



Empirical Well Perforation Design and Evaluation in an Oil Well

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Abstract - Perforation operation is an important step in the process of well completion. It involves developing a flow path between the wellbore and the reservoir for the inflow of the formation fluid into the wellbore. In recent times, special consideration is being given to the design of the perforating procedure in order to develop a completion plan that can enhance productivity. Though there are technologies currently deployed by completion Engineers to improve perforation efficiency in the oil industry, there are still unsatisfactory results due to problems such as the need for optimum perforating size (diameter), perforation length and permeability reduction. This study presents a modification for redesigning the perforation gun based on such parameters as perforation radius (R_p), perforating length (L_p), crush zone permeability (α) and the number of shot (ns). The model was validated using completion and production data of two wells in Niger Delta. The results obtained from this model shows that 45° phase angle gave an optimum production rate of 9800 bbl/day against 9400 bbl/day production rate for 60° degrees' phase angle. Also, sensitivity analysis was carried on the model variables (perforation radius, perforation length, shot density and phase angle) shows that perforation length had the highest influence on the production profile.

Keywords- Perforation, Design, Evaluation

I. INTRODUCTION

Perforation with charged shaped object, is a process of creating a hole through the casing and cement into the formation with the aim of establishing a flow conduit path between the wellbore and the hydrocarbon bearing formation. Perforations are usually achieved with shaped tapering tubes with dimensions (0.2 – 0.3-in diameter, 1.00 – 1.5-in length). Thus perforating design led to the development of non-plugging shaped charges; API recommended practice (RP) 43, for evaluating perforation under simulated hole flow conductions. The development of more effective perforators and perforating techniques is ongoing, although early studies ignored the damage around the perforation tunnel and focused on the importance of length and entrance hole diameter. Putting damage effect aside, the length of the perforation tunnel is theoretically the most critical factor in a natural completion in

which further stimulation or sand control is planned. Hole diameter and shot density becomes more important when some sand control completion designs are planned.

Tovar and Cooper [1], in their work on “Design and Evaluation of Perforation Performance using Dynamic Under Balance”, pointed out that the type of reservoir fluid, interval length, formation mechanical properties, pre-existed formation damage in the well are some of the main considerations for a successful design and implementation of the technique. These parameters vary from low to high depending on the in-situ properties of the well.

Jawad [2], stated in his work on importance of perforation process and its techniques did a comprehensive overview on the perforation processes and pointed that no two wells have the same perforation design. The perforation to be used is influenced and induced by the type the formation, type of well (vertical, horizontal or directional), completion type (barefoot or open hole completion, pre-slotted liner completion or cased hole completion) and selection method suitable for that particular well to optimally enhance production.

Makok [3] studied the effect of perforation technology on the productivity of hydrocarbon well and came up with result findings that formation penetration, hole size, number of shots and the angle between the holes have significant impact on the pressure drop thereby negatively affecting the inflow performance relation (IPR). The inflow performance relation (IPR) describes the effect of the reservoir on well performance. Empirical IPR equations were suggested for under-saturated and saturated oil systems. They were used to illustrate how reservoir inflow is integrated with the composite flow system making up the production unit. He also considered the effect of pressure conditions at the outer boundary of the drainage area and flow restrictions existing at the entry or near an actual wellbore.

Batarseh *et al.* [4] in their paper on “Well Perforation using High Lasers” studied perforation using laser technology as compared to the conventional wellbore perforation technique and found that damage to the permeability and porosity of the adjacent zone was not only reduced but that near-hole permeability in a reservoir sandstone can be increased up to 171% which is a huge jump in permeability as compared to what was previously experienced.

From a rock mechanics view, the use of oriented perforations for hydraulic fracturing became suitable to create a stable tunnel in poorly consolidated formations thereby avoiding sand failure and consequently preventing sand production. To achieve this, the perforations should be placed in the direction of maximum horizontal stress and also in the case of creating multiple fractures, oriented perforations should be considered [5].

Behrmann and Elbel [6] examined the effects and characteristics of the permeability damage around the perforation in a core targets. According to him, the breaking of the larger grains that are replaced with by smaller grains as a result of a region that is generated around the perforation in which loss of permeability occurs.

Marrit and Landman [7] understudied reservoir perforation action within a homogeneous, anisotropic reservoir bounded with amaranthine parallel planes. They discovered that wellbore flow, specified as single or multiphase, recital for the grievance fall onward the borehole due to the well inclination, pipe friction & hole punch influx. To enable flexible wellbore invention, the well is to be partitioned into segments each with its own inclination, length, & scalar of hole punch. Perforation dispensing may be user-defined or optimized through various optimization strategies; for example, maximization of wellbore worth, or uniformity of specific inflow.

However, to increase production, hole punch imperatively infiltrates considerably a-yond the zone of drilling destruction, and imperatively be of the greatest feasible grade. In a wellbore with drilling destruction, an indefinite profound hole punch is more thorough than many shallow ones; outer surface of the boundary of recent technology & dismal science, brutal hole punch destruction cannot be accomplishing prevailing by rising either discharge density or infiltration. This is displayed by Klotz *et al.* [8] in project on effect of hole punch destruction on wellbore yield.

Gruesbeck and Collins [9] did forth-put a current algorithm to determine particle-transport efficiency through perforations. Transport effectiveness is the quantity half of fragments which are convey by the hole punch comparative to all the quantity of fragments introduced. Their deduction was focused on laboratory study of the conveyed of stony fragments carried through perforations by different fluids having a large in scope domain of physical characteristics. Prediction of particle-transport efficiencies based on theoretical considerations was described and an exact figure of experimental results.

A. Design Parameters

For optimum perforation design in this study, the following parameters were considered:

- i. Perforation radius.
- ii. Perforation length.
- iii. Perforation phase angle.
- iv. Number of shot.

II. MODEL DEVELOPMENT

The number of essential empirical methods that have been proposed over time to evaluate perforation performance for optimal production is very little. Hence, there is need to develop a model that can be used in measuring the performance of perforation design in completed well. Adopting the equation presented by McLeod *et al.* [10] for evaluating the pressure changes in an oil and gas wells.

A. McLeod equation

$$P_{wfs} - P_{wf} = a_1 \left(\frac{q}{n_s \times h_p} \right)^2 + b_1 \left(\frac{q}{n_s \times h_p} \right) \quad (1)$$

Where:

$$a_1 = \frac{2.30 \times 10^{-14} \times \beta B_o^2 \rho \left(\frac{1}{r_p} - \frac{1}{r_c} \right)}{L_p^2}$$

and

$$b_1 = \frac{\mu_o B_o \left[\ln \left(\frac{r_c}{r_p} \right) \right]}{7.08 \times 10^{-3} \times L_p K_p}$$

Equations (1) will be subjected to the following assumptions:

- i. The shape of perforation is cylindrical.
- ii. Homogeneous and anisotropic formation.
- iii. Flow into perforations in the vertical plane is elliptical.
- iv. Small or constant fluid compressibility.
- v. The flow is turbulent.
- vi. Constant pressure boundaries.

B. Jones equations

$$P_r - P_{wfs} = a_2 q^2 + b_2 q \quad (2)$$

Where:

$$a_2 = 5.359 \times 10^{-4} \times \frac{B_o^2 \rho}{h_p^2 k^{1.201} r_w}$$

And

$$b_2 = 142.24 \times \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) + \Delta s \right]}{kh}$$

Adding (1) and (2) together

$$P_r - P_{wf} = \left[a_1 + \frac{a_2}{(n_s \times h_p)^2} \right] q^2 + \left[b_1 + \frac{b_2}{(n_s \times h_p)} \right] q \quad (3)$$

Let,

$$A = a_1 + \frac{a_2}{(n_s \times h_p)^2} \quad (4)$$

And

$$B = b_1 + \frac{b_2}{n_s \times h_p} \quad (5)$$

Where,

A = Turbulent term for perforation

B = Darcy flow term for perforation

For the A term,

Substituting the values of a1, and b1 into (4) and (5)

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho}{h_p^2 k^{1.201} r_w} + 2.30 \times 10^{-14} \frac{\beta B_o^2 \rho \left(\frac{1}{r_p} - \frac{1}{r_c} \right)}{n_s^2 \times h_p^2 \times L_p^2} \quad (6)$$

Simplifying equation 1.6 gives

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho}{h_p^2 k^{1.201}} \left[\frac{1}{r_w} + \frac{1}{L_p^2 n_s^2 \alpha^{1.201}} \frac{1}{r_p} \frac{1}{r_c} \right] \quad (7)$$

If the impact of the perforation on the turbulent term is ϕ

$$\phi = \frac{\frac{r_w}{r_p} - \frac{r_w}{r_c}}{L_p^2 n_s^2 \alpha^{1.201}} \quad (8)$$

Substituting equation 8 into equation 7:

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho}{h_p^2 k^{1.201}} \left[\frac{1}{r_w} + \frac{\phi}{r_w} \right] \quad (9)$$

Simplifying equation 9:

$$A = 5.359 \times 10^{-4} \frac{B_o^2 \rho (1 + \phi)}{h_p^2 k^{1.201} r_w} \quad (10)$$

Similarly, for the B term;

$$B = \frac{141.24 \mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} + \Delta s \right) \right]}{kh} + \frac{\mu_o B_o \left[\ln \left(\frac{r_c}{r_p} \right) \right]}{7.08 \times 10^{-3} \times L_p k_p n_s h_p} \quad (11)$$

$$B = \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} + \Delta s \right) \right]}{7.08 \times 10^{-3} kh} + \frac{\mu_o B_o \left[\ln \left(\frac{r_c}{r_p} \right) \right]}{7.08 \times 10^{-3} L_p k_p n_s h_p} \quad (12)$$

$$B = \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} + s_t \right) \right]}{7.08 \times 10^{-3} kh} \quad (13)$$

Solving for s_t in equation 13:

$$s_t = \frac{B \times 7.08 \times 10^{-3} \times kh}{\mu_o B_o} - \ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} \right) \quad (14)$$

The skin caused by perforation can be viewed as:

$$s_{perf} = s_t + \Delta s \quad (15)$$

Also

$$s_{perf} = \frac{\ln \left(\frac{r_c}{r_p} \right)}{n_s L_p \alpha \varepsilon} \quad (16)$$

Thus, (13) becomes

$$B = 141.24 \times \frac{\mu_o B_o \left[\ln \left(0.472 \left\{ \frac{r_e}{r_w} \right\} + \Delta s + s_{perf} \right) \right]}{kh} \quad (17)$$

C. Variation of the perforation tunnel (crushed zone radius)

Assuming the shape of the perforation to be cylindrical and conical as represented by Fig. 1.

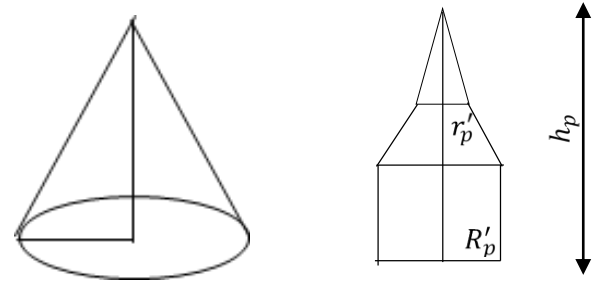


Figure 1. Symmetrical representation of a cone and cylinder (author: self)

Comparing the area of the cylinder and the cone

$$A_{cone} = A_{cylinder} \quad (18)$$

$$\pi R_p \sqrt{R_p^2 + h_p^2} = \pi (R_p + r_p) \sqrt{(R'_p - r_p)^2 + h_p^2} + \pi r_p^2 + \pi R_p^2 + 2\pi R'_p L_p \quad (19)$$

$$r'_p = \frac{(R_p + r_p) \sqrt{(R_p - r_p)^2 + h_p^2} + \pi r_p^2 + \pi R_p^2 + 2\pi R'_p L_p}{\sqrt{R_p^2 + h_p^2}} \quad (20)$$

D. Modification of r_c

volume of cone = volume of cylinder

$$\frac{\pi r_c^2 L_p}{3} - \frac{\pi r_p^2 L_p}{3} = \pi r_c'^2 L_p - \pi r_p'^2 L_p \quad (21)$$

Factorizing and rearranging equation 21:

$$r'_c = \sqrt{\frac{r_c^2 - r_p^2}{3} + r_p'^2} \quad (22)$$

According the Kuchuk and Kirwan [11], the effective perforation radius in an anisotropic formation is given as:

$$r_{pe} = \left(\frac{r_p}{2} \right) \left(1 + \sqrt{\frac{K_v}{K_h}} \right) \quad (23)$$

Thus,

$$r'_{pe} = \left(\frac{r'_p}{2} \right) \left(1 + \sqrt{\frac{K_v}{K_h}} \right) \quad (24)$$

The final equation;

$$r'_{ce} = r'_{pe} + r'_c - r'_p \quad (25)$$

Where,

r'_p = Radius of cylindrical and conical perforation tunnel

R_p = Radius of cone shaped perforation

r'_c = Crushed zone radius of cylindrical shaped Perforation

r_{pe} = Perforation radius

R'_p = Radius of cylindrical shaped perforation

E. Model Testing

The perforation model developed through equations 18-24 was tested using production data from a gas and oil well

respectively. And evaluated in Stimulation software [Beth's Wellbore Perforation Evaluation (BWPE)] which was developed as part of this study. The key parameters tested are R_p , L_p , α , and n_s for all the phase angles (0° , 45° , 60° , 90° , 120° , 180°). Also plots of production rate vs R_p , L_p , α , and n_s for both oil and gas well were obtained. See appendix for the interface of the programs.

F. Data Analysis Technique

In this study, the mathematical model derived was used to generate a table of value from the perforation data and plots created from it using Beth's Wellbore Perforation Evaluation (BWPE). This will be used to analyse the performance of the perforation and recommend ways of improving production.

III. RESULT AND DISCUSSIONS

Fig. 2 shows that as the perforation radius (R_p) increases by 0.25 in, production rate (Q_o) also increases by 1000 bbl/day. At a point of $R_p = 1.50$ in and $Q_o = 9500$ bbl/d the production rate (Q_o) maintains a stable flow rate for the phase angle of 45° (i.e. the highest production). The increase in production rate is as the result of the reservoir pressure pushing the fluid into the wellbore and when it stabilizes, the production rate became constant.

Fig. 3 shows that increase in perforation length (L_p) by 2.0 ft leads to increase in production rate (Q_o) by 2000 bbl/d. The highest production rate Q_o (23000 bbl/d) is with 45° phase angle at perforation length (L_p) of more than 14(ft). Fig. 4 shows that the all the number of shots (n_s) maintained a constant flow rate (Q_o).

Fig. 5 shows that as the perforation radius (R_p) increases by 0.25 in, production rate (Q_o) also increases by 500 bbl/day. At a point of $R_p = 1.25$ in and $Q_o = 5000$ bbl/d the production rate (Q_o) maintains a stable flow rate for the phase angle of 45° (i.e. the highest production). The increase in production rate is as the result of the reservoir pressure pushing the fluid into the wellbore and when it stabilizes, the production rate became constant.

Fig. 6 shows that increase in perforation length (L_p) by 2.0 ft leads to increase in production rate (Q_o) by 2000 bbl/d. The highest production rate Q_o (15500 bbl/d) is with 45° phase angle at perforation length (L_p) of more than 14 ft.

Fig. 7 shows that at phase angle 45° there is a production rate Q_o increase from 21000 bbl/d to 22500 bbl/d at the increments of 2.0 ft number of shots an increment to two shots before maintaining a constant production rate Q_o to 10 ft number of shot.

IV. CONCLUSIONS

In an effort to accomplish the aim of this study, a mathematical model was derived and used to generate a table of value from the perforation data and plots generated using Beth's Wellbore Perforation Evaluation (BWPE) are displayed. The IHS PERFORM was used to validate the program. The testing of the influence of perforation parameters on yielding of hydrocarbon wells leads to the conclusions below:

1. In producing oil, best production may be accomplished by applying of 45° phase angle.
2. The perforation length has the highest influence on the production while the perforation radius possesses the smallest effect.
3. The repercussion of the workings of the perforation procedure is that they are dependent; therefore, long perforations are more preferred than wide ones.
4. Regular adoption that all formation to be perforated possesses similar solution should be discouraged as each formation and production problem is unique & possesses a unique solution, as shown through this study.
5. Proper diagnosis and assessment should be considered for individual wellbore and formation so as to make sure the perforation is fit for the wellbore. It is weighty so as to apply the right service.
6. During the completion, perforation variables like perforation tunnel radius, shot density, phase angle etc. can be considered, analysed and evaluated. Hence adequate technic must be adopted.

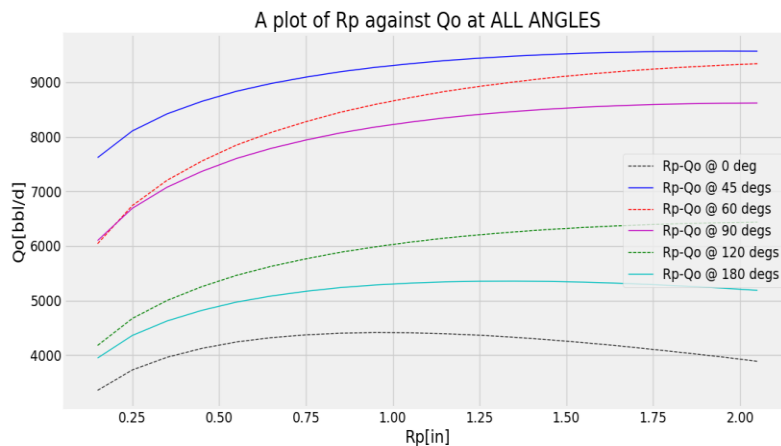


Figure 2. Plots of R_p against Q_o for the different perforation angles for well A

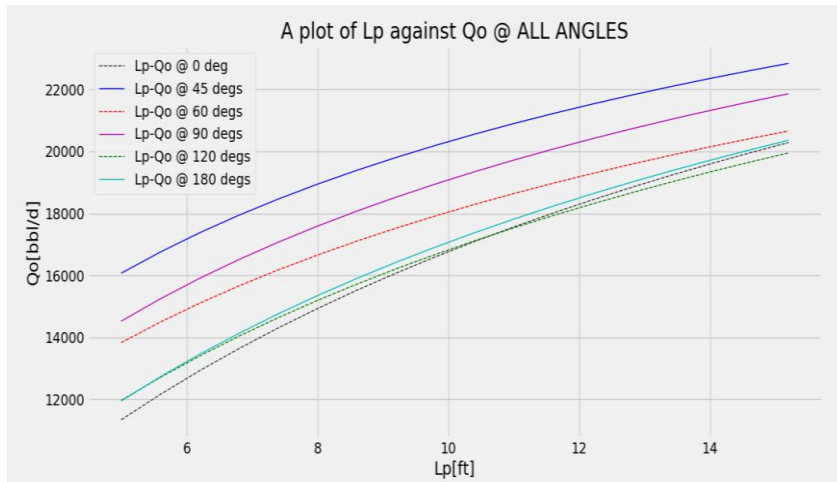


Figure 3. Plots of Lp against Qo for the different perforation angles for well A

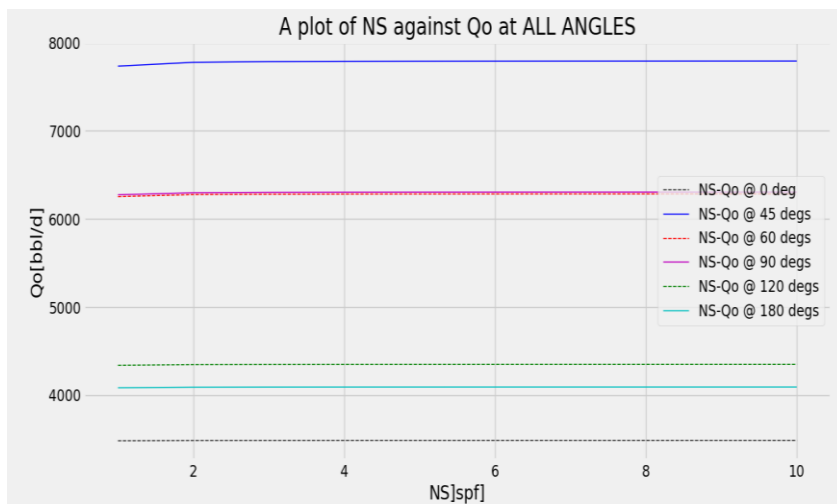


Figure 4. Plots of ns [spf] against Qo for the different perforation angles for well A

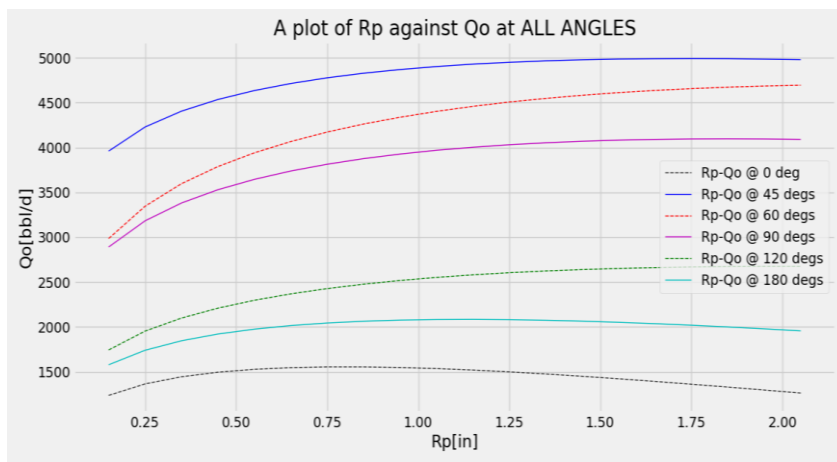


Figure 5. Plots of Rp against Qo for the different perforation angles for well B

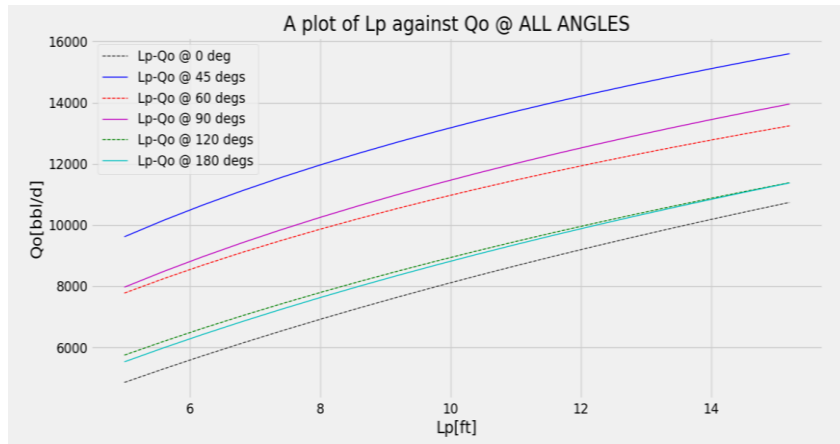


Figure 6. Plots of L_p against Q_o for the different perforation angles for well B

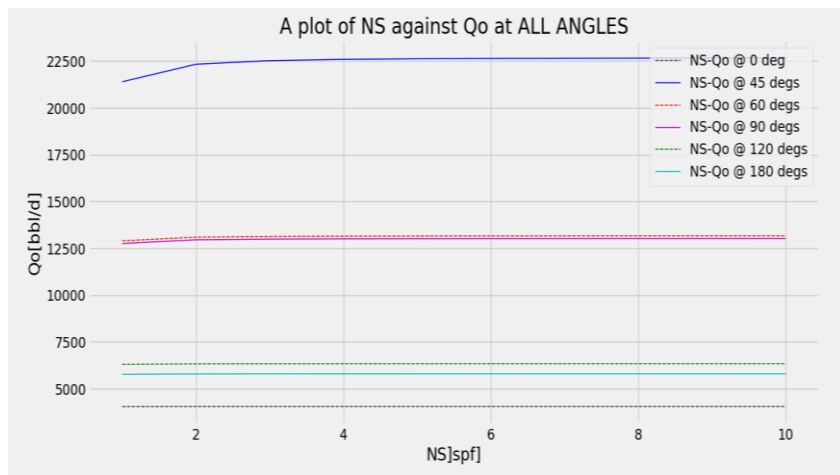


Figure 7. Plots of n_s [spf] against Q_o for the different perforation angles for well B

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