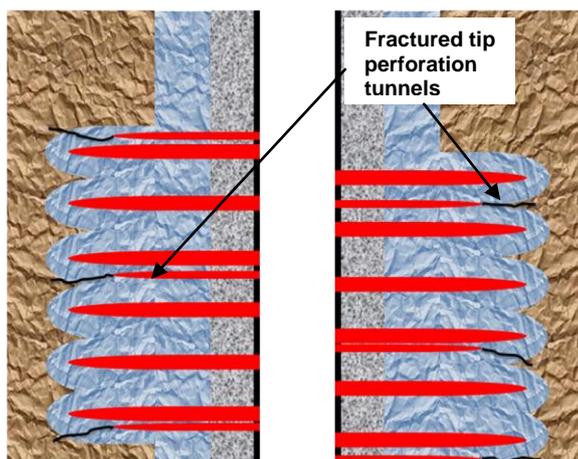


Fig. 14 – Re-perforation

Conclusion

In cased hole completion wells, the perforation is the link which connect the reservoir from the wellbore which plays important role in determining well productivity. Drilling fluid creates damage layer on the near wellbore which is normally bypassed by perforation. However, further damage is induced into the formation to the perforation tunnels by invasion from kill fluid and completion fluid at a later stage of the well. It is critical to have proper well test analysis before and after the well completion to analyse the performance of the well. Productivity impairment observed on the well should be properly diagnosed with systematic analysis and interpretation to help identify the root cause and help to decide the corrective measures needed to rectify the problem. Several options are available for recovering the productivity lost by kill fluid and completion fluid. Matrix stimulation is often the choice for production enhancement in carbonate wells. Hydraulic fracturing is an expensive option for sandstone wells and is usually carried out as the last resort. Re-perforation is the simplest, quickest and

most economical option for production enhancement especially in sandstone gas reservoir. The case study in the paper shows the systematic diagnostic steps taken in diagnosing the problem and how the decision was made to recover the productivity reduction resulted from killing and completion operation. The design consideration for selecting suitable perforation system for the reperforation is critical to achieve optimum results given the well limitation. Re-perforation with reactive liner perforating technology proven to improve the well productivity significantly by creating clean tunnels with fractures tips that bypassed the existing near wellbore damage in the formation.

Nomenclature

<i>in</i>	<i>inch</i>
<i>HNS</i>	<i>hexanitrostilbene</i>
<i>shots/ft</i>	<i>shots per foot</i>
<i>spf</i>	<i>shots per foot</i>
<i>DST</i>	<i>drill stem testing</i>
<i>MMscf/D</i>	<i>million standard cubic feet per day</i>
<i>STB/D</i>	<i>stock-tank barrels per day</i>
<i>gal/min</i>	<i>gallon per minute</i>
<i>FWHP</i>	<i>flowing well head pressure</i>
<i>psi</i>	<i>pound per square inch</i>
P_i	<i>in-situ pressure</i>
<i>k</i>	<i>permeability</i>
<i>h</i>	<i>net pay</i>
<i>md</i>	<i>millidarcy</i>
<i>md.ft</i>	<i>millidarcy feet</i>
<i>AOFPP</i>	<i>absolute open flow potential</i>
<i>FWHT</i>	<i>flowing well head temperature</i>
<i>B/D</i>	<i>barrels per day</i>
<i>IPR</i>	<i>inflow performance relationship</i>
<i>OPR</i>	<i>outflow performance relationship</i>
<i>S</i>	<i>total skin</i>
Q_g	<i>gas flowrate</i>
<i>WHP</i>	<i>well head pressure</i>

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References

- Bell, M.R.G and Cutthill, D.A. 2008. Next-Generation Perforating System Enhances the Testing and Treatment of Fracture Stimulated Wells in Canada. Paper SPE 116226 presented at the 2008 SPE Annual Technical Conference and Exhibition, Denver, Colorado, 21-24 September.
- Bell, M.R.G, Hardesty, J.T. and Clark, N.G. 2009. Reactive Perforating: Conventional and Unconventional Applications, Learnings and Opportunities. Paper SPE 122174 presented at the 2009 SPE European Formation Damage Conference, Scheveningen, The Netherlands, 27-29 May.
- Qayyum, T, Khattak, K, Qureshi, I, Aizad, T, Hameed, S and Akhtar, M.S. 2009. Successful Introduction of Next Generation – Reactive Liner Perforating Technology in Pakistan. Paper SPE/IADC 125901 presented at SPE/IADC Middle East Drilling Technology Conference & Exhibition, Manama, Bahrain, 26-29 October.