



**Sudan University of Science and Technology**

**College of Petroleum Engineering and Technology**

**Department of Petroleum Engineering**



## **Perforation Strategy Optimization for Sand production Prevention with Case Study: Fula North Field-Sudan**

**أفضل استراتيجية للتثقيب لمنع إنتاج الرمل**

**مع دراسة حالة: حقل الفولة الشمالي- السودان**

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صدق الله العظيم

"سورة العلق"

## *Dedication*

*Every challenging work, needs self - efforts as well as guidance of elders especially those who were very close to our heart*

*Our humble effort we dedicate to our sweet and loving Parents*

*Whose affection, love and encouragement make us able to get much success and honor.*

*Along with all hard working and respected Teachers*

## ***Acknowledgment***

*First of all, we want to thank Allah, because he has graced our life with opportunities that we know are not in our hand or of any human hand, and shows us it's a scientific fact that gratitude reciprocates.*

*We're immensely grateful to our advisor Mr. Mohammed Khairy, who not only served us as our supervisor but also encouraged and challenged us throughout our academic program. Without his constant support, encouragement and guidance, this work would not have been possible. We thank him for accepting us as one of his students, being so patient and pushing us to be a better future engineer.*

*We would also like to thank the staff of Petroleum Engineering & Technology College, for their guidance and support in completing this work.*

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## **Abstract**

Managing sand production is critical in Fula field operation. Solid production is often causing issues with completion and surface facilities. Sand management and prevention are the current practices and leaving sand control as the last option if required. To make better informed decision to select sand control, one must understand, managing and preventing two conditions that may cause sand production: formation failure and sand transportation which lead to this study. The integrated approach started from acknowledging the lack of efficiency and higher cost of available sand control methods, followed by studying the availability of better sand control options, data collection of candidate well, data analysis, identification of sand production prone formations, perforation system optimization and wells evaluation. Six producers with sand problems were studied to correlate the production characteristics with sand production behaviors. Significant correlation was observed for the velocity per perforation with the severity of sand production trend. Sand production is less with reduction in the velocity per perforation.

The velocity threshold limit was identified utilizing PIPESIM software for simulation and considering the variation in critical drawdown pressure limits. For this field those wells that are producing higher than the medium limit historically has higher sand production.

The optimum perforation system was evaluated using PIPESIM software. The selection criteria and constraint were strongly governed by adequacy of depth of penetration, perforation spacing that is dictated by the shot density and phasing, sand transportation velocity threshold limit. This will aid in better optimized perforation system to manage potential sand production problem and guideline for production optimization processes.

This research will focus on perforation optimization strategy for sand prevention with a case study for six sand producers in Fula field using the above mentioned approached. The results are favorable.

## التجريد

تعد إدارة الرمل المنتج أمراً بالغ الأهمية في حقل الفولة. غالباً ما تتسبب إنتاج المواد الصلبة مشاكل في عمليات الاكمال والمعدات السطحية. إدارة الرمل ومنعه هو النهج الحالي المستخدم وترك التحكم في الرمال كخيار أخير إذا لزم الأمر. لاتخاذ أفضل قرار لاختيار التحكم في الرمل، فلذلك يجب فهم ومنع والتحكم في اثنين من العوامل التي قد تسبب إنتاج الرمال: انهيار التكوين (الطبقات) وحركة الرمال التي تؤدي إلى هذه الدراسة. بدأ النهج المتكامل بالاعتراف بنقص الكفاءة وارتفاع تكلفة وسائل التحكم في الرمل المتاحة، ثم دراسة مدى توافر خيارات أفضل للتحكم في الرمل المنتج، وجمع بيانات البئر المرشحة، وتحليل البيانات، وتحديد التكوينات المعرضة للرمل، وتحسين نظام الحفر، وتقييم الآبار. تمت دراسة ستة آبار منتجة للرمل لربط خصائص الإنتاج بسلوكيات إنتاج الرمال. ولوحظ ارتباط كبير لسرعة كل ثقب مع شدة إنتاج الرمال. إنتاج الرمال يقل مع انخفاض السرعة لكل ثقب.

تم تحديد مدى السرعة باستخدام برنامج PIPESIM للمحاكاة والنظر في التباين في حدود هبوط الضغط. بالنسبة لهذا الحقل، فإن تلك الآبار التي تنتج أعلى من الحد المتوسط لها تاريخياً إنتاج أعلى للرمال.

تم تقييم أمثل نظام تثقيب يمكن اتباعه باستخدام برنامج PIPESIM. وكانت معايير الاختيار تحكمها عمق الاختراق الكافي، والمسافات بين الثقوب وهي محكومة بكثافة وزاوية التثقيب، وسرعة حركة نقل الرمال. هذا سوف يؤدي الي اختيا رأمثل نظام تثقيب لإدارة مشكلة إنتاج الرمل المحتملة والحصول على أمثل أنتاج.

هذا البحث سيركز على وضع أمثل استراتيجية لمنع إنتاج الرمل مع دراسة حالة لسته آبار منتجة للرمل في حقل الفولة باستخدام النهج المذكور أعلاه واعطت نتائج جيدة.

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## LIST OF ABBREVIATIONS & SYMBOLS USED

Pe	External Pressure
k	Permeability
$\mu$	Viscosity
h	Interval thickness
re	External Radius to the Reservoir Boundary
rw	Wellbore Radius
S	Skin factor
q	Flow Rate
STB	Stock Tank Barrel
psi	Pounds per square inch
md	Milli Darcy
scf	Standard Cubic Feet
Pwf	Bottom hole Flowing Pressure
Spf	Shots per Feet
spm	Shots per Meter
AOF	Area to Open Flow
RDX	Research Department Composition Explosive
HMX	Higher Molecular Explosive
HNS	Hexa ntri stilbene
TATB	Tri amino trinitro benzene
ΥΧΣ	Υνχονφινεδ Χομπρεσσιωε Στρενγτη
PD	Penetration Depth
D	Perforation Diameter
CD	Charge Diameter
TCP	Tubing Conveyed Perforating
ID	Internal Diameter
SPAN	Schlumberger Perforating Analyzer Program
PIPESIM	Schlumberger Pipe Simulator

# **CHAPTER 1**

## **Introduction**

The life of an oil well depends on years of exploration, months of well planning, and weeks of drilling and results in an optimal completion. Completions are the interface between the reservoir and surface production. Well completion incorporates the steps taken to transform a drilled well into a producing one. These steps include casing, cementing, perforating, gravel packing and installing a production tree. Profitability is strongly based on this critical link between the reservoir and wellbore, which begins with the millisecond of perforation.

Perforation is the only way to establish conductive tunnels that link oil and gas reservoirs to steel-cased wellbores. Normally in the process of completion many parameters, such as borehole condition for data acquisition, cementing and formation details to avoid flow impairment are taken under consideration. However, it is often seen that perforation operation usually doesn't get much importance during completion. Perforations can significantly affect the total completion efficiency.

This high explosive activity can create negative effects, like damaging the formation permeability around perforation tunnels. This damage and perforation parameters, like penetration length, penetration hole size, number of shots, and the angle between holes, have a direct impact on pressure drop near a well and therefore, on production. The main objective of perforating is to optimize these parameters and mitigate induced damage.

Sand production has historically been a problem associated with soft or poorly consolidated formations. The result is usually lost production

due to formation sand and fines plugging gravel packs, screens, perforations, tubular, and surface flow lines or separators. In addition to damaging pumps or other downhole equipment, erosion of casing and surface facilities may also occur. Sanding problems may actually cause loss or recompletion of a well due to casing and/or hole collapse.

The methods applied to minimize the effect of sand production include critical production rate, gravel packing, sand consolidation, oriented and/or selective Perforation, expandable sand screen, or a combination of these methods. Completion methods are selected based on sand characterization and failure mechanism. Laboratory testing and mathematical models used for sand prediction are selected based on sand characterization (Davorin Matanovic, 2012).

Sand production from the formation is the result of unconsolidated or disintegrated sand grains around the wellbore or perforations. Usually that are rocks of low or intermediate strength with little or no cementing/bonding material between grains; but in fact sand production is possible also from the higher strength formations with good grain bonding. In both cases sand production can start immediately or can result later in well life cycle.

Fine particles (sand grains) in weakly consolidated formations will start to flow due to stresses caused by fluids flowing into the wellbore. Because of variety of possible situations it is suitable to consider all procurable options. Exclusion of any kind of sand control is done based on the sand prediction analysis. At the same time produced sand lowers the production rate, and any other kind of installed sand control equipment does the same. But at the same time, removal of the infilling, damaged material clears the pore space and rises the near wellbore rock permeability. That can lead to negative skin values and increase of the productivity index in heavy oil production(Davorin Matanovic, 2012).

The fact is that such approach can lead to low-cost solutions with the need of active risk management. It requires the analysis based on extensive field data acquisition, theoretical modeling of all involved physical processes, currently monitoring of production data with well testing to help in completion design optimization and risk assessment. The decision of implement or does not implement any kind of sand control can be done based on the integrated geomechanical and passive sand-control approach proposed by Rahman. It presents a general rock-failure criterion as a function of stresses in the formation, rock strength, reservoir pressure and its changes and wellbore trajectory and perforations spacing and direction(Khalil Rahman, 2008).

### **1.1 Problem Statement:**

Sand Production associated with heavy oil was appeared as one of the most common challenges in Fula oilfield, it causes serious technical and economic challenges.

Some wells produce batches of sand more than 6% of sediments, high daily average sand management cost such as flow lines blockage, sand accumulation lowers the production rate and might lead to non-productive time, High deferred production due to sand related problem. Erosion of surface and down hole equipments in addition to separator Problems; sand could take up a valuable volume of the separators total volume which reduces separators efficiency, reduction in oil flow rate and formation of unwanted emulsions between oil and water.

Due to the unfavorable results from previous sand control initiative, there is a need to seek other options that offers better cost and high efficiency. This can be achieved by optimizing the perforation system

based on an integrated analysis considering all technical aspects but within a field specific production condition.

## **1.2 Research Objectives**

The main objective of this study is to develop sand prevention perforation optimization strategy through:

- 1) Selecting the optimum gun system for sand prevention in Fula field.
- 2) Designing a work flow for future sand control perforation optimization.
- 3) Studying the effect of perforation on well productivity.

## **1.3 General Information about Fula oilfield**

Muglad basin is an interior Mesozoic-to-Cenozoic rift basin located in the south of the Republic of Sudan, covering an area of 112,000 sq.km. Its tectonics is complicated by faulting and continuous fault movement. Seismic data suggested large numbers of tensional faults in this area, and defined several sub-basins; structures within these sub-basins show significant variations in age of formation, complexity and size (RIPED - 2003). Block VI is located in the southwest of Sudan, tectonically in the northwest of the Muglad basin, and covers an area of 59,000 sq. km. Fula sub-basin is located in the northeast of Block VI concession area, and consists of 5 structure belts namely south step-faulted belt, south sub-basin, central structure belt, north sub-basin and north step-faulted belt. Fula oilfield is located just in the Fula central structure belt. The main Blocks in Fula oilfield can be divided into 3 blocks, i.e. Fula-1 Block, Fula North Block, and Fula Central Block; the main pay zones of heavy crude (RIPED -2003) are Bentiu and Aradeiba reservoirs:

- 1) Bentiu Formation (Pan et al 2006) is a major oil bearing sandstone reservoir in the Muglad rift basin of interior Sudan, with thick massive



loose sand. The reservoir has an average reservoir thickness of 83m; it has high porosity ranging from 24.2% to 31.6%, averaging 29.1% and high permeability from 561.5 to  $2926 \times 10^{-3} \mu\text{m}^2$ , at an average of  $2041.2 \times 10^{-3} \mu\text{m}^2$ . The reservoir is composed of thick beds of sands interbedded with thinner beds of clays with a thickness of 1 to 2 meters or less. The average oil viscosity is about 1536.39 cp at 50 °C.

2) Aradeiba (Pan et al 206) is the second reservoir with stratified unconsolidated pay sand; the reservoir has an average reservoir thickness of 15.5m. It has higher porosity and permeability than Bentiu reservoir, at averages of 32.3% and  $3261 \times 10^{-3} \mu\text{m}^2$  respectively. The average oil viscosity is 400cp; viscosity is up to around 450 cp at 50 °C

According to the RFT data from wells, initial pressure at Bentiu formation is 1609.5Psi, and 1502Psi at Aradeiba formation. Initial pressure shows a linear relation with depth with a pore pressure gradient of 125.1 Psi/100m. According to the logging and testing data acquired from different wells, the temperature of Aradeiba formation at the depth of 1,196.9mKB is 62.55°C with a gradient of 2.76°C/100m, and the temperature of Bentiu formation (at the depth of 1,271.6mKB) is 64°C with a gradient of 2.81°C/100m.

Due to the relatively high viscosity of the crude, and the poor consolidation of formation, reservoirs may predictably produce massive amounts of sand. Although sand production problems in Fula Field have been relatively small when compared to other sand producing areas in the world, many problems were found in the field due to sand production, and sand cut reached a value of 6% in some wells. Hence many sand-control methods are proposed to be tested at the field. Technologies of sand removal downhole and sand separation from blending fluid with sand were proposed and generalized in the field; surface sand traps were generalized after detailed study and testing. The analysis and optimization

of sand traps indicated that all the sand of a size greater than 0.45mm can be settled in wellhead sand trap. The general sand removal is greater than 95% as demonstrated by RIPED (2001).

The technique of Cold Heavy Oil Production with Sand (CHOPS) was selected as the strategy to develop the field; the recovery factor of cold production with sand may amount to 12-20% (RIPED, 2003). Other research (Li et al., 2006) was carried out to study the equivalent wormhole module and to optimize the critical parameters, such as reasonable pressure drawdown and production rate for CHOPS. In order to prevent sand production from the formations, and to delay water production from Bentiu formation, the operator decided to drill horizontal wells in state of the conventional vertical wells as the recent technology recommended. As reported by Pan et al. (2006), the horizontally drilled wells have a good performance on controlling sand production and increasing the productivity of the well also extending the water free production.

7"production casing for Aradeiba and Bentiu, completion type of TCP near-balance perforation technology are used for Fula oil field. Shot density 16-32shots/m for 7"production casing and more than 16shots/m for 5-1/2"production casing are used due to Aradeiba and Bentiu are heavy oil formations and Abu Gabra is a light one. KCL perforating fluid for Aradeiba and Bentiu, and using produced water or light oil for perforation fluid for Abu Gabra are performing well with small skin factor.

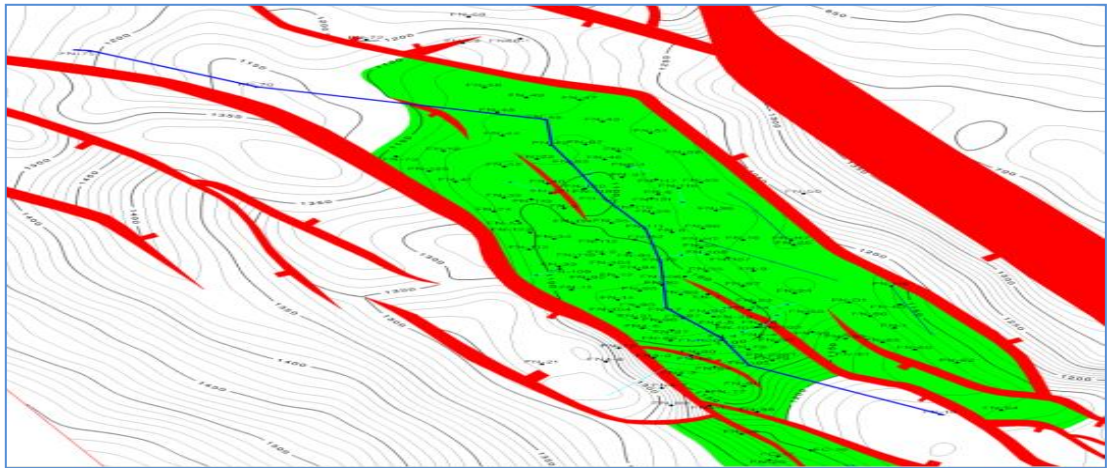
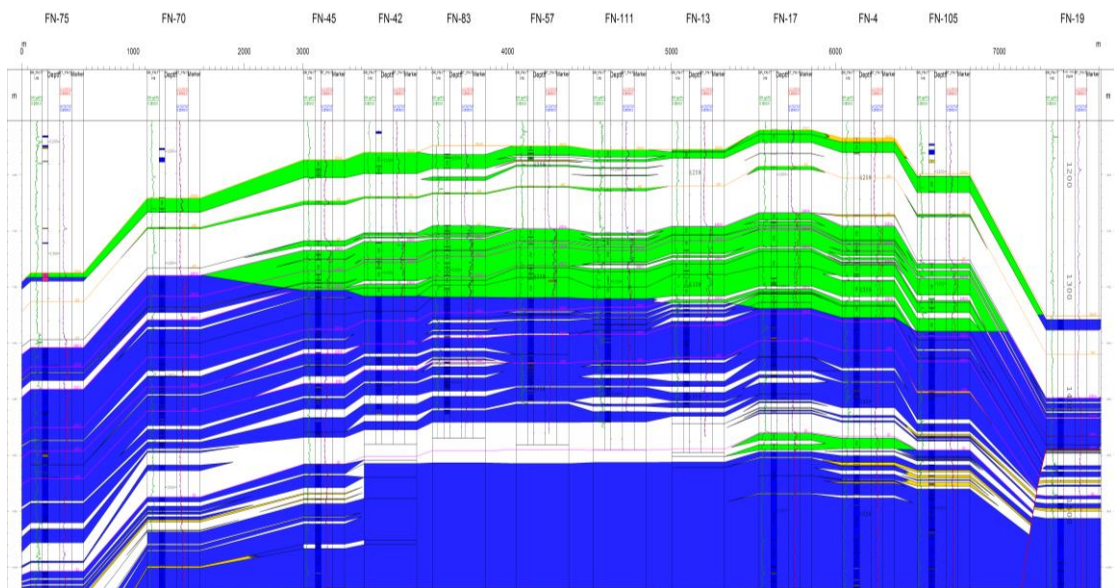


Figure 1.1 Fula field overview



N → S

Legend  
 Oil Zone Water Zone Tight Zone

Figure 1.2 Reservoir Cross Section of Aradeiba and Bentiu

## CHAPTER 2

### Theoretical Background and Literature Review

#### 2.1 Theoretical Background

##### 2.1.1 Introduction to perforation

The majority or completion, once the reservoir had been drilled, production casing or a liner is run into the well and cemented in place. To provide the communication path between the reservoir and the well bore, it will be necessary to produce holes through the wall of the casing, the cement sheath and penetrate into the formation. This is accomplished by a technique called perforating(Davorin Matanovic, 2012).

The basic operation requires that a series of explosive charges are lowered into the well either on an electric conductor cable, or on tubing or drill string, and when the charges are located at the required depth, they are detonated to produce a series of perforations through the wall of the casing and the cement sheath. Since the perforation will hopefully provide the only communication between the reservoir and well-bore, it is necessary to carefully design and execute the perforating operation, to provide the required degree of reservoir depletion control and maximize well productivity/injectivity(Farid, 2012).

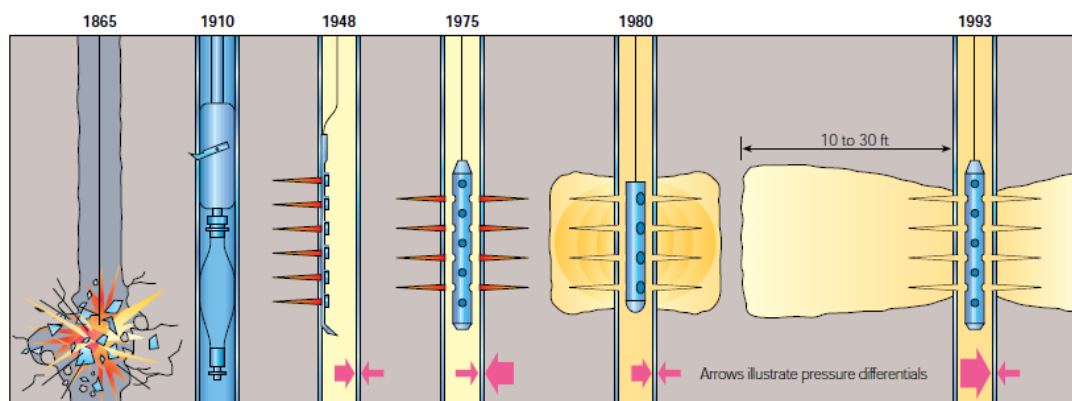


Figure 2.1: Development of Perforation Technology(Farid, 2012)

### **2.1.2 Perforating process**

Is an essential factor of the set-through method of well completion. That is probably the most important of all completion functions in cased holes. Adequate communication between the wellbore and all desired zones is essential to evaluate and to optimize production and recovery from each zone.

Perforation procedure should accomplish the following objectives, not necessarily in the order of importance(Farid, 2012):

- 1) Obtain a clean, undamaged, and productive perforation
- 2) Penetrate the production interval as far as possible
- 3) Shoot a smooth and round entrance hole in the casing
- 4) Minimize casing and cement damage and
- 5) Obtain the maximum flow rate with the minimum number of perforations.

### **2.1.3 Shaped Charge Characteristics and Performance**

A large number of design parameters, as well as operational condition, can markedly affect the performance of shaped charged perforators.

The basic shaped charge consists of:

- 1) A primer explosive charge.
- 2) A main explosive charge.
- 3) A charge case or container.
- 4) A conical metallic liner.

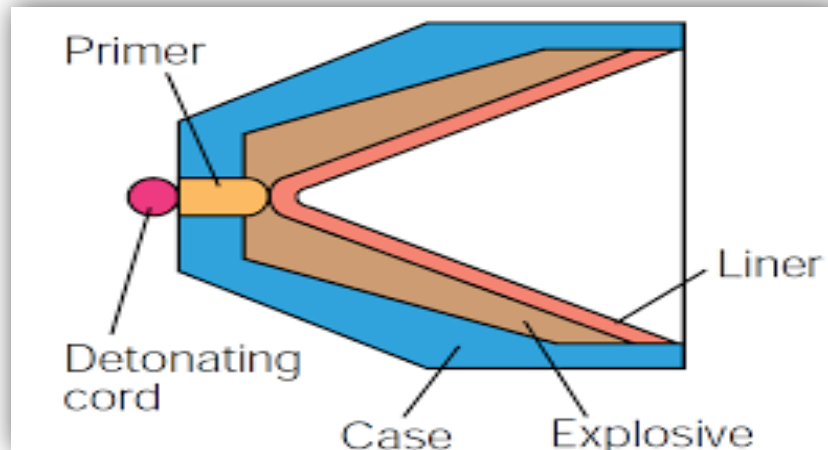


Figure 2.2: Shaped Charge components(Farid, 2012).

The detonation of the primer charge is actuated from surface by either electrical current is the case of a wireline conveyed gun or by mechanical, hydraulic or electrical means if the gun is conveyed on tubing.

The main explosive charge is usually a desensitized RDX (Cyclonite) type of explosive which besides being extremely powerful in terms of the energy released per unit weight of explosive, also reacts very quickly. In fact, once the main charge is detonated the process is completed after only (100 — 300  $\mu$ seconds). This fast reaction time is of importance in that it concentrates the detonation energy of the exploding charge to a very limited target area and also excludes any thermal effects. The main explosive is contained within a charge container which can be manufactured as either a metal or a disintegrateable case.

To concentrate the impact of the explosive force on the target the charge case is normally designed with a conical liner. This conical liner assists in concentrating the explosive force of the charge so that it provides maximum penetration of the target over a limited area.

Flat end is used for the shaped charge, the force of the explosion is spread over a wide area of the target with very limited Penetration. However, if a conical cavity is introduced, the force of the explosion provides much greater penetration of the target. However, if the conical casing is lined with a metallic liner, the penetration is substantially increased.

#### **2.1.4 Factors Influencing Charge performance**

The physical performance of a shaped charge is normally gauged from a number of characteristics:

- 1) Penetration length.
- 2) Penetration diameter.
- 3) Perforation hole volume.
- 4) Burr height on the inside of the casing around the perforation entrance hole.

However, charge Performance will be a complex matter since it will be affected by charge size, material and configuration, the dimensions and shape of the charge case and most importantly the characteristics of the conical liner , as well as the strength characteristics of the formation and the well-bore conditions(Farid, 2012).

#### **2.1.5 Classifications of Perforating Guns according to:**

##### **1- The Carrier guns Geometry**

The two broad categories of guns are exposed and hollow carrier guns. These can be used in two types of perforating operations:

- a) Through — tubing, in which guns are run through a production or test string into larger diameter casing
- b) Through casing, in which guns are larger diameters and run directly into casing.

## 2- Exposed Guns

Exposed guns are run on wireline and have individual shaped charges sealed in capsules and mounted on a strip, in a tube or a long wire. The detonator and detonating cord are exposed to borehole fluids. These guns are used exclusively through tubing and leave debris after firing. For a given diameter, exposed guns carry a larger, deeper penetrating charge than a hollow carrier gun. But exposed gun outer diameter is generally not larger than about  $2\frac{1}{2}$  in. (6 cm), because above this size, the casing becomes more practical, allowing use of larger charges, optimal angle between shot and increased number of shots per linear foot (Farid, 2012).

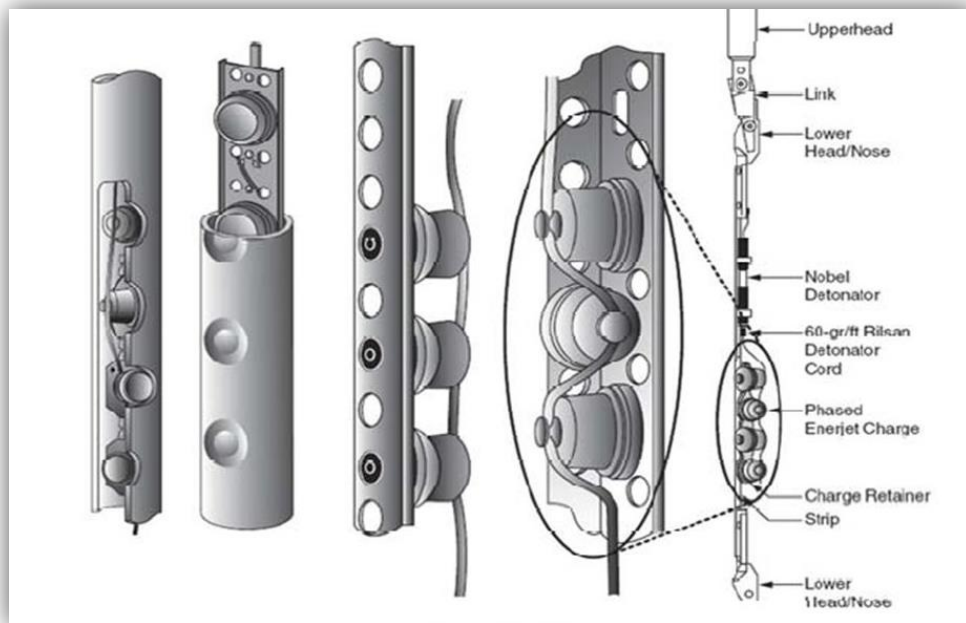


Figure 2.3 Exposed Guns (Farid, 2012)



### 3- Hollow Guns

Hollow carrier guns have shaped charger positioned inside pressure-tight steel tubes. This design is available for most tubing and casing size. It is used through tubing when debris is unacceptable and in hostile conditions that preclude exposed guns.

There are four main types of hollow carrier guns:

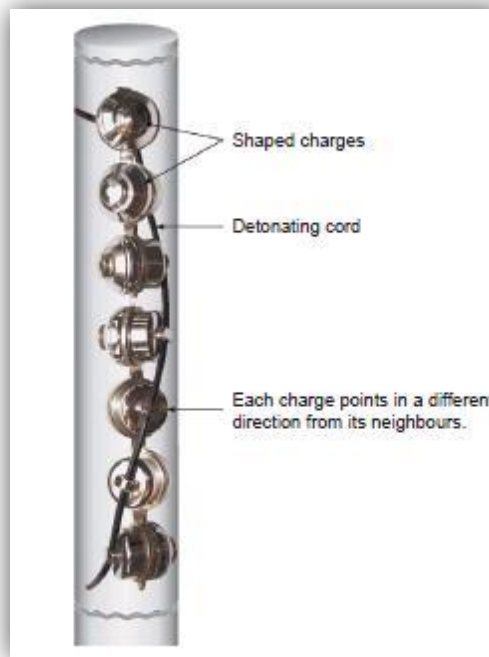


Figure 2.4 Hollow Guns(Farid, 2012)

#### I. Scallop Guns

The name is because the carrier contains a thin-walled, dished-out area through which guns are fired, and the debris is collected in the carrier. They are usually conveyed through wireline through tubing and where minimum debris is obtained



Figure 2.5 Scallop Guns(Farid, 2012)

## II. Port Plug Guns

These are the guns which shoot the charges through replaceable plugs in a reusable carrier. It has also the feature of perforating two intervals at a time with the help of a selective intermediate adaptor, which is remotely operated ,They are usually wireline conveyed and are used for deep penetrations with 4spf shot density.

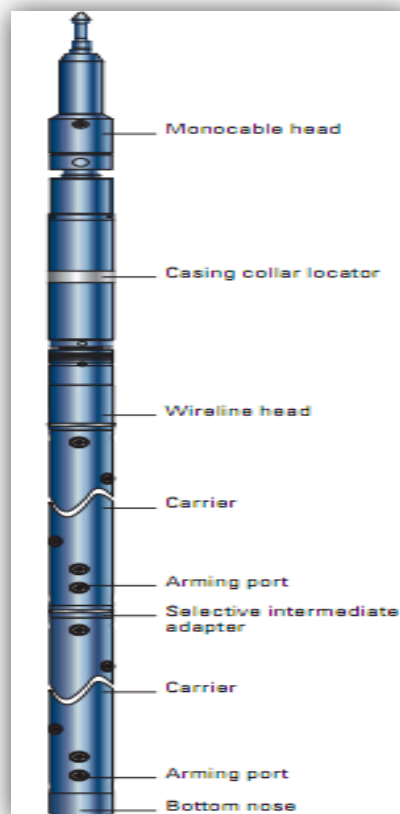


Figure 2.6 Port Plug Guns(Farid, 2012)

### III. High Shot Density Guns

This gun is usually used in sand control completions using high shot density with charges generating large perforation diameters. They can be run down by any means (wireline or tubing), but usually TCP is considered, allowing long interval perforation in one run.



Figure 2.7 High Shot Density Guns(Farid, 2012)

### IV. The (HEGS) High-Efficiency Gun System

This system, usually conveyed through wireline, is similar to port plug guns, with the only difference of having longer length carriers which are faster to load and run.

They are available with diameters of 3 1/8- in. and 4-in(Farid, 2012).

#### 2.1.6 Perforation System Selection Criteria

The selection criteria for the perforation system was defined as to increase 'Area Open to Flow' to reduce the velocity in each perforation tunnel within the critical limit to prevent sand transportation. Secondary requirements were then defined to balance the sand prevention aspect and well productivity. The requirements for geometrical perforating parameters that affect the well's productivity are:

- 1) Effective shot density, SPM/SPF (number of shots per unit length).

- 2) Perforation tunnel length.
- 3) Gun phasing.
- 4) Diameter of perforation (within the formation).

Depending of values of these parameters, “skin,” is created to either enhance or impair flow(Davorin Matanovic, 2012).

The sand production starts because of two main reasons:

- 1) Drawdown changes or flow rate changes,
- 2) Depletion of the reservoir that results with higher effective stress and production of higher water amount. When talking about perforations, sand must first be separated from the perforation tunnel walls and the flowing fluid must be capable to transport it. All of that is controlled by the stability of perforation tunnels over the producing life of the well.

To achieve perforation stability it is recommended to use deep penetrating charges of small diameter, because the smaller holes are more stable than large ones. After determination of rock mechanical properties it is possible to determine how to space perforations in the wellbore. That means to identify shot density and phasing.

The optimal approach is in spacing the perforations with maximum possible distance to preserve formation material. The ideal distance between adjacent perforations is achieved with same distances in all directions(Fig 2.8).

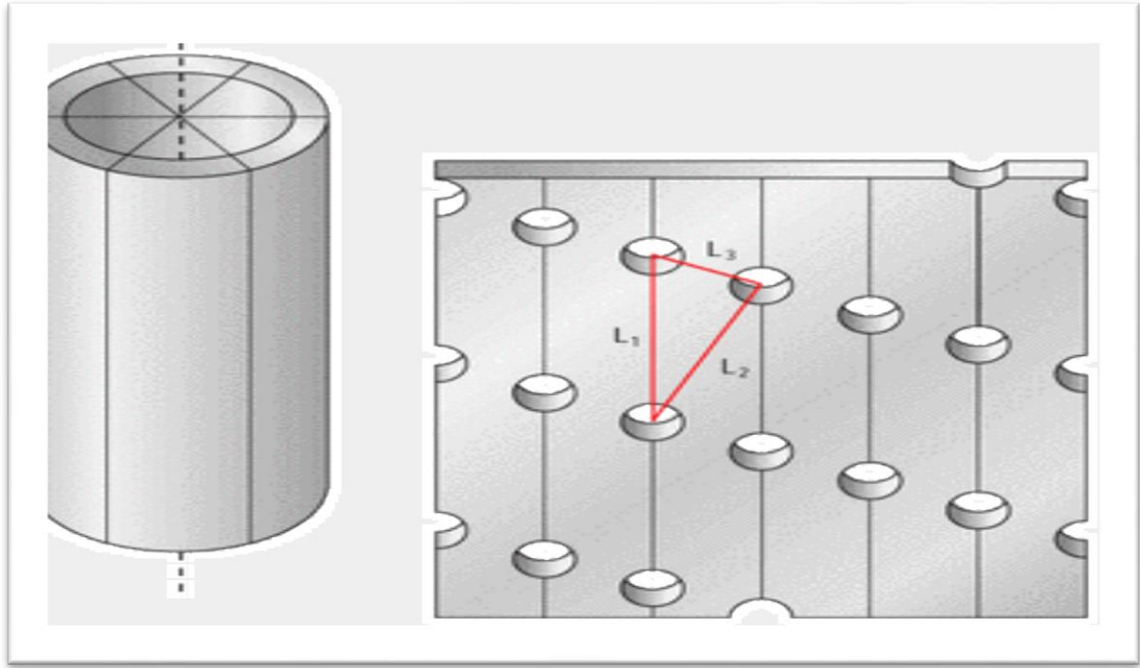


Figure 2.8 Critical distances between adjacent perforations(Davorin Matanovic, 2012)

### **Depth of Penetration**

One of the factors considered for selecting a gun is the length of the perforation tunnel, whether it reaches beyond the damaged zone and connects with the existing fractures. This also depends upon the type of charges in the gun and the formation compressive strength.

Figure 2.9 shows different perforation lengths for different formation strengths. The deeper the perforation length, the greater will be the wellbore effective radius. Penetration length not only depends upon the formation strength, but also on the charge type and stresses due to overburden pressure and pore pressure(Farid, 2012).

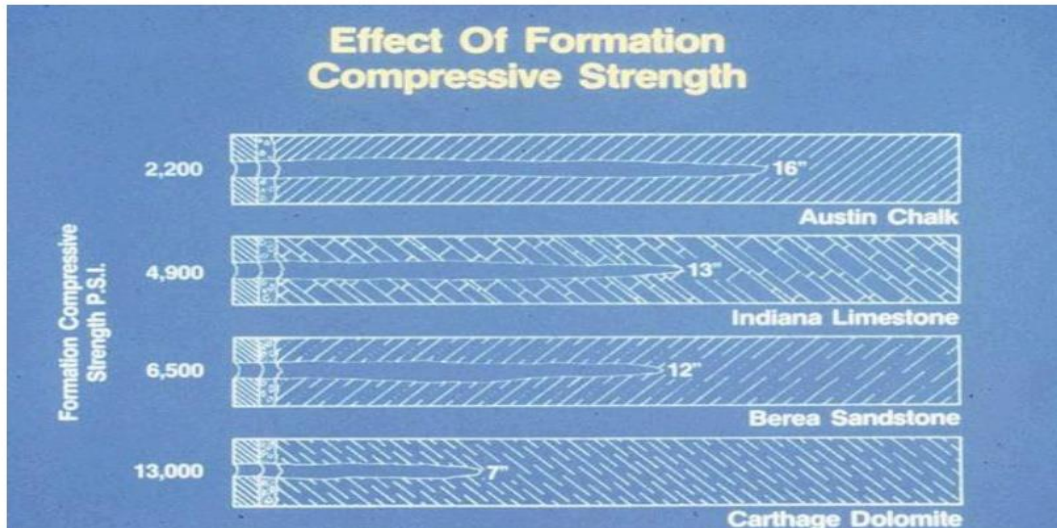


Figure 2.9 Depth of Penetration(Farid, 2012).

## 1. Shot Density

The number of shots made per unit length is a critical parameter for gun selection leading to a number of perforation tunnels in the formation. It depends upon the degree of permeability anisotropy for the reservoir, such as in the case of sandstone, where horizontal permeability is higher than vertical permeability and increasing the number of perforation holes will intersect more productive intervals in the reservoir. However, due to the high variation of permeability and porosity, such as in shale formations, increase in shot density may cause perforation tunnel collapse or high formation damage around the tunnel. In Figure 2.10, perforation lengths at various shot densities are shown against the productivity ratio. Productivity ratio is the measure of the flow rate through a perforated hole as compared to the ideal flow rate through the perforated hole of the same length and diameter. It can be seen that by increasing shot density productivity ratio also increases. Selection of optimum shot densities are carried out through numerous simulations based on detailed log permeability data and also past experience in case of formations with very low porosity or permeability. Due to these formations the number of

successful productive perforations is usually 50% of the total holes in the gun carrier. Maximum shot capacity is possible with 16-27 spf(King, 2007).

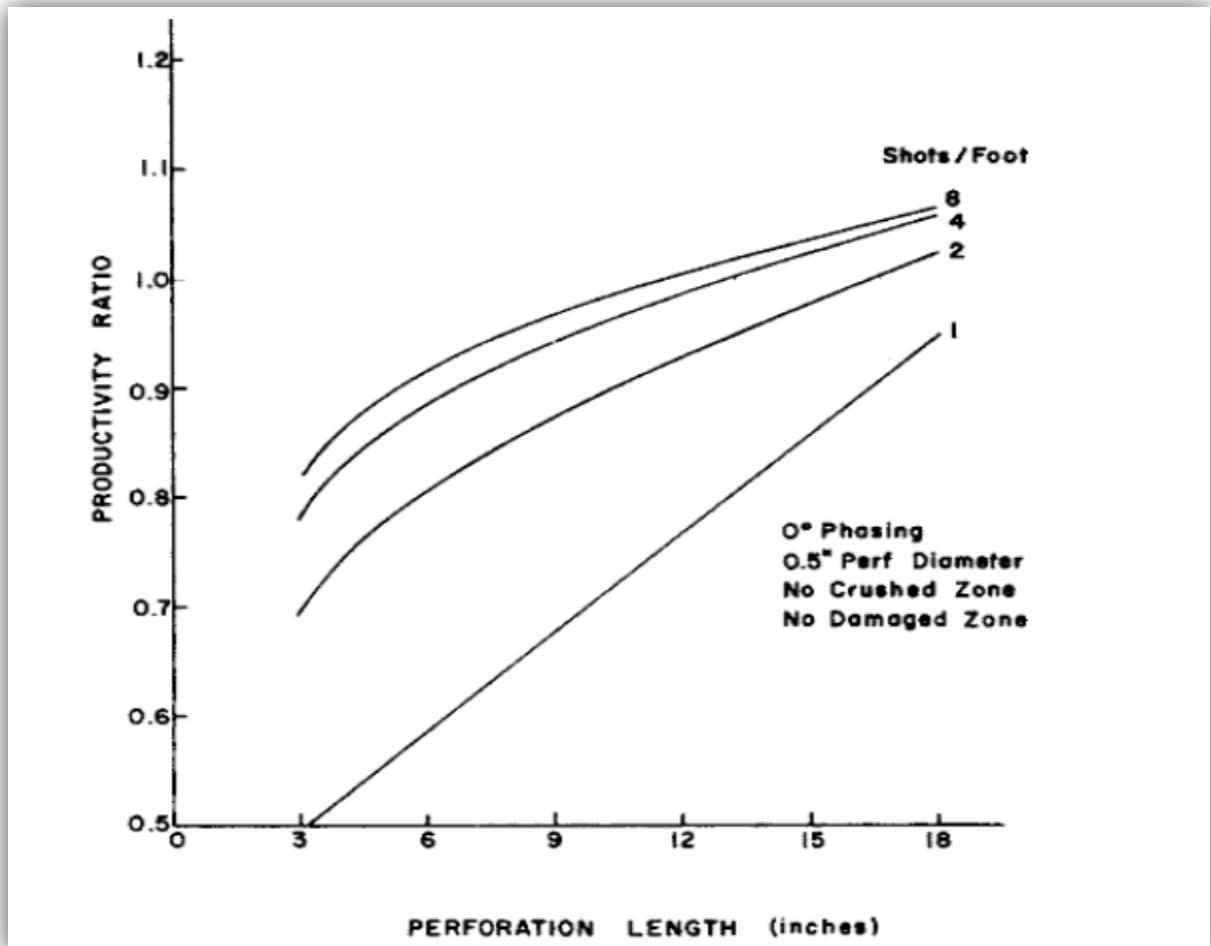


Figure 2.10 Shot Density(Farid, 2012).

## 2. Phasing

The best way for the oil to flow into the wellbore is usually controlled by the effective angle between the shaped charges which is termed as Phasing. Factors like pipe and formation strength, presence of natural fractures, and gun type are taken into account for choosing

different phasing angles, such as  $0^\circ$ ,  $60^\circ$ ,  $90^\circ$  or  $120^\circ$ (Farid, 2012).

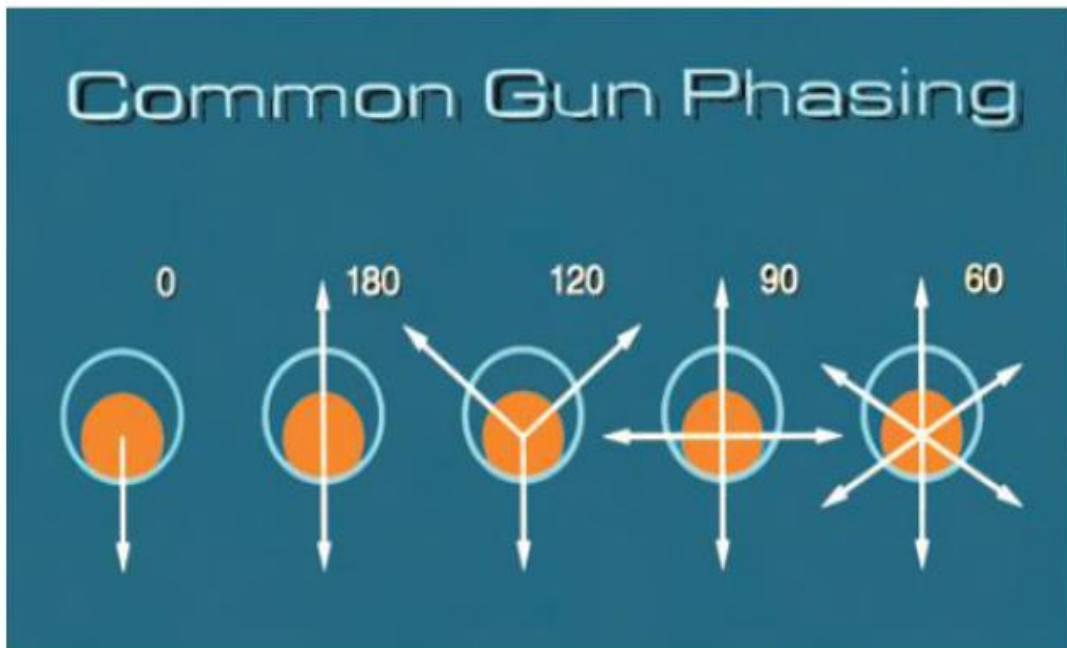


Figure 2.11 Phasing(Farid, 2012).

$0^\circ$  gun phasing is usually used with guns having small outer diameter or large casing diameters, in which all the shots are aligned in a single row. It is better to align the gun to one side closest to the casing wall so that the energy of the charges can be utilized efficiently in generating high penetration depths; however, an increase in formation damage may occur.  $0^\circ$  phasing is not preferred with shot densities higher than 6 spf in a single row as it may affect the casing yield strength leading it to split or collapse.

On the other hand, phasing  $60^\circ$ ,  $90^\circ$ , or  $120^\circ$  are more widely used because of their efficient results of flow properties. They are preferred because they have the ability to perforate at different angles, utilizing the surrounding reservoir body. They are usually used with guns having high outer diameter, due to which centralization of the gun is not required.



Productivity is also affected by phasing. During one of the studies by Locke (1980) in improving the productivity of wells, he discovered that, with the assumption of fixed perforation lengths and no formation damage, of all the phasing,  $90^\circ$  has the highest productivity ratio. However, in actual conditions the value is approximated and still  $90^\circ$  has high productivity values than other phasings.

### **3. Perforation Diameter**

Perforation diameter usually depends upon the type of shaped charge used by the gun. A deep penetrating charge is usually used for high penetration lengths, while a big-hole charge is used for large perforation diameter. High perforation diameter is usually required in stimulated completion or in application of gravel packing. These are the post perforation treatments which are done to minimize any left debris or damage in the tunnel, so that no flow impairment will be encountered during the injection or the production of the fluids. Perforation diameter has a very marginal effect on the productivity ratio in high turbulent flow wells; according to the study by Locke (1981), increasing the perforation diameter above 0.25 in., gives a minute increase in the productivity ratio. He also managed, by using Fanning Equation, to estimate the optimum perforation diameter by knowing the expected flow rate .

In SPAN the prediction of perforation hole diameter is based on the relationship between the entrance hole diameter through casing of grade J55 and the clearance between gun and casing. Perforation hole diameter through casing of grade J55 is experimentally calculated with an average yield of 65,000 psi. Therefore following formula is used for other casing grades used in the perforation process(Locke, 1981).

$$\frac{EH_{new}}{EH_{J55}} = \left[ \frac{2250 + 4.2y}{2250 + 4.2x} \right]^{1/2}$$

Where:

EH = Entrance hole

$x = 2.0 \times (\text{casing yield, kpsi}) + 60$

$y = 2.0 \times (65 \text{ kpsi}) + 60 = 90$

### 2.1.7 Oriented Perforating

In regions where there is a large contrast between the vertical, maximum and minimum horizontal stresses, perforations should be oriented in the direction of maximum stability. In these cases, if the rates per perforation are not too high, 0/180 degree phased perforating guns can be used. If the rate per perforation is a concern: For vertical wells, shoot in direction of maximum perforation tunnel stability at a +/- angle of “phi”(see Figure 2.12) and for horizontal wells shoot up/down at a +/- angle of “phi”. Phi is dependent on the in situ stresses and will typically be between 15 and 25 degrees. The concept of optimum phasing for an oriented gun is similar to that of a continuous phased non-oriented gun: to have a maximum shot density for a given perforation-to-perforation spacing. The current practice is to use 0/180 degree phased guns shot in the direction of maximum perforation stability.

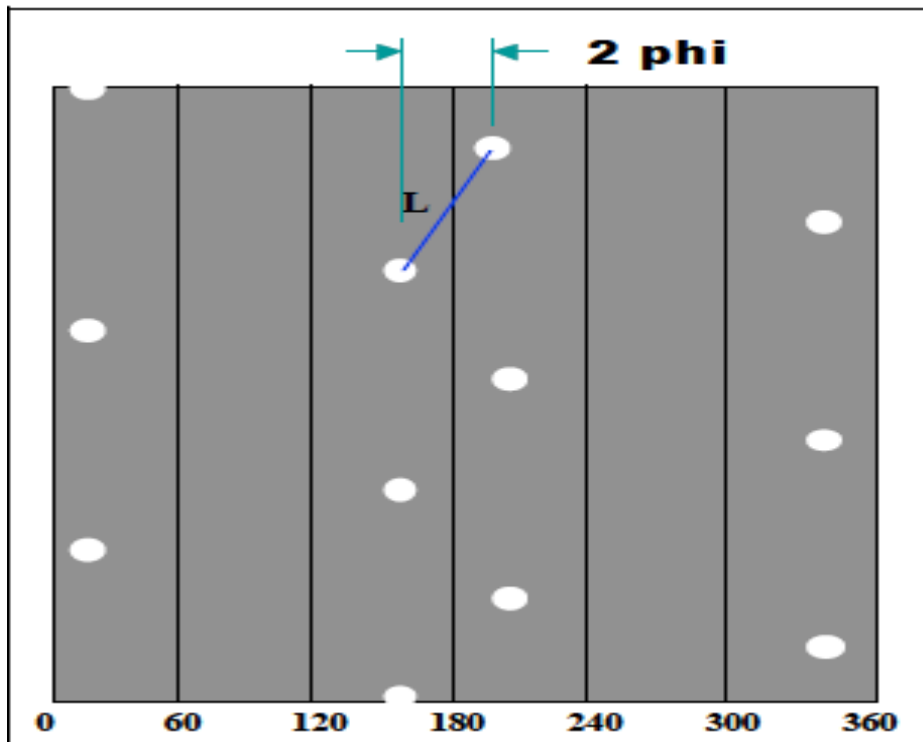


Figure 2.12 Oriented perforating shown in 2-D(Ruslan,2010)

### 2.1.8 Underbalance Perforating

One of the main reasons for perforating underbalance is to reduce the extent of permeability damage in the ‘crushed zone’ (extent of damaged zone around the perforation tunnel walls). If this material is not removed at the time of perforation, it will result in a larger pressure drop at the perforations that can contribute to tensile failure. This may or may not constitute a sand production problem (depending on whether the failure occurs immediately or at later stages when the drawdown is increased, or reservoir depletes, or during water-cut and also depending on whether this material is transported). Perforating at underbalance allows us to produce the sand during the initial stages and thus avoid having to manage transient sand production during later stages of well production. The underbalance value must be chosen to avoid catastrophic failure of the formation (‘sanding in the guns’) at the time of perforation.

The limit on the underbalance can be chosen based on values obtained from perforation stability model(keeping the underbalance value below the critical drawdown value). Single-shot perforation and flow experiments can be used to confirm the underbalance value chosen(A.Venkitaraman,2000).

### **2.1.9 Selective Perforating**

In formations where the strength varies drastically with depth, by avoiding perforating in sections that are weaker, one can maintain sand-free production through out the reservoir life<sup>11</sup>. Both productivity analysis using nodal analysis programs (to study the impact of partial penetration on productivity) and strength analysis (using methods mentioned in previous section) need to be carried out prior to making this choice.

## **2.2 Literature Review**

Sand prevention implies an acceptable risk of sand production over the producing life of the well with no sand control mechanisms implemented. This paper reviews available methods to optimize the choice of perforation parameters(phasing, shot density and charge type) for sand prevention. Prior work has shown that sand production is preceded by failure of the perforation tunnels. In order to have successful sand prevention it is necessary to have stable perforation tunnels through rate (drawdown) changes, depletion, and water-cut. Available methods to determine the ability of perforation tunnels to produce sand free can be classified into theoretical models, experimental methods and historical techniques. Deep penetrating charges are recommended as they produce smaller diameter perforation tunnels that are more stable than larger

diameter tunnels produced by big hole charges. Optimum phasing technique relies on the maximization of distance between adjacent perforations in 3-dimensional space for a given wellbore radius and shot density. This is advantageous in avoiding inter-linking of failed zones around adjacent perforations.

Where there are significant stress contrasts in the formation and the directions are known, oriented perforating can be used to increase the stability of perforation tunnels (especially when increasing drawdown and when depleting the reservoir). It is shown how these three main techniques can be used to perforate for sand prevention. In addition, the research also provides guidelines on how to avoid sand production at the time of perforation, selective perforating where there is a contrast in formation strength with depth and the use of experimental techniques to determine perforation stability due to rate (drawdown) changes, depletion and water-cut. In most unconsolidated and weakly consolidated wells around the world, traditional approach has been to use sand control techniques whenever there was a risk of sand production. This was driven mainly by safety (erosion of surface hardware) and economic concerns. However many wells where sand control mechanisms are installed have proven to be costly in terms of productivity impairment. There has been a two-fold approach to tackling this problem:

a) determine the sources of impairment to sand control methods and find out how to minimize them.

b) prudent use of sand prevention techniques as opposed to total sand exclusion. The essence of sand management is the quantification of the risk of sand production that helps decide if/how/when sand exclusion (control) or sand prevention should be implemented. Sand prevention

incorporates methods to minimize the amount of sand produced and also methods to minimize the impact of sand produced. The objective of this research is to outline best perforating practices for minimizing the amount of sand produced over the producing life of cased and perforated wells. Three main events are responsible for sand production: rate or drawdown changes, depletion (effective stress) and water cut.

Sand production is a two-part decoupled phenomenon: Sand must be separated from the perforation tunnel (failure), and the flowing fluid must transport the failed sand. Stress, controlled by drawdown and depletion does the first, and rate, also controlled by drawdown does the second. Using this theory sand production is dictated by the stability of perforation tunnels. Prior to perforating for sand prevention it is necessary to determine whether the tunnels would be stable over the producing life of the well (A. Venkitaraman, 2000).

### **2.2.1 Perforation Tunnel Stability Determination**

For successful sand prevention, a good understanding of the stability of the tunnels over the producing life of the well is needed before completion. Three different approaches are used by the industry to accomplish this.

**Theoretical Models:** The models originally developed for borehole stability are extended to perforations. Three steps are used, determination of rock mechanical properties (using log data, core samples), determination of in-situ stress conditions, and determination of failure (conditions) using a particular model. Theoretical models are effective in predicting perforation stability with change in stress conditions (drawdown and depletion). Two distinct approaches have been developed: the tensile failure model and the shear failure model.

According to the tensile failure criterion the fluid flow into a cavity at high production rates will induce a tensile stress near the cavity resulting in formation failure (sand grains being pulled away from the tunnel) and subsequent sand production. This model is seldom used as numerical studies and experiments indicated that this criterion predicts unrealistically high production rates to initiate sand production in weak but consolidated sandstone. Also, some sand production experiments showed stress-induced shear failure to precede sand production. Shear failure models can be classified according to the assumed material behavior: linear elastic/brittle, elasto-plastic. The models can also be classified according to the assumed geometry (simple 1D to 3D). The material property requirements and the complexity increase in the more sophisticated geometry and material behavior conditions. Mohr-Coulomb criterion is most widely used for shear failure assessment.

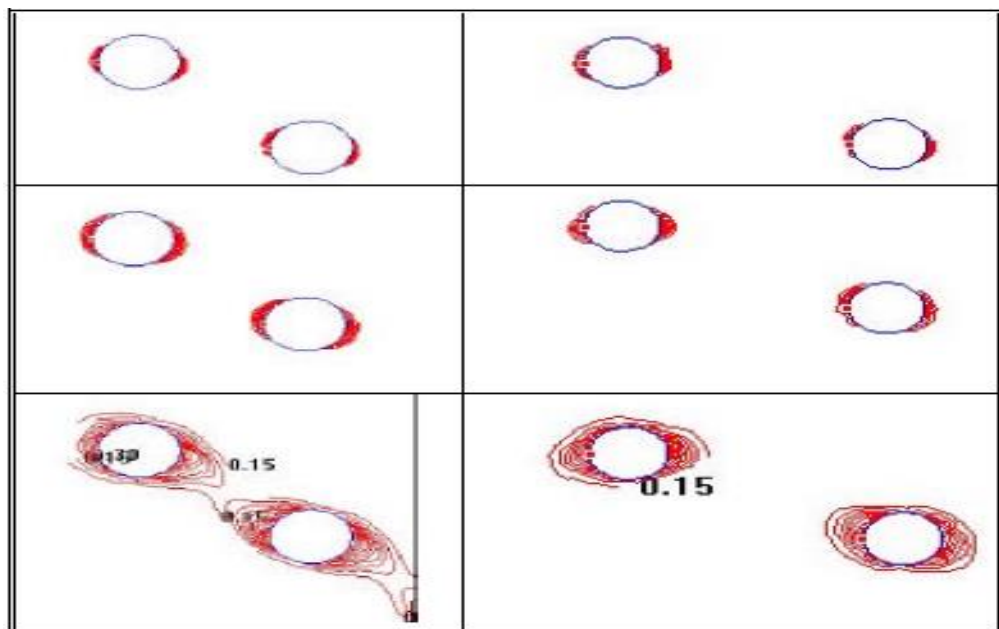


Figure 2.13 Results of 2-D plane strain elasto-plastic simulation of inter-linking between failed zones around adjacent perforations(60 degree phasing and 99 degree phasing) (Ruslan,2010). The effective stress is

increased (depletion) as one moves down the column. The left hand column shows the 60 degree phased adjacent perforation sand the right hand column shows the 99 degree phased perforations. For similar inter-linking to occur for 99 degree phased perforations the effective stress would have to be a factor of 1.3 times the stress at which inter-linking occurred for the 60degree phased perforations

**Experimental Methods:** Experimental methods involve testing of available reservoir core samples or outcrop rock samples (with similar mechanical properties). There are two different types of test: drilled hole tests and single-shot perforation and flow tests.

In a typical drilled hole test, a cylindrical cavity of uniform diameter is drilled in a core sample. The drilled sample is then placed inside a rubber sleeve and isotropic confining pressure is applied on the outside of the core.

The stress on the sample is increased until the yield point is reached. According to elastic theory when the circumferential stress on the inner wall of the hole reaches the (apparent) strength of the material the hole will fail. The main drawback is that the sample size/hole size ratio of the hollow cylinder can influence the resultobtained<sup>7</sup>.Though not widely used, available core sample from the well is perforated and flowed at different rate, depletion and water-cut conditions<sup>8</sup>. The test parameters can be chosen based on the expected conditions during the producing life of the well. This method can be used to augment analyses from theoretical models and to check for sand production during water-cut. The tests can also help determine (the stability of perforation tunnel or) sand production at the time of underbalance perforating. The drawbacks



to this method are the discrete nature of data (core sample from specific depths) and availability of samples.

**Historical:** Historical sand production prediction criteria rely on production experiences (rate, drawdown, percentage water cut) on other wells in the same reservoir to arrive at a choice between sand control and sand prevention. In some cases reservoir strength data is used as the yardstick to compare and predict potential for sanding across different reservoirs. This is by far the most widely used technique. The best use of this approach utilizes available data to calibrate theoretical models for future sand production prediction (A. Venkitaraman, 2000).

Based on the geomechanics analysis in this field, calibrated log properties were used with some correlations to estimate formation strength and failure conditions to get reasonable results for the formations under study. Initial analysis indicates that a small amount of sand will be produced under any conditions; generally sand will be increased if the flow rate reaches a critical value. Thus, the formation stability is greatly affected by the perforation diameter and grain size.

According to Stein's concept, amount of sand will be produced with any flow rate from those formations, while sanding may be a problem under a certain conditions for this field. Hence an alternative method for modeling sanding to avoid sanding conditions for this area is required (Elham and Zhang, 2010).

There are many ways to avoid or minimize sand transportation. In very weak, unconsolidated reservoirs, downhole methods to exclude sand production (gravel packs, high-rate water packs, frac packing, stand-alone screens etc.) are very popular. However, previous experience in the area

resulted in expensive installation of downhole hardware and considerable reductions in production rate. Other option is to produce a well below a critical hydrodynamic force and sand will not be transported out from the reservoir to the wellbore. This is basically achievable via optimizing the perforation strategies.

The initial high level completion screening was evaluated using Bayesian knowledge engine and extensive historical case base reasoning which integrates reservoir information, production parameters and operational constraints which was calculated in similar field conditions as per table below. The best recommended option highlighted in green, potential options in yellow and discarded options highlighted in red. The result indicates that perforation system optimization would be the best solution up to certain production parameters.

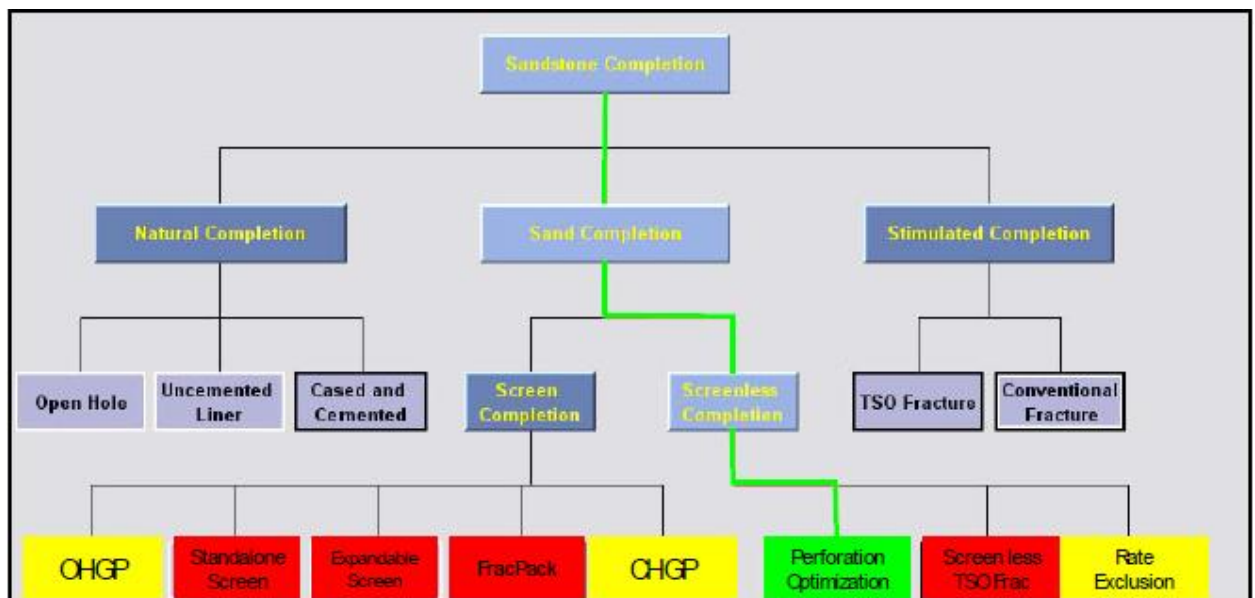


Figure 2.14 Bayesian Knowledge Completion Screening Tool Result(Ruslan,2010)

### 2.2.2 Monte Carlo Probabilistic Analysis

In order to further verify the applicability of the concept, a set of producers was selected for a statistical analysis to correlate the production

characteristics with sand production trend. Probabilistic model was developed based on below equation.

Briefly, if Q, flow rate is constant, with the increase of A, area open to flow, V, the velocity in perforation which translated to hydrodynamic force to transport sand will be reduced. The area open to flow is calculated based on total perforated interval, entrance hole perforation diameter and open perforation.

$$Q(L^3/T) = A(L^2) \uparrow \times V(L/T) \downarrow \dots\dots\dots(2.1)$$

Probabilistic distribution was defined for below inputs and theoretical ranges of velocity in perforation were calculated. The objective is to consider the expected production range over the well life and to control the uncertainty in those values that contributes to the total area:

1. Perforated interval length
2. Perforation entrance hole diameter
3. % open perforation area
4. Well production

A sensitivity chart was generated and it indicates that the area open to flow has the biggest impact to reduce the velocity in perforation. This concludes the need to optimize the perforation system. Fig.2.15 Monte Carlo Sensitivity Chart. Considering a uniform and homogeneous reservoir, an initial estimate of fluid velocity per perforation can be obtained(Ruslan,2010).

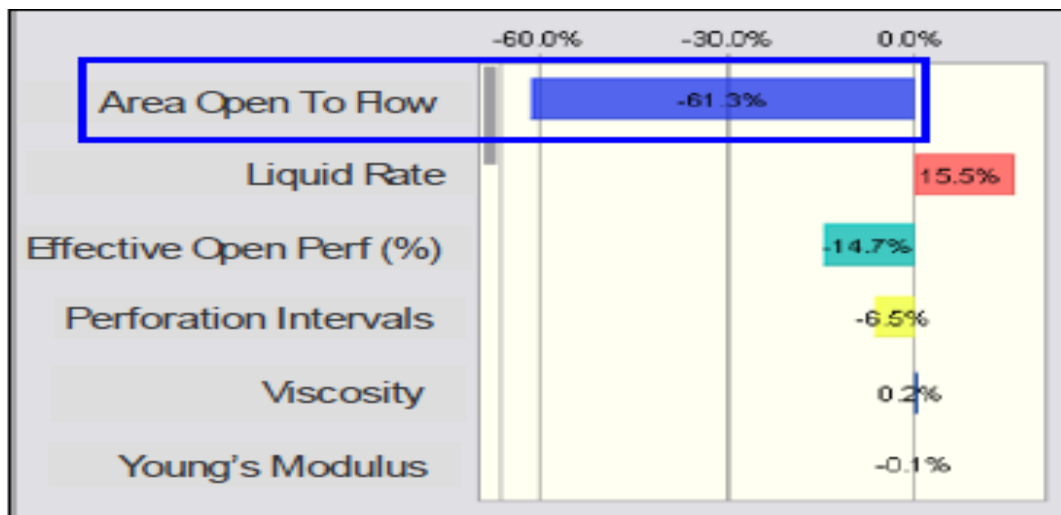


Figure 2.15 Monte Carlo Sensitivity Chart(Ruslan,2010)

Additionally, in the case of no presence of perforation tunnel, smaller perforated entrance is more favorable to form a stability arch. The resorting of the formation sand will act as natural filter to sand but very susceptible to drastic changes in production conditions especially hydrodynamic forces. Refer Figure 2.16.

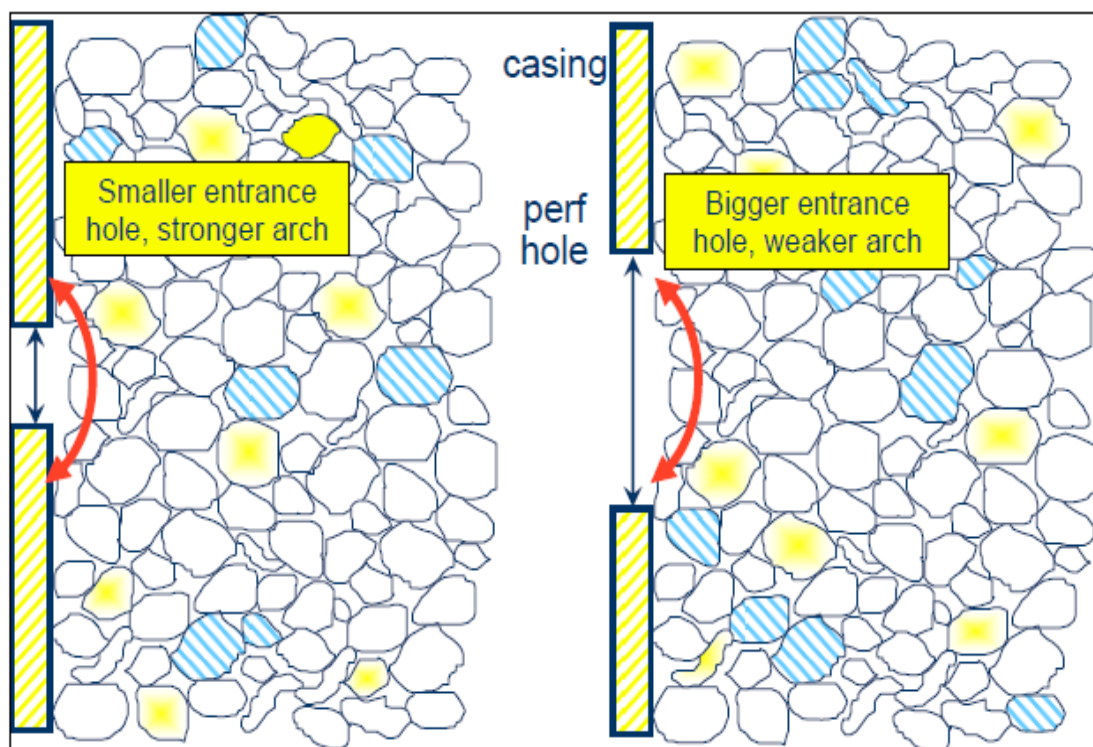


Figure 2.16 Effect of entrance hole to stability arch(Ruslan,2010)

# **CHAPTER 3**

## **Methodology**

### **3.1 Methodology Brief**

Due to the unfavorable results from previous sand control initiative, there is a need to optimize the perforation system specifically focusing in managing sand production. The project major scope is technical analysis. Following of series evolutions and studies, it was identified that sand production can be mitigated, or prevented, if the velocity at each perforation tunnel is below the critical limit to transport the sand from the formation to the wellbore. This can be achieved by optimizing the perforation system based on an integrated analysis from well productivity up to well performance but within a field specific production condition.

Some of the producers with sand problems were selected for a statistical analysis to correlate the production characteristics with sand production behaviors using PIPESIM software. Sand production is less with reduction in the velocity per perforation.

The optimum perforation system was evaluated using PIPESIM software. The selection criteria and constraint were strongly governed by the well productivity and sand transportation velocity threshold limit. This tool enables perforation system optimization to manage potential sand production problem and guideline for production optimization processes.

### **3.2 High Level Completion Screening**

Failure at the sand-grain scale during hydrocarbon exploitation can cause wellbore-stability problems, casing collapse, reduced production,

and in some cases, the loss of a wellbore. Sand production occurs in two phases. Initially the rock should fail mechanically. After that, loose sand grains are mobilized and transported. In Fula field, the first condition is presence in most wells, but in very specific formations. Many layers have low critical drawdown at 100, 150 and 360psi(Elham and Zhang 2010).Thus, major focus is draw to second condition, preventing sand transportation.

### **3.3 Estimating Maximum Sand Free Production Rate**

Numerous sensitivities and fine tuning to the probabilistic model were carried out to ensure possible representative range obtained. The forecast probable critical velocity should be cross checked with the actual well historical sand production. Those well that producing below the medium limit should produce significant lower sand. Based on above considerations, the possible range of critical velocity for the upper reservoir sand was identified as below: Low: 0.017 ft/s Medium: 0.023 ft/s High: 0.066 ft/s These limits are rather reservoir specific and each reservoir should be measured or estimated separately. The value is dependent to surface area of the hemispherical arch, permeability of the formation, number of perforations, reservoir fluid pressure, radius of the arch and reservoir fluid viscosity. Combining these results with the previous analysis, indicate that those wells producing above the medium limit, had sand production increase rapidly compare to average sand production for wells producing below this limit. This again, confirms the applicability of the concept and the statistical and probabilistic models were properly configured.

### 3.4 Process Chart

A simple process chart was created and followed during this research as in Figure 3.1

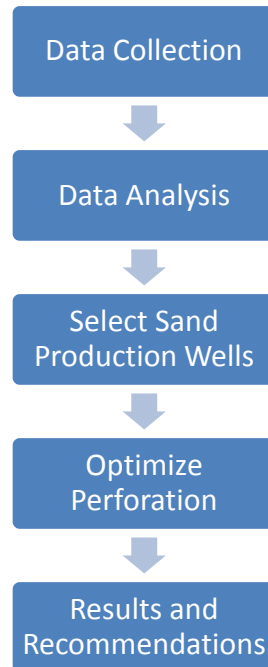


Figure 3.1 Simple Process Chart

#### 3.4.1 Data Collection

Fula field is producing heavy viscous oil associated with sand we have focus in our research on the data from completion and workover because it's more accurate and each well has many workovers from start-up, and sand accumulation has been calculated from the periods between well commissioning or previous workover until last workover program for each selected well.

#### 3.4.2 Data Analysis

Major consideration was given between balancing shot density and perforation tunnel diameter towards increasing area open to flow. Shot density need to be as high as possible to obtain bigger area open to flow

but at the same time the tunnel diameter should be reduced to improve the formation stability.

In this research two methods of analysis techniques have been used, which include the following:

1. PIPESIM Software
2. Microsoft Excel Sheet

PIPESIM software allows view, relate, and analyze reservoir and production data with comprehensive workflow tools, in addition to Nodal analysis to check the effect of chosen gun on productivity.

Microsoft Excel Sheet was used as plotting tool to help analyze the acquired PIPESIM result.

### **3.4.3 Well Selection**

Sand production is a challenging problem in Fula field which causes blockage of flow line sand process piping due to sand deposition, Fula is good candidate for sand related research since it has shallow reservoir and viscous oil, all these factors played a role in increased sand production. Any positive result from this research will help in mitigate or prevent this costly problem.

Wells were chosen according to their sand production and data availability.



# CHAPTER 4

## Result and Discussion

### 4.1 Process Flow Chart

Based on the methodology used and project development phases, perforation system optimization process flow chart was developed for existing and the new wells. Refer to Figure 4.1

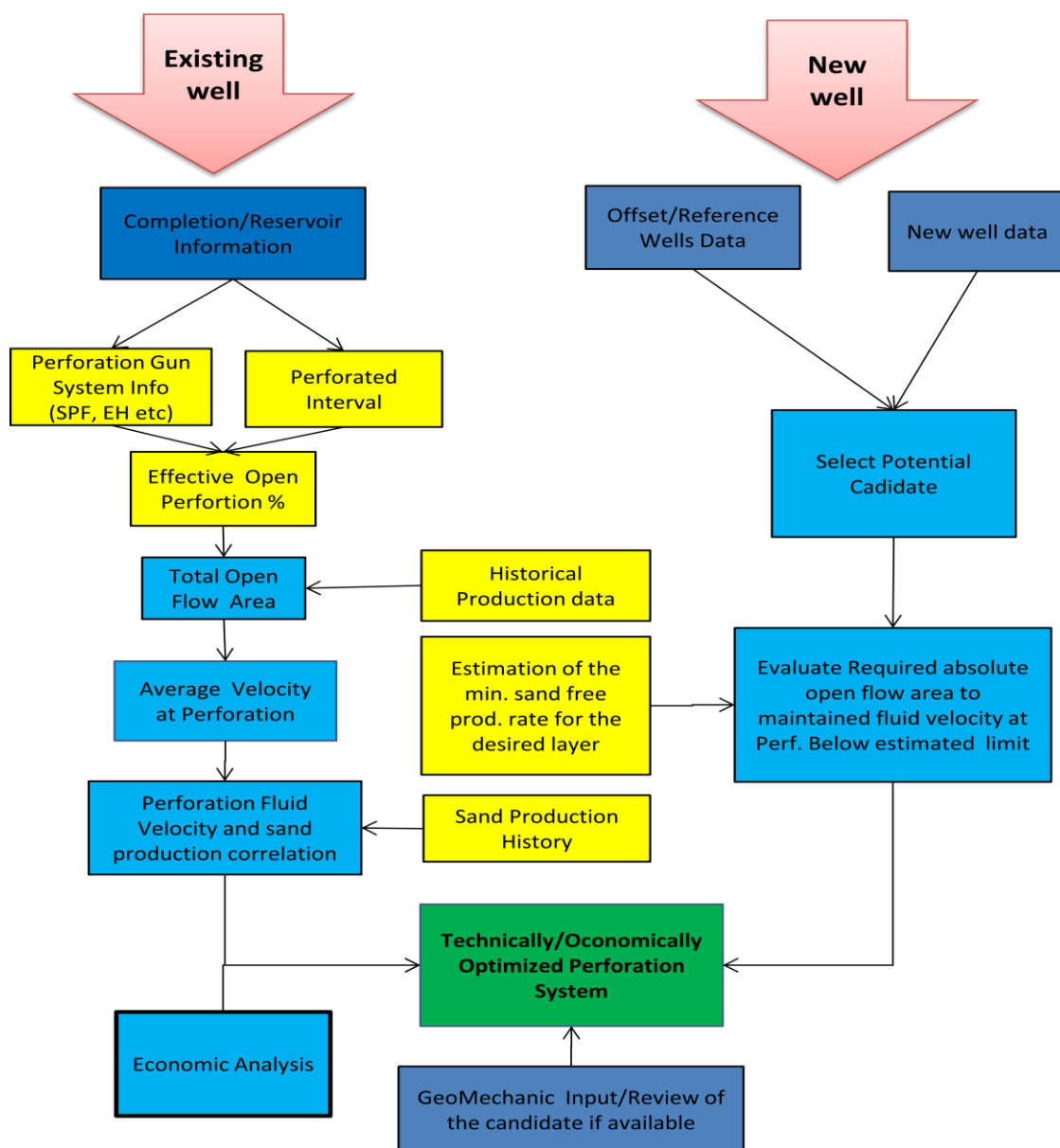


Figure 4.1 Process flow chart for existing and the new wells

## 4. 2 Acquired PIPESIM Data

Six wells were chosen for extensive analyses and has shown a remarkable improvements compared to the original gun system that was used in these well that will eventually lead to sand prevention.

Several scenarios were tested using PIPESIM using different phasing, charge types and shot densities.

Table 4.1 and 4.2 are the acquired results from PIPESIM that will be plotted to show different relationships that supports the main claim in different ways.

Table 4.1: 4.5” HSD, 90°, 5spf

Wells	Area Open to Flow (in <sup>2</sup> )	Average Velocity (ft/s)	Flow Rate (bbl/d)	Drawdown Pressure (psi)
Well NO-1	0.55	0.018346	63.65152	121.0012
Well NO-2	0.58	0.02966456	92.09558	132.723748
Well NO-3	0.59	0.02384944	74.02126	113.0092
Well NO-4	0.59	0.039104	60.56743	124.8866
Well NO-5	0.59	0.02213	60.1325	119.55
Well NO-6	0.87	0.076406	144.0695	202.43755

Table 4.2: 4.5” HSD, 135°/45°, 12spf

Wells	Area Open to Flow (in <sup>2</sup> )	Average Velocity (ft/s)	Flow Rate (bbl/d)	Drawdown Pressure (psi)
Well NO-1	1.06	0.016436	61.0712	118.1133
Well NO-2	1.06	0.02817212	87.46223	129.55532
Well NO-3	1.06	0.0218306	71.02192	110.9914
Well NO-4	1.06	0.03673	55.04532	118.00123
Well NO-5	1.06	0.01844088	57.25082	117.998
Well NO-6	1.06	0.05433075	137.626	198.37433

### 4.3 Data Analysis

Figure 4.2 is showing the relationship between production rate and the actual sand production volumes in each well with time taken from Fula field production history. We can notice some correlation exists and that they to some extent proportional to each other.

Depending on the productivity and sand production, six wells were chosen for perforation optimization from the below plotted data.

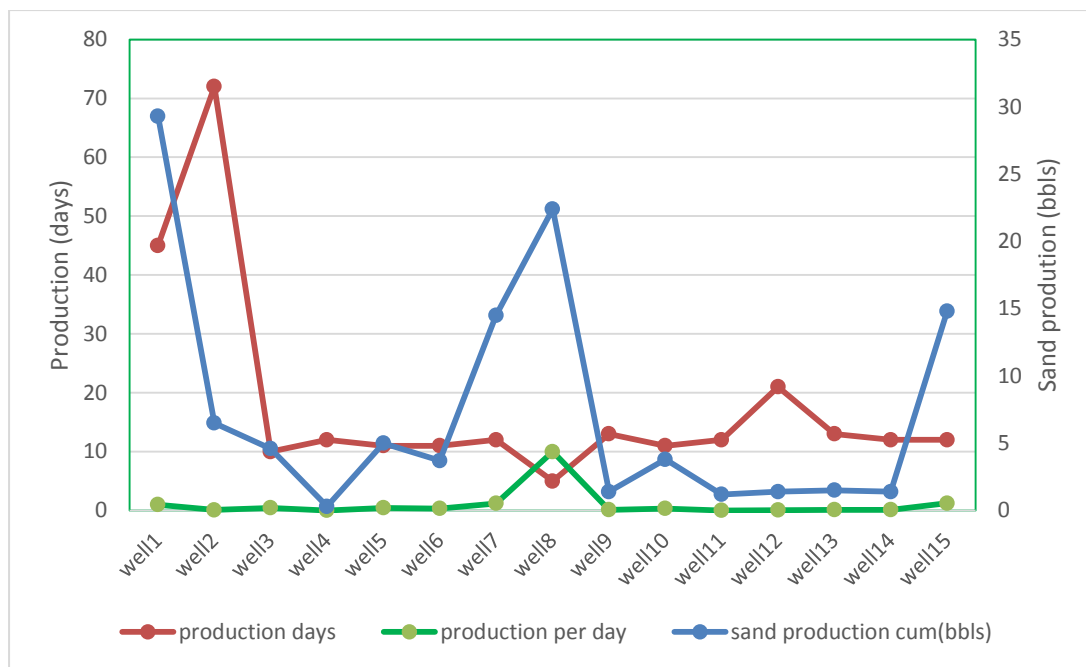
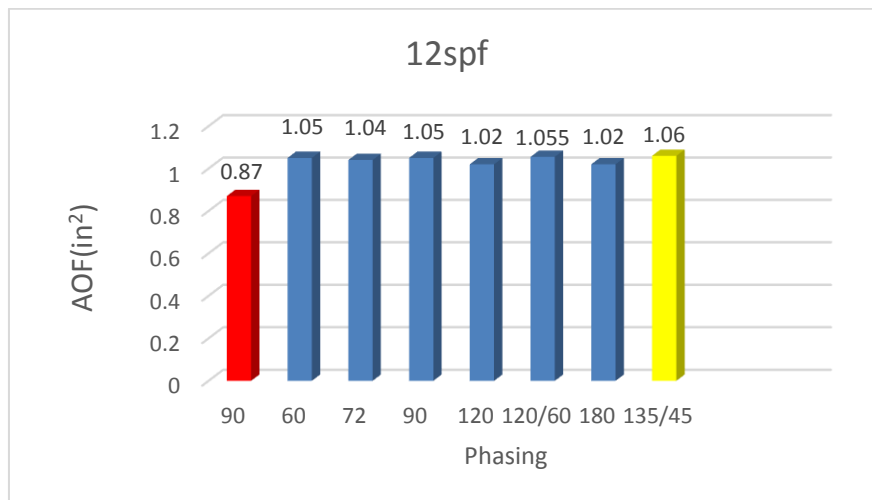
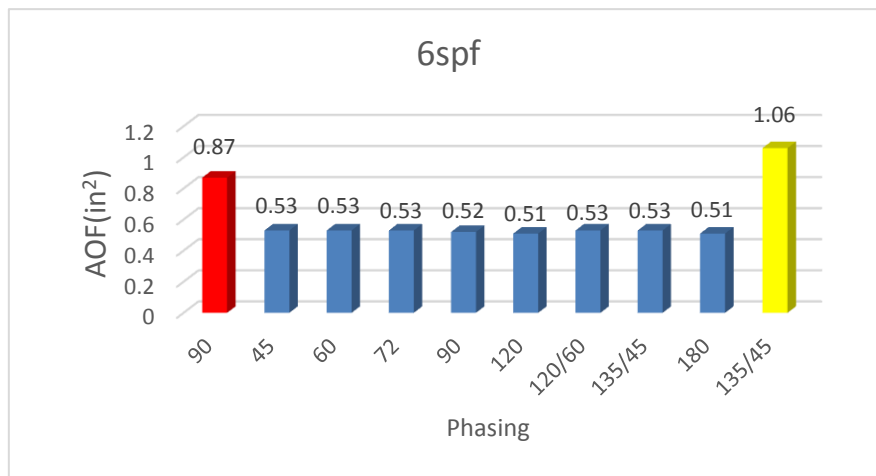
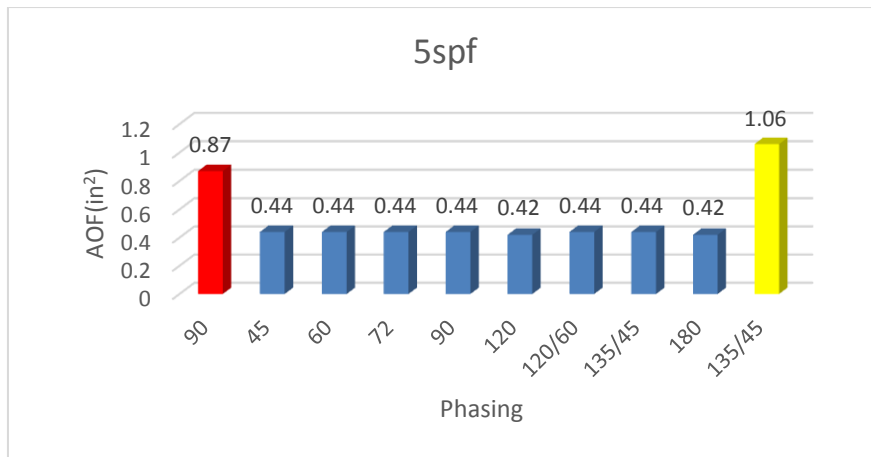
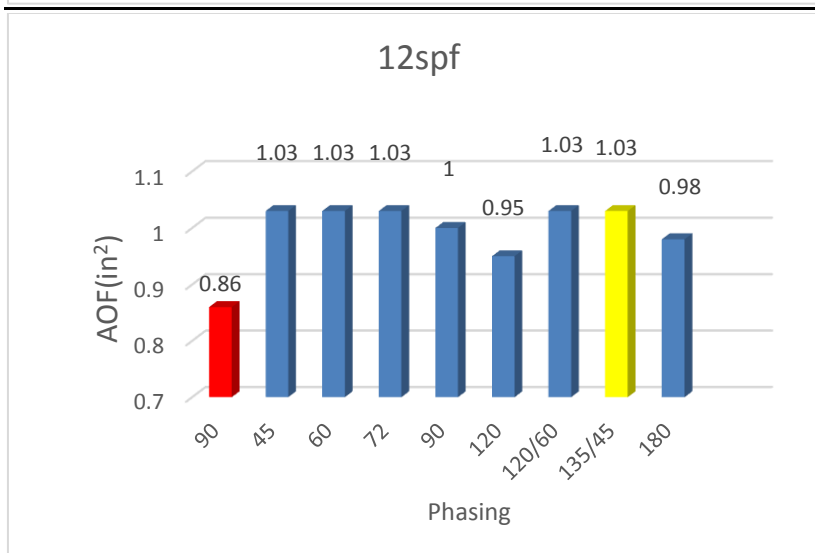
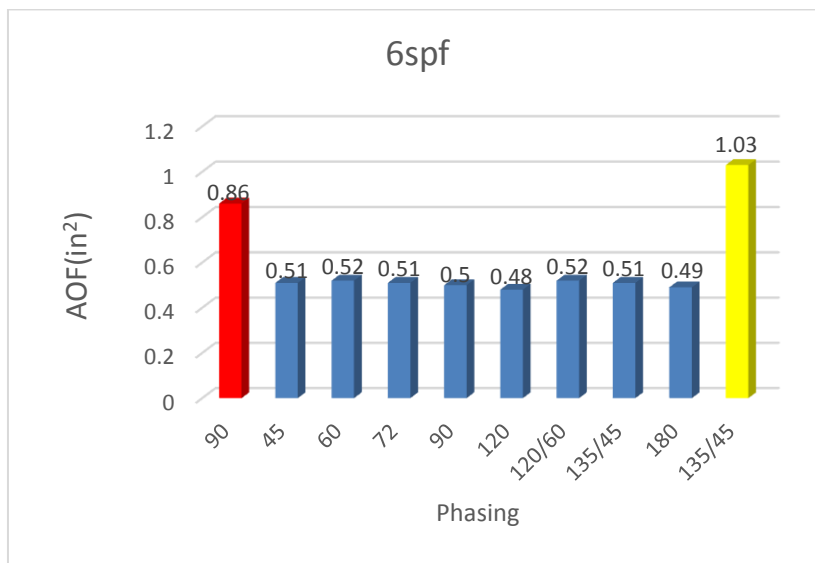
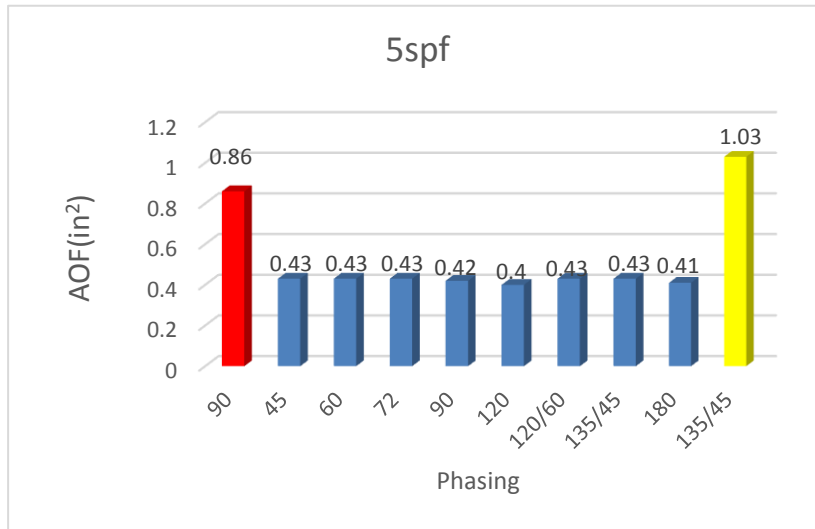


Figure 4.2 Relationship between production and the actual sand production volumes in each well with time.

In the below figures the original gun system which is now used in there wells are shown in RED while the optimized perforation system is shown in YELLOW.



Figures 4.3 Area open to flow with different phasing angles and shot density for Well No-1



Figures 4.4 Area open to flow with different phasing angles and shot density for Well No-2

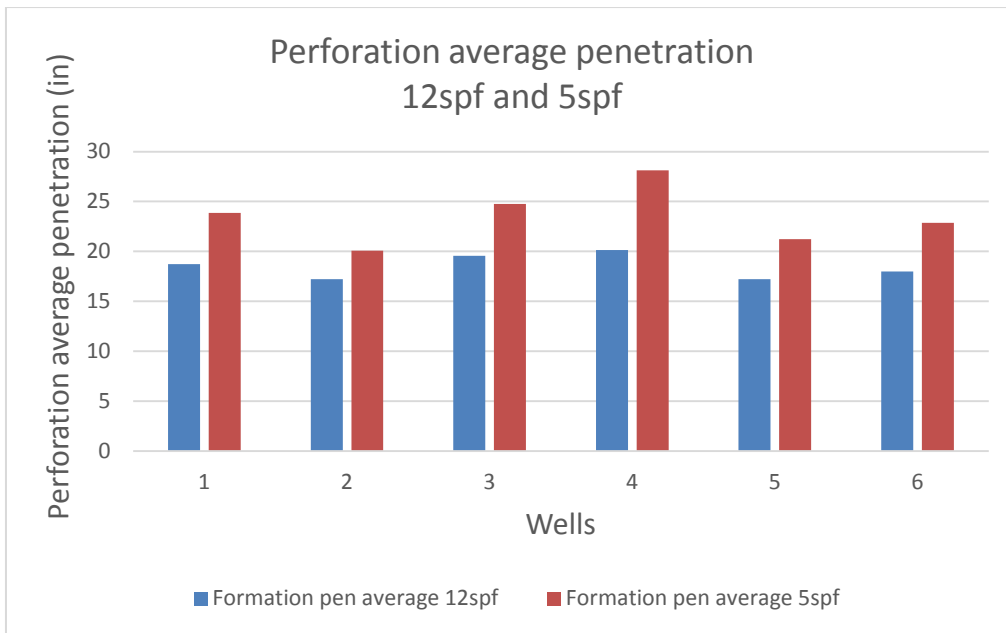


Figure 4.5 Perforation average penetrations for 5spf and 12spf for different wells.

Depth of penetration is higher for current well with 5spf that will lead to increased well productivity. But even with 12spf the gun penetration depth is beyond the damaged zone which makes the difference in productivity minimal.

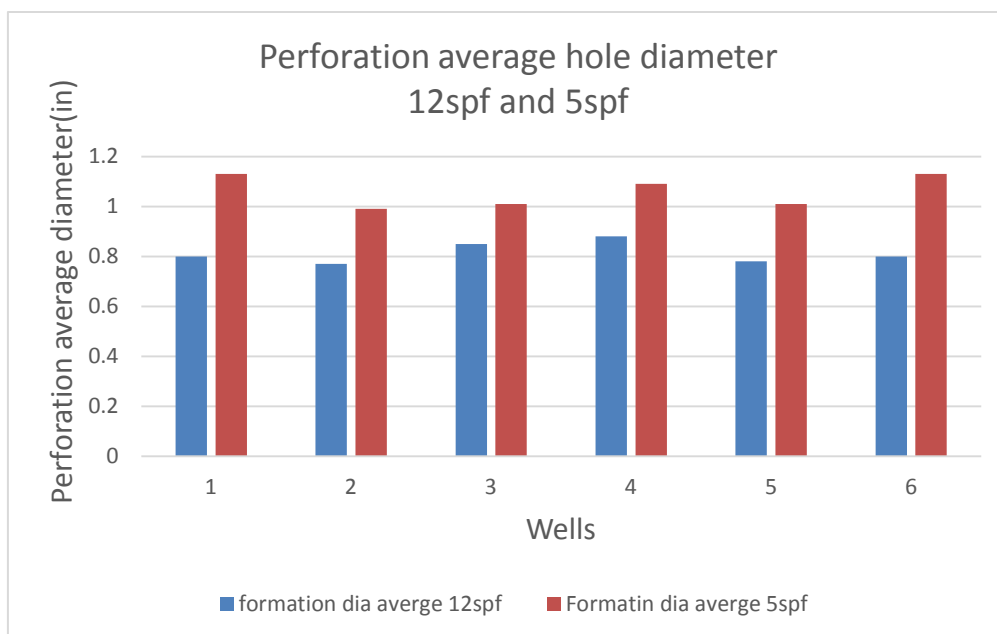


Figure 4.6 Perforation average single hole for different wells using 5spf and 12spf.

The figure above show a noticeable decrease in single hole diameter when using 12spf unlike the currently used 5spf hole diameter, thus better arcing/bridging effect that increases hole stability.

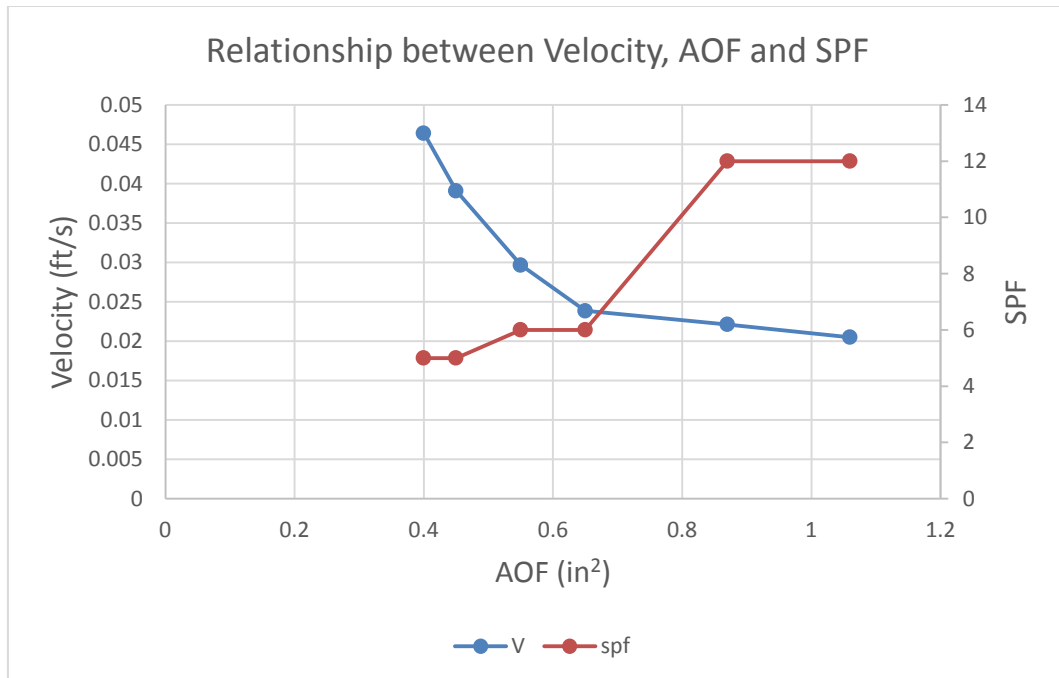


Figure 4.7 Relationship between Fluid velocity, SPF and AOF

The current perforation system of 4.5”HSD gun, 5 spf, 38.3 g HMX was evaluated and it was concluded that the area open to flow need to be optimized to reduce the velocity per perforation, improves the formation stability and well deliverability as in above.

When plotting the average fluid velocity with shot density and area open to flow it is clear that once we increase the shot density the velocity decreases as a result of increased area open to flow which supports the main claim which was mentioned earlier.

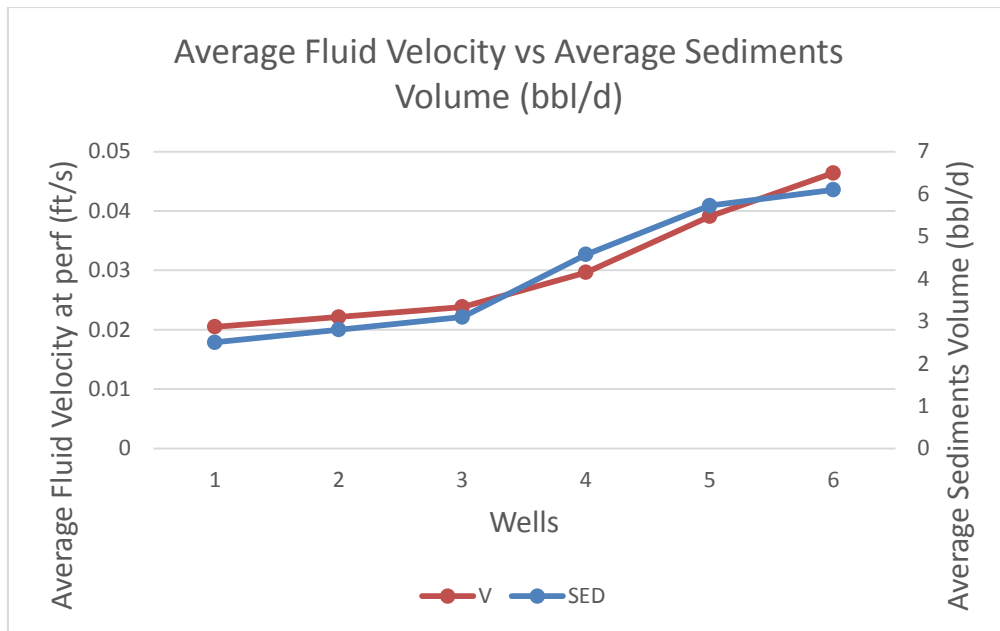


Figure 4.8 Average fluid velocities with average sediment volume for different wells.

Above figure is showing the relationship between the velocity range in each perforation and the actual sand production volumes accumulated. This exercise is important in order to check if the identified average velocity limits agrees with the well historical sand production taken from the difference between the last setting depth of the bridge plug and the current tag as a result of sand accumulation, this was used as an indicator since there are no real time monitoring for sand production in Fula field.

Significant correlation exists for the velocity in perforation with amount of sand production. Less sand was observed with lower velocity at each perforation. The assumption that all perforations are uniform and homogenous reservoir is the main approach.

An increase in sand production trend after certain level of velocity, suggest the existence of the critical limit but the possible range in unclear. The main reason for such correlation is that the fluid flow imposes a sufficient hydrodynamic force to destabilize and fluidizes the sand in the



formation. This suggests that sand production can be reduced if the velocity at the perforation is below a certain limit.

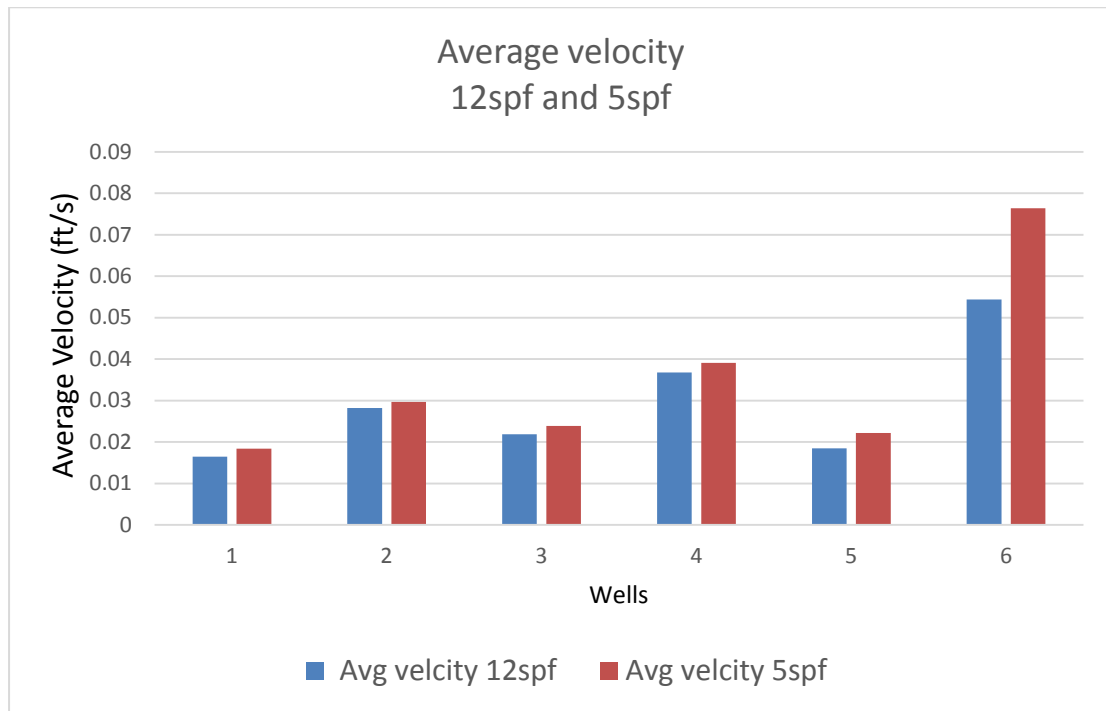


Figure 4.9 Current vs. optimized fluid velocities in different wells

We can notice that velocity has decreased for chosen optimized gun system that has larger area open to flow in DARK BLUE and the one currently used in the well BROWN as in Figure 4.9, also for wells 1,3 and 6 when velocity was reduced below the critical level sand production was reduced significantly.

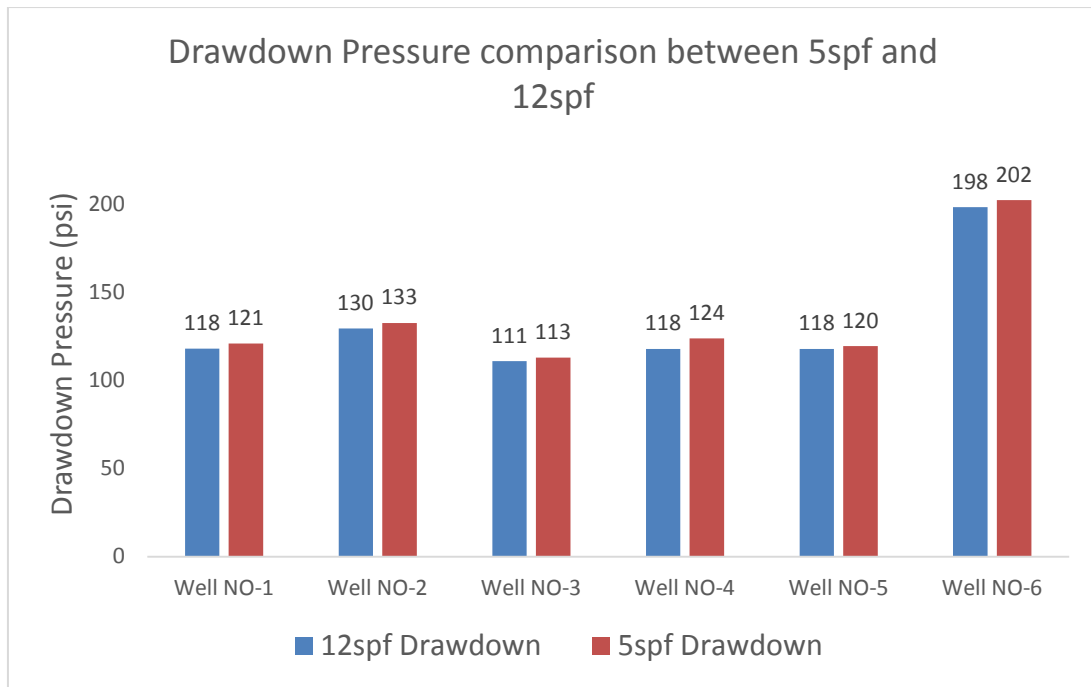


Figure 4.10 shows the drawdown pressure for different wells

Drawdown pressure is high for the current well perforation system but low for the optimized gun system hence reduces the sand production as a result.

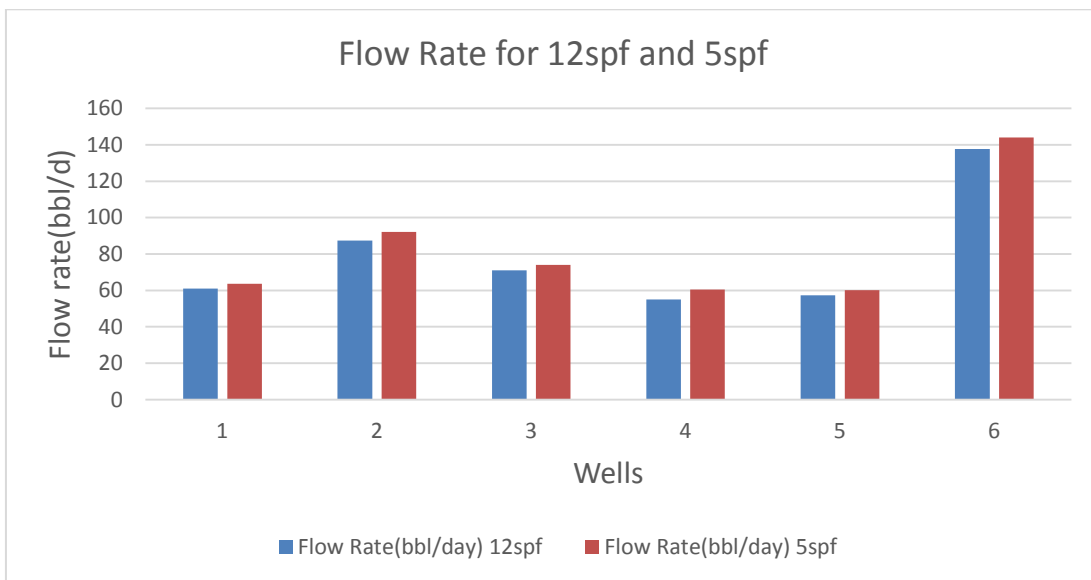


Figure 4.11 Flow rate comparisons between current and optimized strategy using 5spf and 12spf for different wells.

We can notice that when using 5spf the flow rate is higher which the current perforation strategy is since velocity is higher in this situation, but when using 12spf we sacrifice losing some production in order to prevent sand production.

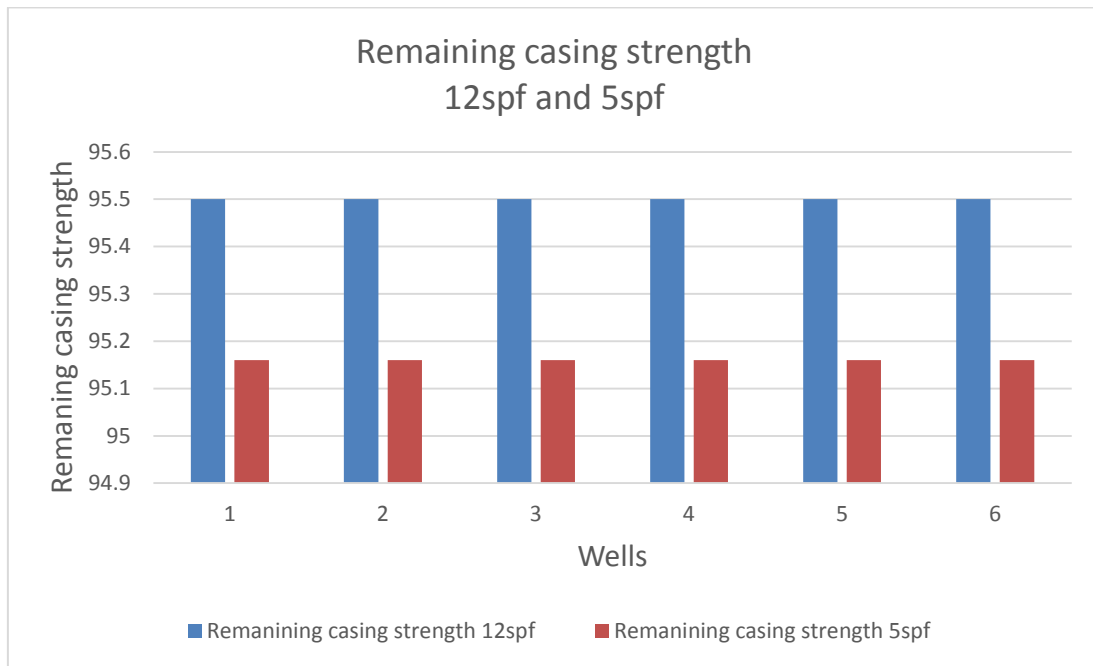
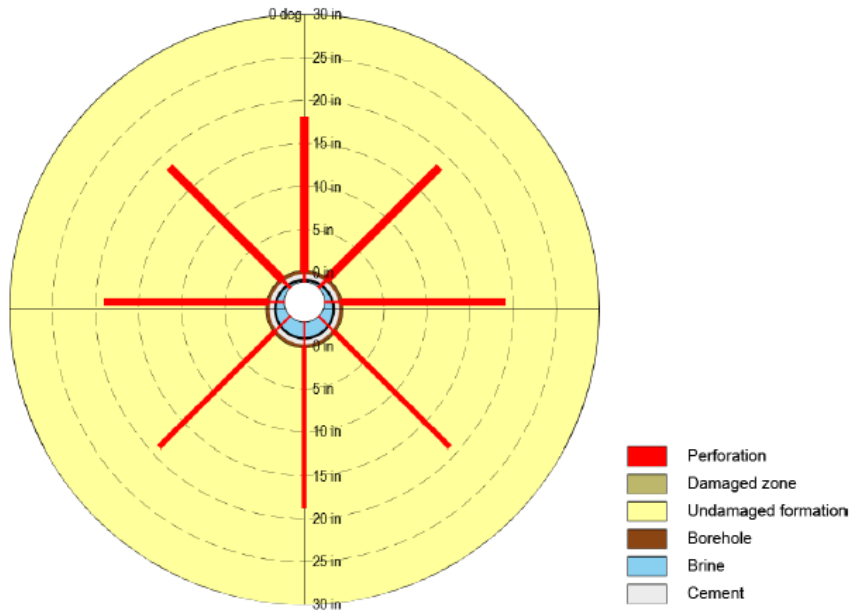


Figure 4.12 Remaining casing strength after perforation for different well using 5spf and 12spf guns

Above chart shows a better remaining casing strength when 12spf was used using the same casing for both cases thus a better well integrity.

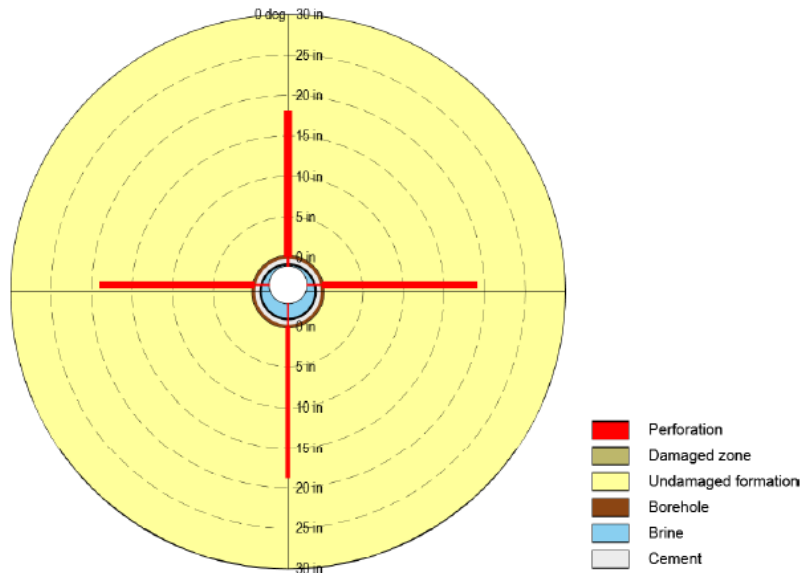
### Perforating System

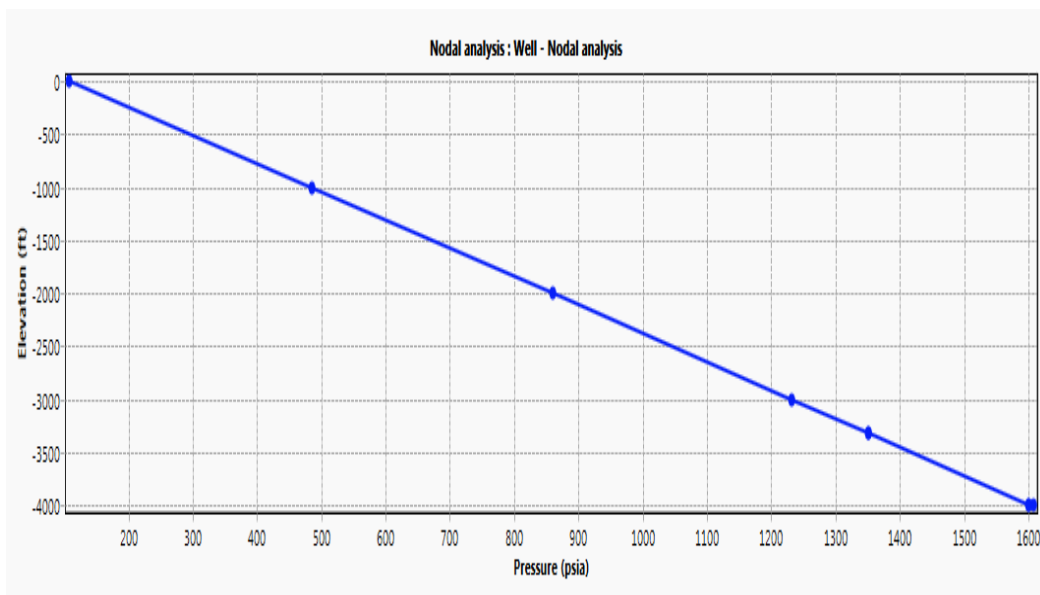
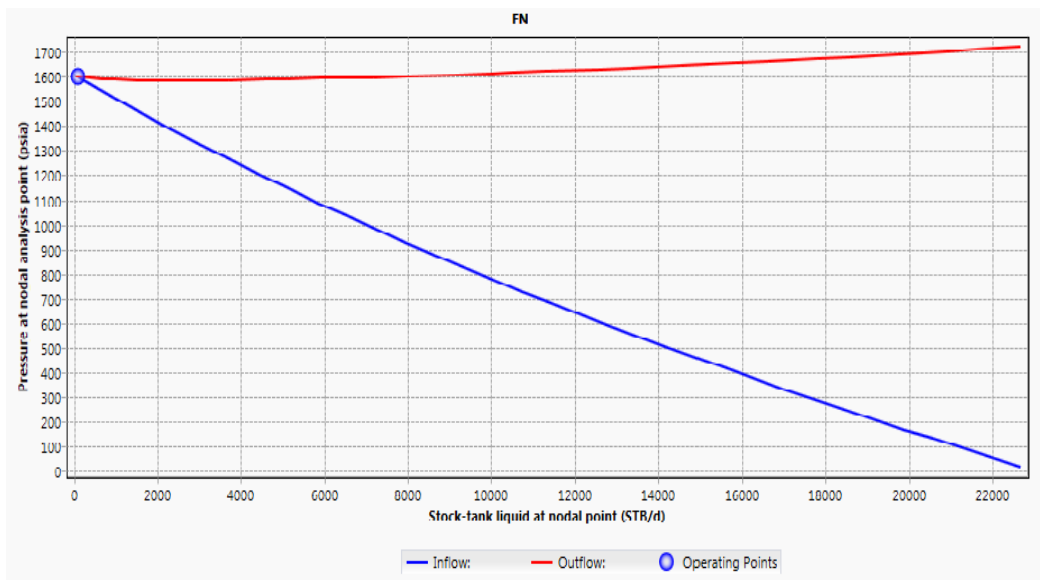
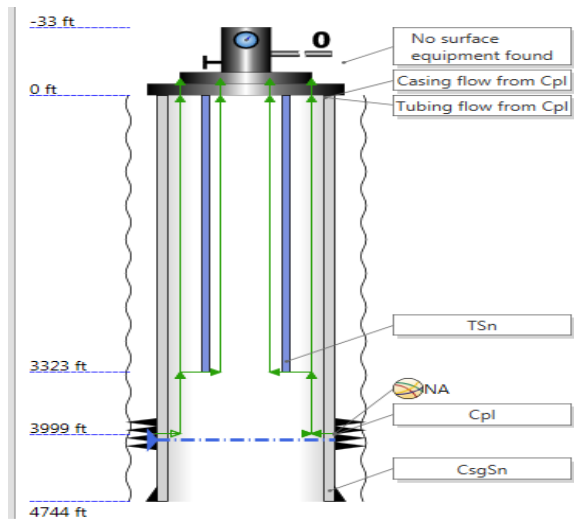
4-1/2" HSD, Power Jet Omega 4512, HMX, 22.00 g, 4.50 in  
135/45° Phasing, 12 shots/ft



### Perforating System

4-1/2" HSD, Power Jet Omega 4512, HMX, 22.00 g, 4.50 in  
90° Phasing, 5 shots/ft





Figures 4.13 PIPESIM software results

## 4.4 Economic Overview

According to sand cleaning schedule which is implemented for high sand production wells, each well will be shut in once per month for flushing and pigging or work over, Some wells will shut in for a few days and the other wells shut in for many days while in normal cleaning spend 4 hours per month, That means the average down time for each well estimated around 10 hours per month for removing sand from down hole or flow line.

Average production 80 bbl/day for each well, total production lost per year due to work over, flushing and pigging job calculation as below:

$$6 \text{ wells} * 10/24 * 12 \text{ month} * 80 \text{ bbl} = 2400 \text{ bbl/year}$$

Oil price approximately 50\$ for one barrel.

$$2400 * 50 = 120,000\$ \text{ per year}$$

The total lost per year equals 120,000\$ per year beside the cost of equipment operation such as rig, sand truck, pump truck and water tanker.

If this method prove effective we could save the cost of using the other sand managements techniques that could cost as following:

Methods	Estimated Cost
Screen gravel packing	550,000 \$
Filtrating pipe	50,000 \$
Frac packing	1,200,000 \$

Above calculations illustrate an economic overview and does not reflect detailed economic study.

# CHAPTER 5

## Conclusions and Recommendations

### 5.1 Conclusions:

Based on the work presented through this study the following conclusions can be pointed:

- ✓ Data collection and Analysis has been done to determine the high sand wells in Fula oil Field.
- ✓ 6 wells have been selected out of 13 wells because their data is satisfactory for this case study.
- ✓ After studying various types of guns and shaped charges used in perforating Operations and depending on the degree of the formation consolidation it was concluded that (4.5” HSD, 135°/45°, 12spf) is the best gun type that can be used for perforating in the Fula field which minimize the pressure drop through the holes, increases area open to flow, decreases velocity and as a result sand prevention.
- ✓ During the selection of the perforation strategy, phasing is one of a key element for the optimal flow rate production and to reduce the amount of sand produced during and after perforating operations has been reached that the best phasing of 135/45° degrees to minimize inter-linking of failed zones around adjacent perforations (minimize risk of collapse of structure) without compromising rate/perforation.
- ✓ Use 12spf to keep rate/perforation below a critical value to minimize transport of sand.

- ✓ Use deep penetrating charges to minimize perforation damage, for tunnel stability through depletion and drawdown, and to have good perforation spacing using appropriate minimum entrance hole diameter.

## **5.2 Recommendations**

- ✓ Calculation of critical velocity for each layer for better optimization using dual packer tester.
- ✓ Real time monitoring for sand production for better more accurate analysis.
- ✓ It is highly recommended to conduct a detailed study for the sand problem in Fula oil Field.
- ✓ This study focus only on the perforation optimization of the field without considering the economic side in details, so its recommended that incase a new study made, economic aspect can be taken into consideration with more details.



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