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Topic

Study of the Efficiency of Multistage Fracturing Using BroadBand Sequence Technology North Africa – Algeria Case

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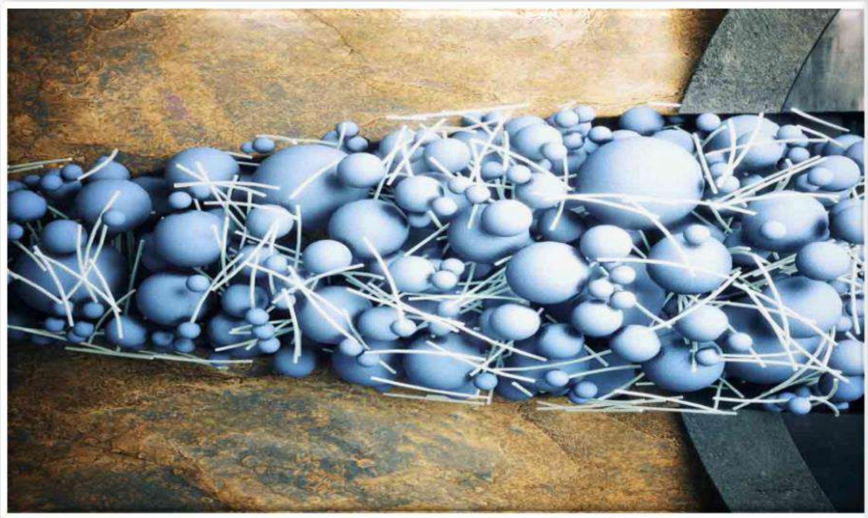
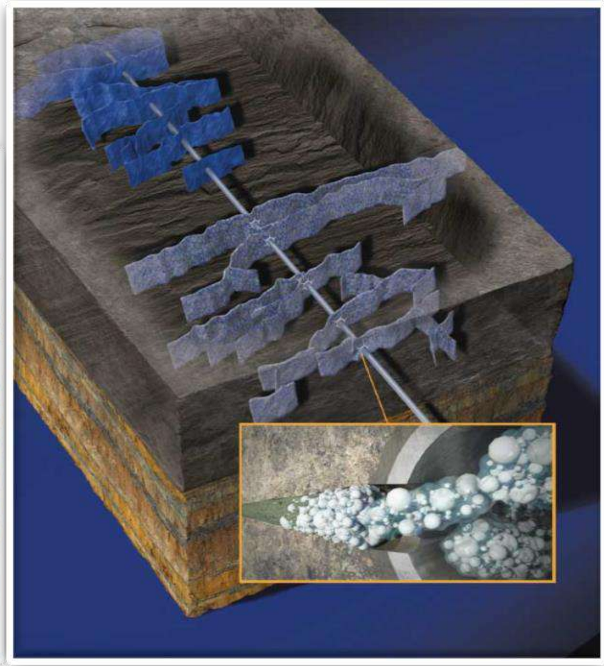
Schlumberger

Final Studies Project

Multistage Fracturing Stimulation Using BroadBand Sequence





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Dedication

I dedicate my dissertation work to:

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Whose love, encouragement and prays of day and night make me able to get such success and honor. No dedication could ever express my respect and profound feelings towards them.

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Anis

Abstract

This thesis is on Multistage fracturing using BroadBand Sequence technology that was recently executed in Algeria by Schlumberger. It is an effective technique that has been successfully applied to enhance hydrocarbon recovery.

This study is focused on the efficiency of this technology which showed clear evidence of the possibility of treating longer intervals while reducing completion cost and time using PETREL code software. Our case study targeted one of Hassi Messaoud wells that was a candidate for BBS and was successfully performed for the first time in Algeria.

Key words: Multistage fracturing, efficiency, Broadband Sequence, hydrocarbons recovery.

Résumé

Ce mémoire est élaboré dans le cadre de l’étude de fracturation multi-stages en utilisant la technologie BroadBand Sequence qui a été récemment réalisée en Algérie par Schlumberger. C’est une technologie fascinante utilisée pour améliorer la récupération des hydrocarbures.

La présente étude est axée sur l’efficacité de cette technologie qui a démontré clairement la possibilité de traiter des intervalles plus longs tout en réduisant le cout et le temps de complétion. Notre étude de cas a ciblé l’un des puits de Hassi Messaoud qui était un bon candidat pour la BBS et qui a été réalisée avec succès pour la 1ème fois en Algérie.

Mots clés : Fracturation multi-stages, efficacité, Broadband Sequence, récupération des hydrocarbures, code PETREL.

ملخص

تم إنجاز هذه المذكرة في إطار دراسة التكسير الهيدروليكي متعدد المراحل باستخدام تقنية البرود باند سيكونس التي تم تطبيقها مؤخرًا في الجزائر من طرف شلمبرجير. إنها تقنية فعالة تم تطبيقها بنجاح لتعزيز استعادة المحروقات في الحقول الناضجة

تركز هذه الدراسة على كفاءة هذه التكنولوجيا التي أظهرت دليلاً واضحًا على إمكانية علاج مجالات أطول مع تقليل تكلفة ووقت إكمال البئر. استهدفت دراستنا أحد آبار حاسي مسعود الذي كان مرشحا لتكنولوجيا للمعالجة بتقنية البرود باند سيكونس والتي تم تطبيقها بنجاح للمرة الاولى في الجزائر

الكلمات المفتاحية: التكسير المتعدد المراحل، فعالية، البرود باند سيكونس، إستعادة المحروقات

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

List of figures

LIST OF FIGURES

LIST OF FIGURES

List of tables

List of abbreviation

API	American Petroleum Institute
BBS	BroadBand Sequence
BHLPP	Bottom Hole last pumping pressure
BHP	Bottom Hole pressure
BHST	Bottom Hole Static Temperature
BPM	Barrel per minute
C.F.P.A	Compagnie Française de Pétrole d'Algérie
CT	Coiled Tubing
D	Drain
FG	Factor gradient
FOI	Folds of increase
FVF	Formation Volume Factor
GOR	Gas Oil ratio
GR	Gamma Ray
HC	Hydrocarbons
HF	Hydraulic Fracturing
HHP	Hydraulic horse power
HMD	Hassi Messaoud
HSP	High strength proppant
ID	Inside diameter
ISIP	Instantaneous Shut in Pressure
KGD	Kristianovich- Geerstma Klerk model
LPP	Last pumping pressure
MPLT	Memory production logging tool
NPT	No productive time
NPV	Net present value
OD	Outside diameter
Pc	Closure pressure

LIST OF ABBREVIATION

PCM	Precious continuous mixer
Ph	Hydrostatic pressure
PKN	Perkins- Kern- Nordgren model
PLT	Production logging tool
Pnet	Net pressure
POD	Programmable optimum density
P-3D	Pseudo 3D
PPA	Proppant concentration, pounds of proppant added per gallon.
PSI	Pound square inch
Pw	Wellhead treating pressure
QA	Quality assurance
QC	Quality control
SLPP	Surface last pumping pressure
SN. REPAL	Société National de Recherche Pétrole en Algérie
TCV	Treatment control vehicle
WI	Water Injection
WOC	Water oil contact
WL	Wire Line

Nomenclature

BBL	Barrel
CP	Viscosity, centipoise
S	Skin
ST	Total Skin
Sf	Skin results from a fracture.
Swi	Water saturation
DegC	Temperature, degree Celsius
degF	Temperature, degree Fahrenheit
K	Permeability of the reservoir
Ks	Permeability of the damaged zone
rs	Radius of the damaged zone
rw	Radius of the well
Q	Production rate
Q'	Productivity of fractured well.
Qo	Productivity of no fractured well.
J	Productivity index
Ef	Flow efficiency
Q new	Flow rate after change in skin factor
q old	Flow rate before change in skin factor
Ef new	Flow efficiency after change in skin factor
Ef old	Flow efficiency before change in skin factor
q	Oil rate in bottom hole conditions
k	Permeability
h	Reservoir height
µ	Oil viscosity
Lb	Mass, Pounds
Pr	Reservoir pressure
Pfd	Dynamic bottom hole pressure

Nomenclature

re	Drainage radius (well drainage)
rw	Well radius
Bo	Volumetric factor
σ	Stress
E	Young's modulus
Σ	Strain
V	Poisson's ratio
Δd	Rock's lateral expansion
Δl	Rock's longitudinal
G	Shear modulus
FCD	Fracture conductivity dimensionless
Wf	Propped fracture width
Xf	Fracture half-length
Kf	Fracture permeability
H	Fracture height
W	Fracture width
P_{Pipe}	Pipe friction
P_{Per}	Perforation friction
P_{NWB}	Near wellbore friction
η	Fluid efficiency
Vf	Volume within the fracture.
Vt	Total volume injected.
Vsh	Shale Volume
Gal	Gallon
Ft	Length, feet
Φ	Porosity

General Introduction

Well operations can damage the formation from the moment the drill bit first penetrates a permeable formation which will continue to end its productive life. This formation damage is a partial or complete plugging of the near-wellbore area. **[1]**

The indicators of this plugging phenomenon include a **reduction in permeability, skin damage, and a loss of well performance.** An effective treatment strategy can be developed by knowing the damage mechanism, location, and how it affects flow. In other terms, damage characterization is the key to a proper design of stimulation treatments. **[2]**

Stimulation is a well intervention method performed on oil and gas wells to increase flow capacity to a well. This term with respect to petroleum production refers to a range of activities used to increase productivity from reservoirs by increasing reservoir permeability. It falls into two main techniques; matrix acidizing and hydraulic fracturing. If removing the skin effect by matrix stimulation and good completion practices does not lead to commercial production rates, a short conductive hydraulic fracture is often the desired solution which is the purpose of our study.

Hydraulic fracturing is a technology used in the oil and gas industry for many decades to create highly conductive channels in formations having very low permeability values. It plays a crucial role in increasing well reserves and productivity. This technique consists of injecting a highly viscous fluid into the formation at high flow rates, causing an increase in pressure and a subsequent formation breaking.

An effective hydraulic fracturing design is a key to achieving the expected results in terms of production, starting with a proper formation evaluation of underground formations containing hydrocarbons. The engineer in charge of the economic success of such a well must design the optimal fracture treatment and then assures that the optimal treatment is pumped successfully. **[1]**

Many hydraulic fracturing techniques have been developed recently; one of them is the 'Broadband Sequence Technology' that Schlumberger has commercialized. It is a brand new technique in Algeria that was successfully performed in Hassi Messaoud field in 2019.

The primary objective of this fracturing service is to maximize well productivity and improve completion efficiency while significantly reducing completion cost. It sequentially isolates fractures at the wellbore to ensure every cluster in each completion zone is fractured and can contribute to the well's full potential.

Therefore, the objective of the present thesis is to study the efficiency, candidate selection, and the mechanism of multistage fracturing using the Broadband Sequence technique.

Hence, the problematic that will arise from this objective is:

'What is the mechanism of Multistage Broadband Sequence? And how does it enhance the productivity of the well?'

In order to highlight this technique and respond to the problematic raised, we drew the following plan. This thesis has been divided into four chapters.

- **Chapter I: An overview of formation damage**

The first chapter includes a broad view of formation damage and the different types and mechanisms of damage, followed by a discussion of the methods used to identify and quantify this damage in oil and gas wells.

- **Chapter II: Introduction to hydraulic fracturing**

This chapter aims to give an introduction to hydraulic fracturing; the evaluation, design, process, and execution of this operation are also discussed;

- **Chapter III: Multistage Broadband Sequence technology**

The third chapter focuses on the theory of Multistage Broadband Sequence technology, the operational and economic aspects, the selection of candidate wells, and the challenges faced.

- **Chapter IV: Case study and simulation results with Petrel**

This chapter is dedicated to X field introduction, production, and stimulation data analysis, and finally, the problems and their solutions are also presented. Finally, we finish our study with conclusions and recommendations.

Chapter I:

Overview of Formation Damage

I.1-Introduction

Formation damage is a generic terminology referring to a reduced permeability near the wellbore. It reduces the permeability of reservoirs, thereby reducing their natural productivity. It is actually an undesirable operational and economic problem that can occur during the various phases of a well life. Classifying damage correctly requires a good knowledge of field operating conditions, and damage characterization is the key to a proper design of removal treatments. **[2]**

This chapter aims to give a broad view of formation damage. First, a general description of the different types and mechanisms of damage, followed by a discussion of the methods used to identify and quantify this damage in oil and gas wells.

I-1 Damage Concept

Well operations can damage the formation from the moment the drill bit first penetrates a permeable formation which will continue to end its productive life. Formation damage is defined as a partial or complete plugging of the near-wellbore area, which reduces the initial permeability of the formation. This damage can be anything that obstructs the normal flow to the surface**. [1]**
The figure shows some common types of damage; these production impairments can occur anywhere in the production system, from the wellbore to perforations and into the formation.

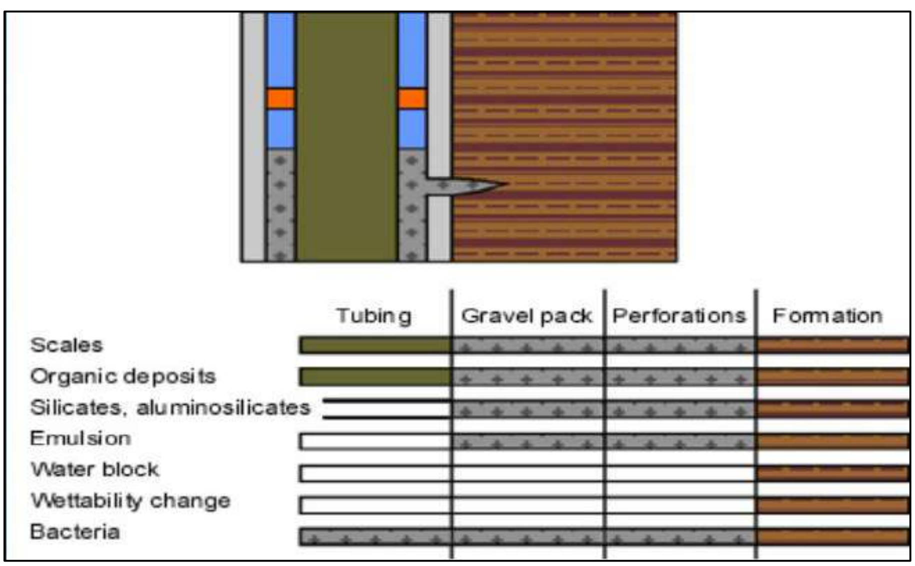


Fig I- 1 : Location of various types of damage. [1]

Ⅰ-2 Formation Damage Mechanisms

In general, there are four main types of formation damage which can be mechanical, chemical, biological or thermal, these types can be divided into smaller categories:

Ⅰ-2-1 Mechanical damage

These mechanisms are related to direct interaction between the equipment or fluids and the formation that leads to a reduction in permeability, this type includes:

- ***Formation damage caused by drilling, completion and workover:***

This damage may be caused by the precipitation of some solid particles suspended in work over fluid or by the incompatibility of the work over fluids with the producing fluids.

In general, clear brines are commonly used as workover fluids; brines always contain some solids such as corrosion products, bacteria, and debris from the wellbore and surface tanks that may push into the formation resulting in a loss of permeability in the near-wellbore region. **[3]**

- ***Formation Damage caused by Water Blocks:***

It is caused by the invasion of water-based drilling fluid or completion fluid; as a result, a region of high water saturation around the wellbore. The increased presence of water leads to the formation of fine clay and some particles in the formation that causes a loss in permeability.

Water-block treatments typically use mutual solvents such as alcohols to dissolve the water and remove it through a change in phase behavior, also the use of surfactants is very important to reduce the surface tension between oil and water**. [3]**

- ***Formation Damage Caused by Fines Migration:***

This type of damage is the most common mechanism that occurs predominantly in clastic formations, which refers to the movement of fine clay, quartz particles, or similar materials in the pore system within the reservoir formation due to the drag forces during the production. **[4]**

As a remedial measure for this problem, reducing production rates and increasing the flow area by adding perforations can reduce the drag forces. In addition, HF acid is recommended to dissolve fines in sandstone formations; while in carbonate formations, they disperse fines in the wormholes using HCL acid.

- ***Formation damage caused by perforations:***

Perforations are holes that are punched through the casing and cement and extend for a distance in the formation. Perforation is a process used to establish a flow between the reservoir and the wellbore. It is a vital part of well-completion operations. However, if it is incorrectly carried out, the well's productivity will appear to be low due to damage.

Ⅰ-2-2 Chemical damage:

Chemical damage mechanisms refer to the interaction between the introduced fluids such as drilling mud and formations fluids (water, oil) or between these fluids and the reservoir rock.

- ***Formation damage caused by clay swelling:***

The presence of swelling clays is generally associated with drilling problems, completion, stimulation fluids once the water-based mud filtrate to the formation that may expand when interacting with low-salinity water, reducing formation permeability by plugging pore throats.

Brines such as potassium chloride (KCL) or high-salinity drilling during operations will be a good option to keep reactive clays from becoming expanded. **[5]**

- ***Formation damage caused by wettability change:***

Wettability alteration is the oil wetting of rock from hydrocarbon deposits, mainly asphaltene or adsorption of an oleophilic (attracts oil) surfactant from drilling fluid or from dispersants in stimulation fluids. The formation's permeability to water increases while oil permeability decreases resulting in an additional pressure drop around the wellbore. The use of mutual solvent followed by water-wetting surfactant may be recommended. **[1]**

- ***Formation damage resulting from emulsions:***

Invasion of filtrates into oil zones or mixing of oil-based filtrates with formation brines or the incompatibilities between two immiscible fluids at a high shear rate in the formation can lead to the creation of emulsions with higher viscosity and make one phase dispersed in another; as a result, the plugging of pore throats and a decrease in permeability. Mutual solvents such as alcohols and surfactants are used to remove emulsions.

- ***Scale & inorganic precipitates***

Scales are precipitated mineral deposits that occurs due to lower temperatures and pressures encountered in the near wellbore or incompatibility between mixing waters. Typical scales are Sodium chloride(Nacl), calcium carbonate($CaCO_3$), calcium sulfate($CaSO_4$), barium sulfate($BaSO_4$), strontium sulfate($SrSO_4$),iron,silica,hydroxides. For their remedial, acidizing (HCL) is used for carbonates or injection of fresh water for chlorides.

- ***Organic deposits:***

Organic deposits are precipitated heavy hydrocarbons (paraffin or asphaltenes). The formation of these deposits are usually associated with a change in temperature or pressure in the near wellbore during production. **[1]**

1- Paraffin deposition

The major cause of wax deposition is the loss in solubility of crude oil due to a decrease in temperature. Moreover, reductions in pressure lead to a loss of volatiles from crude oil and can induce the precipitation of paraffin. **[3]**

2- Asphaltene Precipitation

This damage is mainly due to a sudden drop in reservoir pressure. In other terms, as the pressure decreases, the amount of asphaltenes increases to reach a max at the bubble point. This damage can reduce effective hydrocarbon mobility by blocking the pore throats; adsorbing onto the rock, thereby altering the formation wettability from water-wet to oil-wet. **[3]**

Treatment: Aromatic solvents (Xylene, Toluene) and mutual solvents. **[1]**

Ⅰ-2-3 Biological Damage

Biological damage can occur when bacteria and nutrients are introduced to the formation. Bacterial contamination occurs during water injection or drilling with water-base fluids. The use of a bactericide or biocides is recommended to prevent the increase of bacteria in water. **[3]**

Ⅰ-2-4 Thermal damage

Thermally induced formation damage is unique to heavy oil reservoirs. This damage is due to thermal energy which changes the permeability and the flow rates.

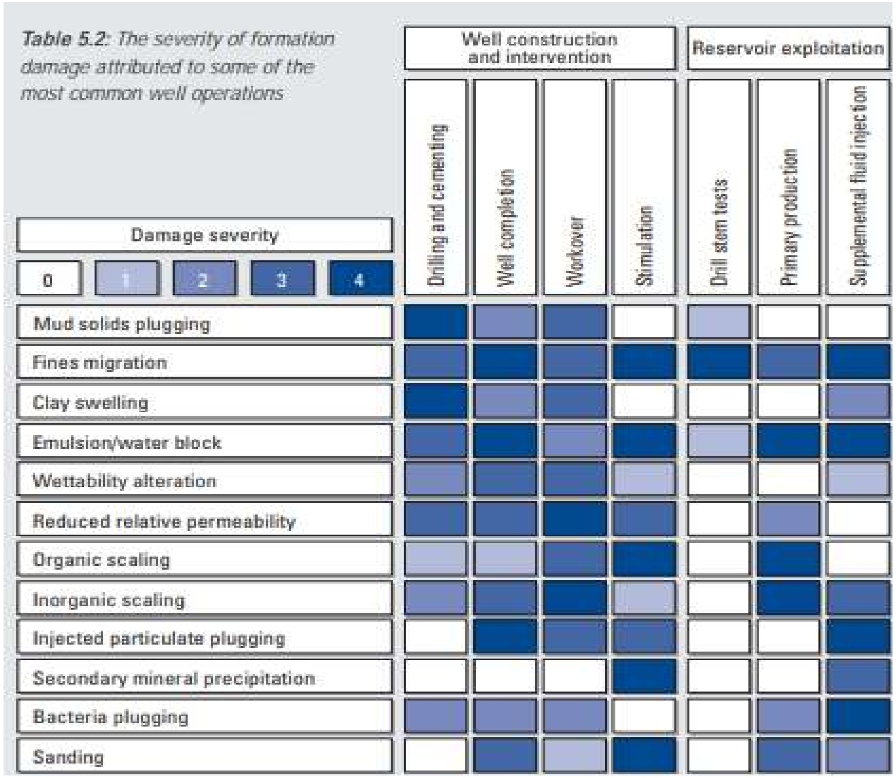


Fig I- 2 : The severity of formation damage attributed to well operations [6]

I-3 Quantifying formation damage

Ⅰ-3-1 The Skin factor

The Skin is a factor expressing the reduction in the formation permeability compared to the original one, which causes an additional pressure drop that decreases the production rate. **[7]**

Moreover, the skin concept has always been used to measure flow anomalies near the wellbore. It characterizes any deviation from the ideal state of a vertical open hole well in a homogenous undamaged formation.

$$S = \left(\frac{kh}{141.2\; q\; \mu\; B}\right)\Delta pskin \quad [8] \qquad \text{I-1}$$

The figure below shows how flow restrictions in the near-wellbore region can increase the pressure gradient, resulting in an additional pressure drop caused by formation damage (Δpskin).

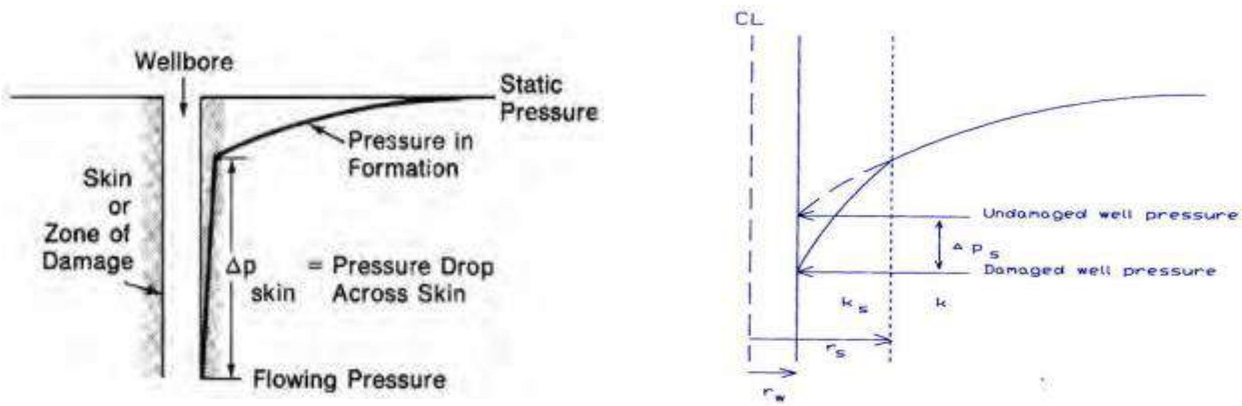
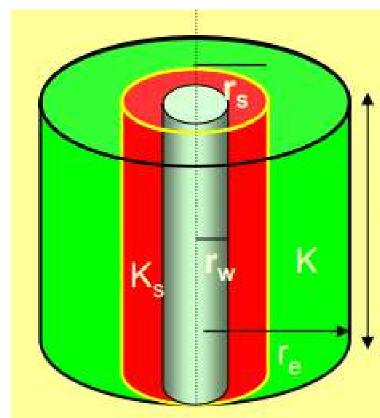


Fig I- 3 :Pressure profile in the NWB region for an ideal well and a damaged well [8]

Ⅰ-3-2 Effect of Skin on permeability



This effect is represented by the Hawkins' formula below:

For vertical wells:

$$S = [\frac{k}{ks} - 1]\ln\frac{rs}{rw} \quad [1] \qquad \text{I-2}$$

For horizontal wells:

$$S = [\frac{\sqrt{kH\,kV}}{\sqrt{kHS\,kVS}} - 1]\ln\frac{rs}{rw} \quad [1] \qquad \text{I-3}$$

S: skin

k: permeability of the reservoir

ks: permeability of the damaged zone

rs : radius of the damaged zone

rw : radius of the well

Ⅰ-3-3 Effect of Skin on productivity index

A commonly used measure of well productivity is the productivity index which is defined as the flow associated with a pressure drop between the reservoir and the wellbore. It is the potential of a well that is expressed for the case of a liquid in a circular radial flow; steady state.

$$J = \frac{Q}{Pr - Pwf} \quad [9] \qquad \text{I-4}$$

If the reservoir had a positive skin **(S > 0)** the pressure drop increases **(ΔPs),** the permeability decreases and the productivity index **(J)** will be less, thus a decrease in the production rate **(Q).** In this case, the well has to be restored by **stimulation.**

We can express the degree of damage on stimulation with the flow efficiency.

- For a well with neither damage nor stimulation **Ef = 1.**
- For a damaged well **Ef < 1**
- For a stimulated well **Ef > 1**

The flow efficiency is**:**

$$Ef=\frac{J\,actual}{J\,ideal}=\frac{Pr-Pwf-\Delta ps}{Pr-Pwf}$$ **[9]** **I-5**

Ⅰ-3-4 Flow efficiency and effect of skin on oil rate

We can use the flow efficiency to calculate the effect of changes in skin factor on the production rate corresponding to a given pressure drawdown.

$$qnew= qold\,\frac{Ef\,new}{Ef\,old}$$ **[9]** **I-6**

qnew = Flow rate after change in skin factor

qold = Flow rate before change in skin factor

Efnew = Flow efficiency after change in skin factor

Efold = Flow efficiency before change in skin factor

Ⅰ-3-5 Effect of Skin on production

The IPR and the Hawkins equation are essential to understand the effect of formation damage on well productivity. For an oil well the IPR equation is:

$$q=\frac{kh(Pr-pwf)}{141.2\mu B(ln\frac{re}{rw}+S)}$$ **[7]** **I-7**

q: Oil rate in bottom hole conditions (bbl/d)

k : Permeability (md)

h : reservoir height (ft)

μ : Oil viscosity (cp)

Pr: reservoir pressure (psi)

Pfd: dynamic bottom hole pressure (psi)

re : drainage radius (ft)

rw : well radius (ft)

S: total Skin

Bo: volumetric factor (bbl/ST)

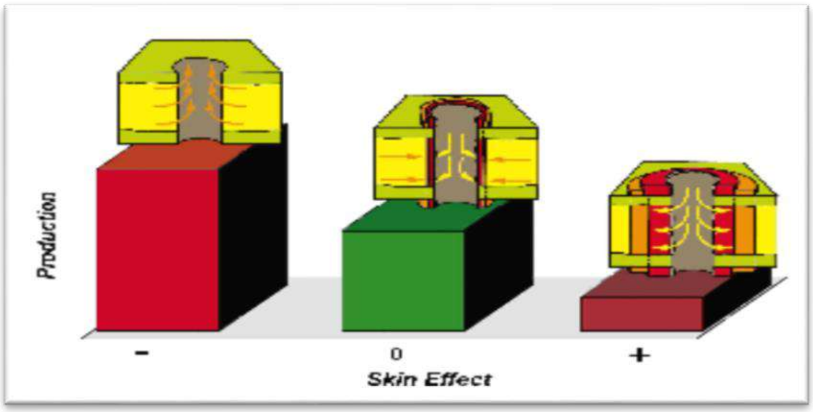


Fig I- 4 : Effect of Skin on production [7]

Ι -3-6 Types of Skin

The total Skin (ST) is the combination of mechanical and pseudo-skins. It is the total skin value that is obtained directly from a well-test analysis. It is classified based on their origin.

Formation Damage Vs Pseudo damage:

It is important to clearly distinguish formation damage from well completion and reservoir effects that are a consequence of how the wellbore penetrates the reservoir and where the perforations are placed which are referred to as pseudo-skin effects.

I-3-6-1 Mechanical Skin (Formation damage)

Mathematically defined as an infinitely thin zone that creates a steady state pressure drop at the sand face. The Mechanical Skin is the only type that can be removed by stimulation. **[1]**

S > 0 Damaged Formation

S = 0 Neither damaged nor stimulated

S < 0 Stimulated formation

I-3-6-2 Geometric Skin (Pseudo Skin)

Not all the skin values obtained by well tests are due to formation damage; other contributions are not related to formation but may be due to the completion of the configuration of the well. These factors are called Pseudo skin. It is caused by well-exploitation conditions and the choice of poorly designed equipment. Therefore, the value of Pseudo skin has to be subtracted from the value of total skin estimated by well tests in order to obtain the real skin of the formation.

I-4 Formation damage identification methods

Ⅰ-4-1 History of the well

The search for the identity of the damage begins in the production and development history of the well and also from neighboring wells. Drilling records, completion design, offset well performance, operator experiences and past treatment records are all sources of information. So the information of well production history and reservoir data may give clues to progressive changes associated with damaging processes. **[2]**

Ⅰ-4-2 Well tests

Reductions or changes in well productivity can be identified through well tests. Pressure transient analysis is the conventional oil industry method for identifying any impairment of well productivity, which is conventionally quantified in terms of skin factor. As such, well tests are the cornerstone of the information available to detect formation damage and quantify the effect. **[10]**

Ⅰ-4-3 Drilling, completion and workover records

Drilling, completion and workover data represent the basic record of engineering operations. They form a basis for the initial identification of possible problems (e.g. drilling difficulties, use of loss agents, nature of perforation, dirty kill fluid). They also help engineers devise laboratory tests to assess potential damage arising from fluid/fluid or fluid/rock incompatibilities. **[10]**

Ⅰ-4-4 Production logging tools

Production logs are another source of information to indicate formation damage. They are used to allocate production on a zone-by-zone basis and also to diagnose production problems such as formation damage by determining the location of damage (Ex: PLT).

Ⅰ-4-5 Laboratory tests and core analysis

Laboratory tests are used to model the effectiveness of remedial treatments. In addition, they can identify damage mechanisms and aid in determining options for avoiding or removing the damage.

While core analysis can be performed on reservoir rock samples after extracted cores from the reservoir. Then, formation damage specialists measure permeability changes by testing cores before and after they have been exposed to drilling and completion fluids at representative downhole temperature and pressure conditions. **[4]**

I-5 Importance of minimizing damage:

Minimizing or removing damage is a significant objective in stimulation operations because formation damage strongly affects the near-wellbore permeability. As a result, it reduces productivity. This situation leads engineers and operators to study **damage** mechanisms and develop methods to control or prevent them. By doing so, operators can plan and execute drilling, completion, and production operations with optimal efficiency and economic viability.Methods and technologies to quantify and measure formation damage will continue to develop; in order to enhance well productivity and thus, the ultimate engineer objectives are minimized damage and maximized productivity.

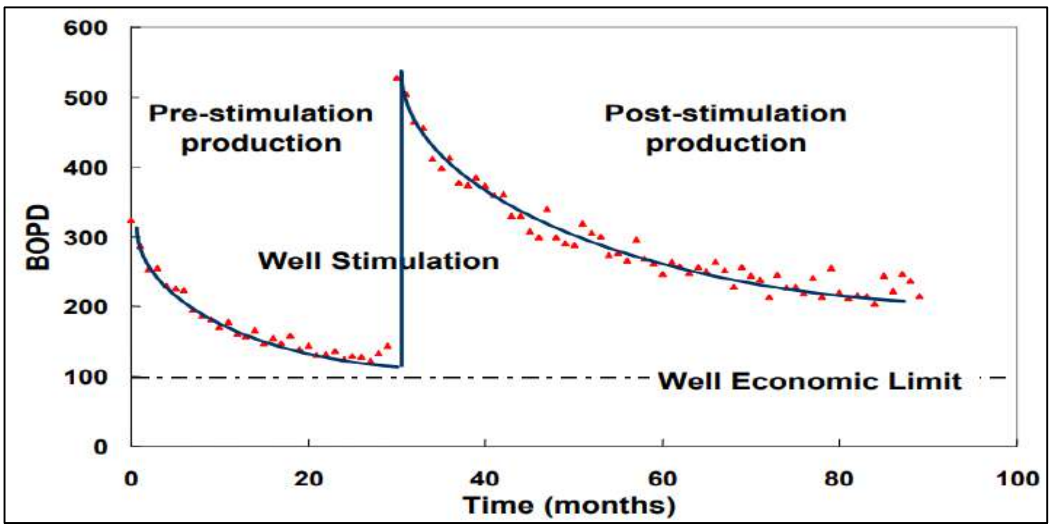


Fig I- 5 : Post Stimulation Production Increase [1]

I.6-Conclusion:

Reservoir engineers must be vigilant about the potential for formation damage. However, they can mitigate its impact by understanding its mechanisms and how various types of damage might affect oil and gas recovery. This will allow them to find the appropriate treatment that will reduce the extent of formation damage and maximize well productivity. Finally, assessment, control, and remediation of formation damage are crucial to ensuring efficient use of the world's HC resources.

Chapter II:

Introduction to Hydraulic Fracturing

II.1- Introduction:

If the removal of the skin effect by matrix stimulation and good completion practices does not lead to economic potential, a short conductive hydraulic fracture is often the desired solution.

In many cases, especially for low-permeability reservoirs, damaged reservoirs, or horizontal wells, the well would be uneconomical unless a successful hydraulic fracture treatment is designed and pumped. The engineer in charge of the economic success of such a well must design the optimal fracture treatment and then assures that the optimal treatment is pumped successfully. **[8]**

This chapter aims to give an introduction to hydraulic fracturing, the evaluation, design, process and execution of this operation are also discussed.

II-1-Well Stimulation

Stimulation is a chemical or mechanical method of increasing flow capacity to a well. It is a well intervention performed on an oil or gas well to increase production by improving the flow of hydrocarbons from the drainage area into the wellbore. This term with respect to petroleum production refers to a range of activities used to increase productivity from reservoirs by increasing reservoir permeability. **[2]**

II-2-Hydraulic Fracturing

II-1-1-Hydraulic fracturing definition

Hydraulic fracturing is a stimulation treatment that is performed on oil and gas wells in order to increase well productivity by creating a highly conductive path compared to the reservoir permeability which allows oil and gas to move more freely from the reservoir to the wellbore.

It is a pressure-induced fracture caused by injecting fluid into a target rock formation. The fluid is pumped into the formation at pressures that exceed the fracture pressure which is the pressure at which the breaks. **[12]**

Moreover, it is generally performed in low permeability reservoirs to enhance the production rate. In damaged reservoirs to bypass near wellbore damage and also in high permeable reservoirs to reduce sand production. Besides, this technique is crucial for producing unconventional reservoirs with very low permeability, such as shale and tight reservoirs.

II-3-Purpose of fracturing:

The main purpose of fracturing is to change the flow path from radial flow toward the smaller area of the wellbore to linear flow to the larger area of the fracture face.

The fracturing treatment is therefore designed to create a fracture of significant penetration or half-length Xf with sufficient conductivity to significantly increase production. The longer the fracture, the greater the contact area with the reservoir and theoretically more production. **[13]**

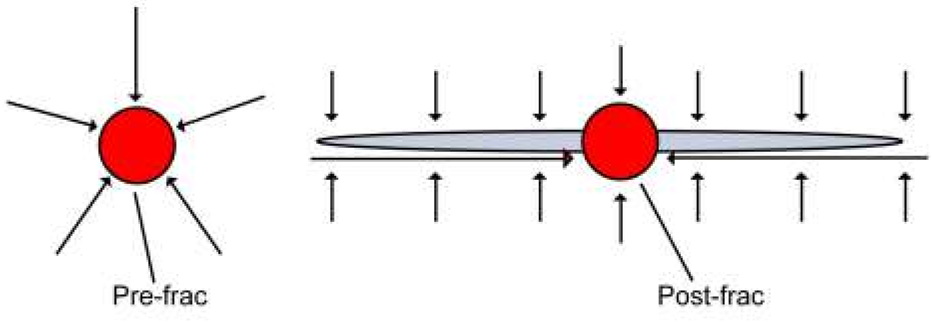


Fig II- 1 : Fracturing flow paths [13]

II-4-Objectives of Hydraulic Fracturing:

There are many purposes for hydraulic fracturing depending upon particular situations which are:

- ✓ Increase the productivity index of a producing well by changing the flow regime from radial to linear.
- ✓ Create high-conductivity communication deep into the formation and bypass any damage in the near-wellbore area.
- ✓ Connect the natural fractures in the formation to the wellbore.
- ✓ Reduce sand production.

II-5-The Process of hydraulic fracturing:

- Specially engineered fluids are pumped at high pressure and rate into the reservoir interval to be treated causing a vertical fracture to open.
- The wings of the fracture extend away from the wellbore in opposing directions according to the natural stresses within the formation. The fracture has to be perpendicular to the minimum horizontal stress.
- When the treatment is complete, Proppant such as grains of sand of a particular size is injected with the fracturing fluid to keep the fracture open.

- As a result, hydraulic fracturing creates high conductivity communication with a large area of the reservoir and bypasses any damage that may exist in the near-wellbore area. **[11]**

II-6-Rock Mechanical Properties:

The determination of mechanical properties of reservoir rocks falls under a specialized area called rock mechanics, which includes the study of the strength properties of rocks:

II-6-1-In-situ-stresses:

In-situ stresses and mechanical properties of the rock formation are vital for the assessment of wellbore construction and production. Underground formations are confined and under stress which is defined as the Force applied per Unit Area:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{Force}\ (\boldsymbol{Pound})}{\boldsymbol{Area}\ (\boldsymbol{in})}\ (\boldsymbol{Psi})$$ **[14]** **II-1**

The stresses can be divided into three principal stresses:

- σ_1 is the vertical Stress (overburden)
- σ_2 is the minimum horizontal Stress
- σ_3 is the maximum horizontal Stress.

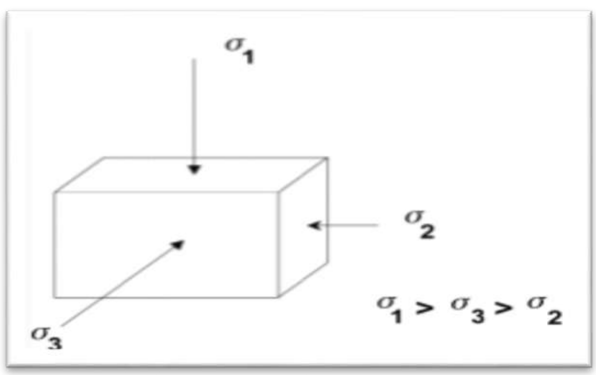


Fig II- 2 : The three principal compressive stresses [14]

The magnitude and direction of these stresses control the pressure required to create and propagate the fracture, shape, and direction. A hydraulic fracture will propagate perpendicular to the minimum horizontal stress.

II-6-2-Young's modulus (E):

Young's modulus measures the stiffness of the rock or the parameter expressing the resistance of rock to deformation. If the modulus is large, the material is stiff. **[14]**

It governs how wide the fracture will open at a given downhole pressure in Hydraulic fracturing. When the young's modulus increases, the width of the fracture decreases.

Hook's law expresses this modulus by:

$$E=\frac{\sigma}{\Sigma}$$ [14] II-2

E: Young's modulus.

Σ : Strain

σ : Stress.

II-6-3-Poisson's ratio (V):

During a fracture, the compressive force on a cylinder of rock will cause deformation.

Poisson's ratio is the ratio of a rock's lateral expansion (change in diameter) to its longitudinal contraction (change in length).

$$v=\frac{\Delta d/d}{\Delta l/l}$$ [14] II-3

II-6-4-Shear Modulus:

The shear modulus is one of several quantities for measuring the stiffness of materials, it looks like Young's modulus except that the material will be put under shear and not under compression or torsion.

$$G=\frac{E}{2(1+V)}$$ [14] II-4

II-7-Fracture Geometry:

-Length (L): Radial distance from the wellbore to the outer tip of a fracture penetrated by the well.

-Width (W): It is the distance between the two vertical faces of the fracture along the normal direction. It can be determined by acoustic imaging and conventional logs.

-Height (H): the distance measured vertically between the two points associated with a zero thickness. It can be determined by thermolog.

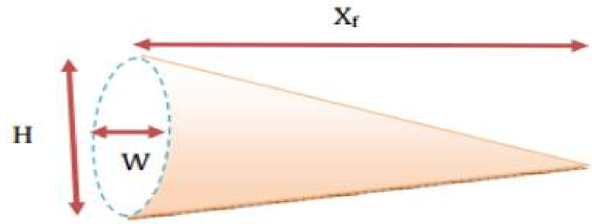


Fig II- 3 : Simplified model of a fracture [15]

II-8-Fracture Conductivity:

The dimensionless conductivity is the ratio of the ability of the fracture to carry flow divided by the ability of the formation to feed the fracture. Defined as**: [2]**

$$C_{fD} = \frac{Kf\ Wf}{K\ Xf} \quad [2] \qquad \text{II-5}$$

Where:

FCD: fracture conductivity dimensionless

Kf: fracture permeability (mD)

K: formation permeability (mD)

Wf: propped fracture width (ft)

Xf: fracture half-length (ft)

The conductivity of the fracture can be reduced during the life of the well because of:

-Increasing stress on the Proppant agents.

-Proppant crushing.

-Damage resulting from gel-residue or fluid-loss additive.

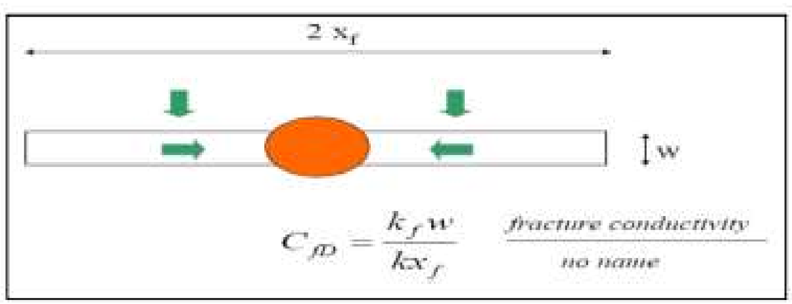


Fig II- 4 : Representation of the dimensionless conductivity of the fracture [15]

II-9-Fracture initiation and propagation pressure:

The figure represents a schematic curve of the evolution of pressure during hydraulic fracturing. It is divided into two parts:

-Injection part

-Closure part

The first part the fluid is pumped into the targeted stimulation zone at a prescribed rate and pressure builds to a peak at the breakdown pressure followed by a stability, which corresponds to the initiation and propagation of the fracture. The second part begins with a sudden drop in pressure followed by a stability. This corresponds to:

-Instantaneous Shut in Pressure (ISIP): the point where the pumping stops.

-The period of fracture closure (Pc).

- **Net fracture pressure:**

The net pressure is the additional pressure above the fracture pressure required to keep the fracture open after pumping stops. It is an indication of the energy available to propagate the fracture. Defined as: $$\Delta pnet = ISIP_{BH} - Pc \qquad \text{II-6}$$

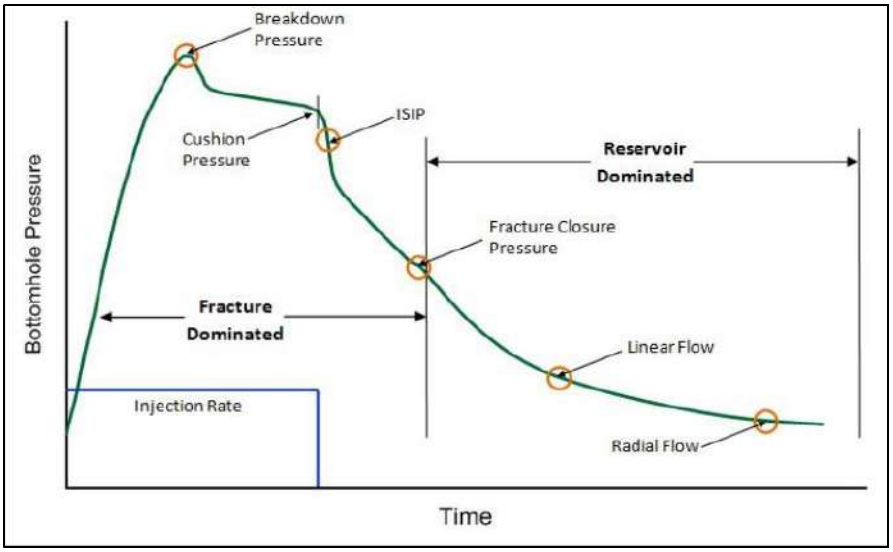


Fig II- 5 : Evolution of hydraulic pressure curve [11]

II-10-Fracture Propagation Model:

The fracture geometry is a complex function of initial reservoir stress conditions and reservoir rock proprieties. So, in order to module this complicated system, Bi- and Tri-dimensional models, are currently proposed on the basis of simplifying assumptions in order to give values of magnitude close to reality.

II-10-1-Two-Dimensional Fracture Propagation Models:

With 2D model, the engineer fixes one of the dimensions, normally the fracture height, then calculates the other parameters. The classical models for fracture geometry in two dimensions are the so-called PKN and KGD:

II-10-2-Model of Perkins & Kern «PKN»:

This model is used when the fracture length is much greater than the fracture height **(XL > h).** In this model, a 2D plane-strain model is assumed in the vertical plane where the fracture has an elliptical cross-section both in the horizontal and vertical directions; it is beneficial when the stresses of the barriers on the permeable zone are significant, and the formation shows an increase in pressure during pumping. This model is very useful in thin zones.

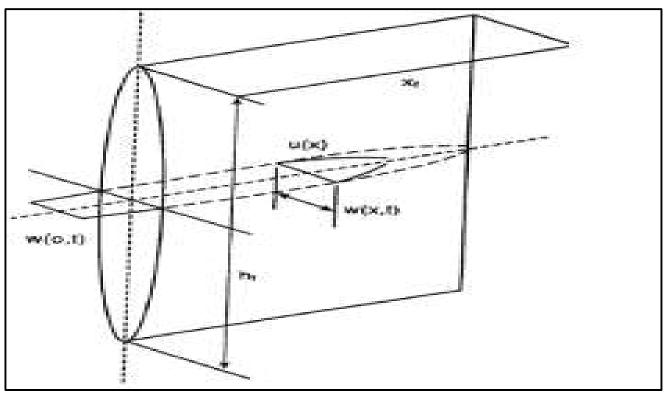


Fig II- 6 : PKN geometry for a 2D fracture [15]

II-10-3-Model of Greetsma-de Klerk « KGD»:

The KGD model assumes a 2D plane-strain model in a horizontal plane with a constant fracture height larger than the fracture length **(XL< h)**. In this model, an elliptical horizontal cross-section and rectangular vertical cross-section are assumed where the fracture width is independent of the fracture height. It is very useful when the stresses of the barriers on the permeable zone are large, and the formation shows a decrease in pressure during pumping. Therefore, this model is used for very thick zones.

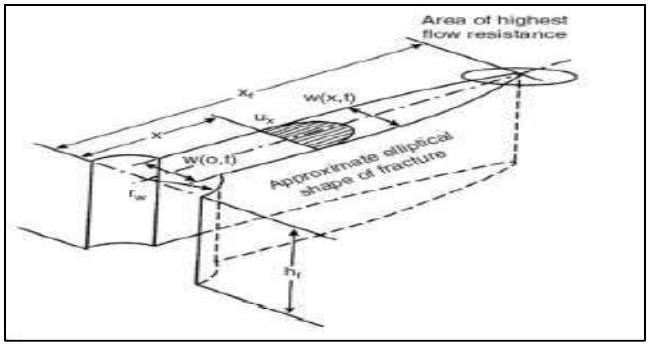


Fig II- 7 : KGD geometry for 2D fracture [15]

II-10-4-Radial Model:

The radial model is characterized by a circular profile in the vertical plane with an elliptical section. In this model, the height of the fracture is equal to its length **(X_L= h).** It is used when the permeable zone is small and has only weak intercalations of barriers.

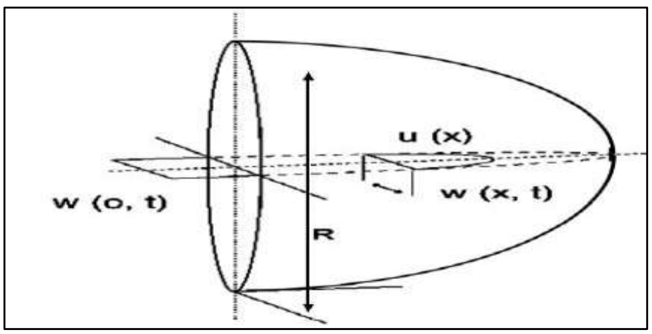


Fig II- 8 : Radial geometry for 2D fracture [15]

II-10-5-Three-dimensional Fracture Propagation Model:

Today, with technology and high-powered computers, Pseudo-three dimensional (P3D) models are the most used. P3D models are better than 2D models because they give more realistic estimates of fracture geometry and dimensions which can lead to a better design**. [16]**

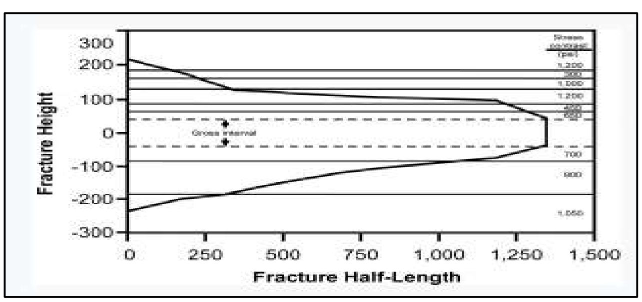


Fig II- 9 : Length and height distribution from a P3D model [16]

II-11-Fracturing fluids:

The fracturing fluid is a critical component of hydraulic fracturing treatments. It has two primary responsibilities:

- ✓ Initiate and propagate the fracture.
- ✓ Transport the Proppant along its length.

II-11-1-Properties of the fracturing fluids:

-Have proper viscosity to open the fracture and transport the propping agent.

-Be compatible with the formation of rock and fluid to avoid emulsion.

-Generate enough pressure to drop down the fracture to create a wide fracture.

-Be able to break and clean up quickly after the treatment.

-Be able to withstand high temperatures within the formation.

-Safety and environmental concerns.

II-11-2-Fracturing fluid types:

There are various types of hydraulic fracturing systems in the industry, and every formation requires a specific system.

II-11-2-1-Water-based fluids:

Water-based fluids are the most widely used fracturing fluids because of their low cost, high performance, and ease of handling.

II-11-2-2-Oil-based fluids:

These fluids are now only used in water sensitive formations. It is less damaging to the formation than the previous type. However, it is expensive and operationally difficult to handle. **[17]**

II-11-2-3-Acid-Based fluids:

The acid-based fluid is usually used to fracture carbonate formations in what is called Acid fracturing technique. It presents higher operational risk.

II-11-2-4-Multiphase Fluids:

Foams:

Foam is a stable mixture of liquid and gas. Foam fluids are most often used to fracture low reservoir pressures. Nitrogen and carbon dioxide are the mostly used as energizing gases.

Emulsions:

Emulsion-based fracturing fluids are highly viscous solutions with good transport properties. The drawbacks of emulsions are the operational difficulties of mixing and higher friction pressure. **[17]**

II-11-3-Fracturing fluid Components:

II-11-3-1-Gelling Agent:

Gelling agents are added to the Fracturing fluid to increase viscosity; this increases the fracture width to improve proppant transport and reduce the friction pressure. In addition, the chemical structure of gelling agents allows for crosslinking. One of the first polymers used to vicosify water for fracturing applications was **guar.** It is a long chain, high molecular weight polymer composed of mannose and galactose sugars. When the guar is added to water, the polymer molecules become associated with many water molecules and unfold and extend out into the solution as a result, the guar particle swell and hydrate**. [17]**

II-11-3-2-Additives:

Various additives have been developed to enhance the performance of fracturing fluids:

Table II- 1 : Types of additives used in fracturing fluids and their role

Additive Type	**Description of Purpose**
Cross-linker	Crosslinking agents are used to increase the molecular weight of the polymer, therefore increasing the viscosity of the solution.
Buffers	Buffers are weak acids or bases added to the fracturing fluid to control and maintain the desired PH value.
Clay stabilizer	Clay stabilizers are chemicals used to stabilize clays and fines to prevent the clay from swelling and/or migrating through the matrix.
Surfactant	Used to prevent emulsions and promote cleanup of the fracturing fluid from the fracture. Moreover, it leaves the formation water-wet.
Bactericide	Enzymes from bacteria can feed on the polymers causing gel degradation. As a result, bactericides are added to the fracturing fluids to prevent the growth of it.
Fluid-loss additives	Fluid-loss agents are pumped during the pre-pad and pad stages of the fracturing treatment to reduce fluid loss into formation.
Breaker	A Gel breaker is introduced to reduce the fluid's viscosity intermingled with the proppant by cleaving the polymer into small-molecular-weight fragments.
Temperature stabilizer	Temperature stabilizers are used to prevent the degradation of gels at temperatures greater than 200 **°F.**
Friction reducer	Allows fracture fluids to be injected at optimum rates and pressures by minimizing friction.

II-12-Proppant:

Proppant is a solid material, typically Sand, Treated Sand or manufactured ceramic materials. It is used to keep fractures open after the fracturing job is completed. In other terms, it prevents the fracture from closing due to overburden stress. It provides a high-conductivity pathway for hydrocarbons to flow from the reservoir to the well.

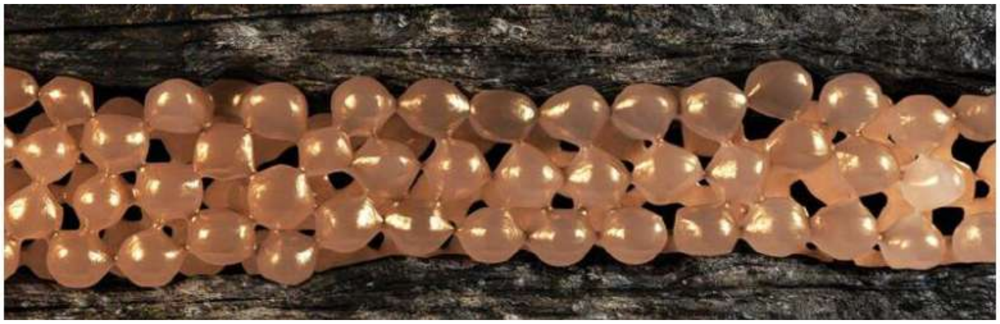


Fig II- 10 : An illustration of recently introduced coating

II-12-1-Proppant Proprieties:

The Proppant properties that affect fracture conductivity include:

- **Grain size and Strength:** Large grains have more space between them, providing more permeability and allowing more hydrocarbons to flow when placed. Moreover, the grains of the proppant must be strong to withstand the closure stress.
- **Fines and Impurities:** A high percentage of fines or impurities present in the proppant can partially block the conductive path.
- **Roundness and Sphericity:** The rounder or spherical the proppant grain the better the proppant-pack porosity will be. This last is able to withstand higher closure stress while angular grains produce fines that reduce the proppant-pack conductivity.
- **Proppant density:** High-density proppants are more difficult to suspend in fracturing fluids and have a greater tendency to settle. [17]

II-12-2-Types of Proppant:

II-12-2-1- Sand:

Due to its relatively low cost and availability, Sand is the most commonly used proppant, especially in reservoirs with a low closure pressure of less than 6000 Psi.

Fig II- 11 : sand [18]

II-12-2-2- Resin-coated Sand:

Resin coatings may be applied to Sand to improve proppant strength or prevent proppant flow back. It is used in operations where the closure pressure is less than 8,000 Psi.

Fig II- 12 : Resin-coated sand [18]

II-12-2-3- Intermediate-strength proppant:

Because they are manufactured, they maintain better sphericity and particle size distribution. As a result, a greater fracture conductivity than the Sand. They are used in reservoirs where the closure pressures are up to 10,000 Psi.

Fig II- 13 : Intermediate strength Proppant [18]

II-12-2-4- High-strength Proppant:

Sintered bauxite and Zirconium oxide are high-strength propping agents. However, they are generally limited to use in wells with very high confining stresses (>10,000 psi) because of their greater cost.

Fig II- 14 : High-strength proppant [18]

II-13 The workflow of hydraulic fracturing design:

In order to design a hydraulic fracturing job, engineers should understand how pumping rate and fluid properties affect the fracture geometry and propagation within the in situ stress to achieve a targeted propped fracture length. **[12]**

It involves rock mechanics to consider the possibility of obtaining a desired fracture geometry. Plus, fluid mechanic considerations to confirm that the required Proppant transport is possible and rheology to determine if the required fluid properties are possible. It also includes material selection and on-site operational considerations. **[2]**

II-13-1 Data collection:

- **Reservoir information:**

It includes: (In-situ Stresses**,** type of formation & lithology, permeability & porosity**,** initial Reservoir Pressure & BHST**,** rock mechanical properties from Sonic log**,** the skin factor and damage mechanism. **[19]**

- **Well information:**
  - Hole survey
  - Completions (casing & tubing)
  - Perforations

II-13-2 Fracturing fluid selection:

Selection of the fracturing fluid is based on the different properties of the fluid including viscosity, compatibility, resistance at high temperatures and the ability of degradation.

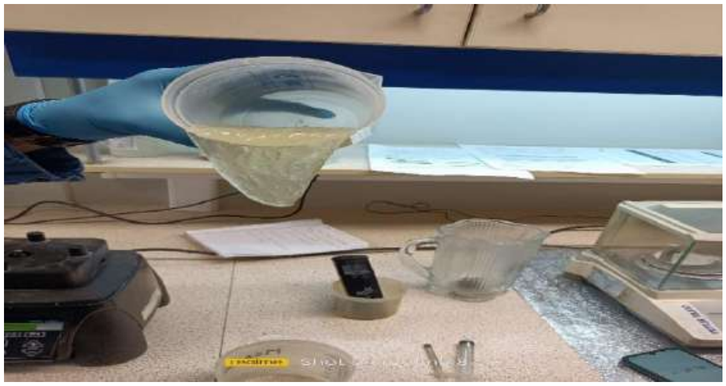


Fig II- 15 : Fracturing fluid preparation in the LAB

II-13-3 Proppant selection:

Proppant must be selected on the basis of in situ stress conditions and other considerations which include: Good physical properties (Strength, grain size and distribution**,** roundness and sphericity**,** proppant density), the permeability of the Proppant and the conductivity of the fracture. **[19]**

The major concerns of proppant selection are compressive strength and the effect of stress on proppant permeability. In general, bigger proppant yields better permeability. The figure shows permeabilities of various types of proppant under fracture closure stress.

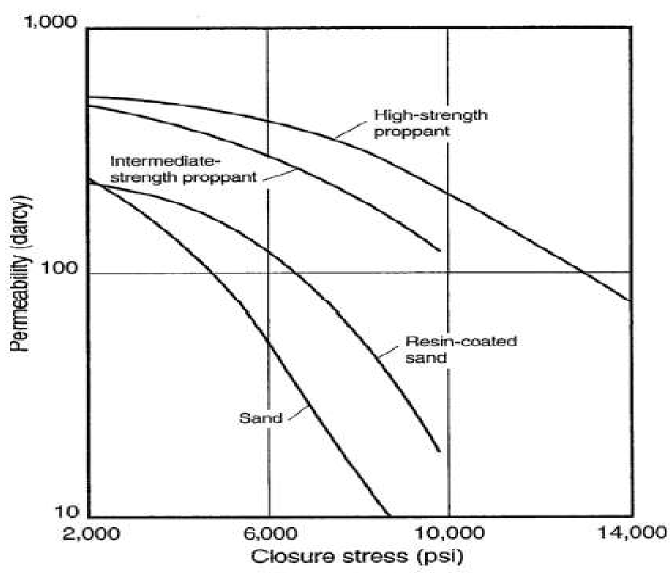


Fig II- 16 Effect of fracture closure stress on proppant pack permeability [20]

II-13-4 Selection of fracture model:

An appropriate fracture propagation model is selected for the formation characteristics and pressure behavior on the basis of in situ stresses and laboratory tests. Clearly a final schedule is generally developed using a fracture geometry model. However, the use of a properly calibrated fracture geometry model also enables the consideration of multiple scenarios for designing the optimum treatment for a specific application. **[20]**

II-13-5 Injection test (break down test):

Prior to the Calibration test a break down injection will be performed with Treated Water to identify the breakdown pressure which is considered as the upper bound of the closure. **[19]**

Moreover, it is used to:

- Verify if the formation absorbs the fluid
- Determine fracture gradient and thus the treating pressure
- Check the state of the downhole equipment and the quality of cementing

II-13-6 DataFRAC (calibration test):

A DataFRAC test is an injection-falloff diagnostic test performed without Proppant before a main fracture stimulation treatment. A total PAD volume will be injected into the formation then over flushed to the displacement volume with linear Gel in order to create a non-propped fracture in sufficient period of time.

The process is to break down the formation to create a short fracture during the injection period and observe closure of the fracture system during the ensuing falloff period. The DataFRAC identifies values of parameters including that are critical to optimize fracture treatment design such as closure pressure, fluid efficiency, leak off coefficient. This will lead to estimate frictions, fracture gradient, fracture geometry and the propagation model.

The advantages of this test are:

- Minimizes the possibility of screen out resulting from inaccurate parameters.
- Optimizes treatment even when reservoir information is limited.
- Determines the essential parameters of the formation and the well.
- Reduces proppant-pack damage and treatment costs.

In addition, this test is a decisive step to calibrate the stress profile and decide on the job volume.

II-13-6-1 Hydraulic Fracturing Parameters:

- **Bottom-hole treating pressure (BHTP):**

BHTP is the pressure along the fracture face that keeps the fracture open. It must be greater than the closure pressure to open and extend it.

$$BHTP = P_w + P_h - P_{Pipe} - P_{Per} - P_{NWB} \quad \text{II-7}$$

Where:

Pw : Wellhead treating pressure

Ph : Hydrostatic pressure

P_{Pipe} : Pipe friction

P_{Per} : Perforation friction

P_{NWB}: Near wellbore friction.

- **Fracture Gradient (FG):**

Fracture gradient (FG) is the pressure at which the formation breaks.

$$FG = \frac{ISIP\ Bottom\ hole}{TVD\ Midperf} \quad [15] \quad \text{II-8}$$

- **Fluid efficiency:**

Fluid efficiency is the ratio of stored volume within the fracture to the total fluid injected. Fluid efficiency is inversely related to fluid leak-off; high fluid efficiency means lower fluid leak-off and vice versa.

$$\eta = \frac{Vf}{Vt} \quad [15] \quad \text{II-9}$$

η: fluid efficiency.

Vf: Volume within the fracture.

Vt: total volume injected.

- **Fluid loss coefficient:**

It is a major fracture design variable. It occurs after the filter cake is developed. Excessive fluid loss prevents fracture propagation because of insufficient fluid volume accumulation in the fracture. Therefore, a fracture fluid with the lowest possible value of fluid-loss (leak-off) coefficient should be selected.

II-13-7 Temperature log:

Thermolog will be carried out right after the calibration Injection stages to estimate the fracture height by detecting the cool anomalies or zones that indicate the locations of cool fracture fluids injected. The temperature log is interpreted by looking for anomalies or departures from the reference gradient. These anomalies are normally related to the entry into the borehole or fluid exit into the formation. The reference temperatures will then be compared to the post DataFRAC temperature log and then the fracture height will be estimated.

II-13-8 Pressure matching & Redesign:

Pressure matching with a computer software is the first step to evaluate the fracturing job. Matching the Net Pressure during Calibration Treatment and the Pad. This match is a part of the set of analysis performed on-site for the redesign of injection schedule.

Using all the aforementioned steps of DataFRAC, the formation mechanical properties and fluid leak off coefficient will be calibrated after performing a pressure match which is a simulation between the pressure decline curve obtained from the DataFRAC and the curve given by the software; taking into account the results of the temperature survey. And this all will allow re-designing an optimized treatment in order to start the execution of the main frac.

II-13-9 Main frac & pump schedule:

A fracturing job should progress in the following stages:

1- **Pre-pad:** low viscosity fluid (linear gel) is pumped before the fracturing treatment to initiate the fracture. This fluid cools the casing and tubulars and reduces the high temperatures that may degrade the fracturing fluid.
2- **Pad Stage:** a higher-viscosity fluid is pumped down the borehole at high rate leads to breaking down the formation and creating a pad.
3- **Slurry:** is a mixture of the fracturing fluid and proppant that keeps the fractures open and should have a compressive strength to bear stresses from the formation.
4- **Flush:** Clear fluid (linear gel) is pumped to displace the slurry out of the wellbore.

Fig II- 17 : Fracturing stages in a Conventional Frac job On-field

II-14-Surface equipment of hydraulic fracturing:

The success of a hydraulic fracturing job is achieved by series of special equipment and highly qualified personnel which are:

- **Frac Tanks:**

It is used to store water for the preparation of the fracturing gel. The number of tanks depends on the volume of water required for the operation.

Fig II- 18 : Frac Tanks

- **Hydration unit (PCM):**

Precision continuous mixer is an equipment that continuously mixes dry polymer loadings with water that comes from tanks resulting in a linear gel. It is composed of centrifugal pumps, hydration tanks and mixers where water and polymer are mixed, a polymer storage bin and four liquid additives. This equipment is Built to reduce time and cost on location means no waiting time between mixing and pumping.

Fig II- 19 : Hydration Unit (PCM)

- **Blender (POD):**

The blenders accurately mix Proppant, fracturing fluid and additives in the Vortex at a specified density in a preprogrammed, automatic mode. This density is measured by a radioactive densitometer that is based on the absorption of gamma rays by the measured fluid that will be captured by detectors that sense the gamma rays transmitted through the fluid and converts this signal into an electrical signal. The electronic panel processes the electrical signal into a density indication. Finally, the slurry is pumped in the low pressure line of the manifold. **[2]**

Fig II- 20 : POD Blender

- **Sand Chief (Sand Feeder):**

The sand chief is an equipment used to store Proppant on location and deliver it to the sand hopper of the blender. It is divided into four parts containing the different sizes of Proppant. The conveyor-equipped sand bin is the most commonly used unit for delivering proppants to the blender. These units have several compartments for storing proppant. Each compartment has a set of hydraulically controlled gates at the bottom. When the gates are opened, proppant falls from the container onto a conveyor belt that leads to the blender. **[2]**

Fig II- 21 : Sand Chief

- **Missile (Frac Manifold):**

It is an arrangement of piping or valves designed to control, distribute and typically monitor fluid flow; A frac manifold is used for directing treatment fluid and Organize both low-pressure flow from the blender to the pumps and the high-pressure flow from the pumps down the well. It also provides an easy and efficient hook-up for up to 10 high pressure pumps.

Fig II- 22 : Missile

- **High pressure pumps:**

A Triplex pump sends the fracturing fluid at high pressure and rate to the well in the high pressure line of the missile. High-pressure pumps should be installed close enough to the blender so that the discharge pumps on the blender can easily feed slurry to the intake manifolds on the pumps. The number of pumps used is based on the horse power of each pump (HHP). **[2]**

Fig 23: High pressure pumps

- **Annulus pump:**

It applies pressure inside the annulus to provide underbalanced pressure and prevents the collapse of tubing caused by the high pressures performed during hydraulic fracturing.

- **Treating iron:**

The size of the high-pressure pipe called treating iron used on a treatment between the high pressure pumps and the wellhead isolator is dictated by both the anticipated rates and pressures. Smaller lines have a higher maximum treating pressure limitation than the larger sizes.

- **Wellhead isolation tool (Tree saver):**

Treatments pressure can exceed the maximum working pressures of the wellhead equipment. Thus, the tree saver is used to protect the Christmas tree at the wellhead from damage and the possible failure that results from exposure to high pressure and abrasive fluids during fracturing jobs; It is mounted on the Christmas tree.

Fig II- 24: Wellhead isolation tool

- **Treatment control vehicle (TCV):**

It is a Data Monitoring Truck to control and operate the equipment using a data acquisition system called ‘FracCAT. It is a PC-based data acquisition and control system designed to monitor, and control pumping, mixing and blending equipment through sensors and cables related to equipment.

Fig II- 25: Treatment Control Vehicle

II-15-Post fracture productivity:

Hydraulically created fractures gather fluids from reservoir and provide channels for the fluid to flow into the wellbore. Apparently, the productivity of fractured wells depends on two steps:

1- Receiving fluids from formation
2- Transporting the received fluid to the wellbore **[20]**

Usually one of the steps is a limiting step that controls the well-production rate. The efficiency of the first step depends on fracture dimension (and the second one depends on fracture permeability. Therefore, the productivity after a HF treatment is represented by the concept of **folds of increase.**

II-15-1 The Folds of increase:

The folds of increase (FOI) for steady-state flow can be defined as the post fracture increase in well productivity compared with pre-fracture productivity calculated from**: [2]**

where re is the well drainage or reservoir radius, rw is the normal wellbore radius, and s is any pre-fracture skin effect resulting from wellbore damage, scale buildup, etc.

$$\mathbf{FOI} = \frac{Q'}{Qo} = \frac{\ln\frac{re}{rw}}{\ln\frac{re}{rw} + Sf} \qquad [20] \qquad \text{II-10}$$

Where:

Q'= The flow rate of the Post-frac (stb/day-psi)

Qo= The flow rate of the Pre-frac (stb/day-psi).

An equivalent skin effect sf resulting from a fracture is:

$$\mathbf{Sf = -Ln\ (r'w / rw)} \qquad [20] \qquad \text{II-11}$$

II-16 Conclusion:

In conclusion, HF is used to create a conductive path between the reservoir and the wellbore for enhanced productivity. The success of this job greatly depends on several parameters such as rock mechanics and in-situ stresses. As well as, material selection and on-site operational considerations in order to avoid any job failure. Because the completion design of multistage fracturing is complicated, costly and long time wasted through perforating and plugging stages.

New sequenced fracturing technique was developed and successfully tested to deal with these challenges by achieving higher productivity and operations efficiency. This technology is called **“Broadband Sequence”** which will be detailed in the next chapter.

Chapter III:

Multistage Fracturing Using BroadBand Sequence Technology

III-1 -Introduction:

The purpose of using a diverting technique while hydraulic fracturing is to assure that each separate formation interval is fractured. However, fluids pumped at fracturing pressures will first enter and fracture zones with the least resistance (lower stress, lower pressure), making stimulation treatments inefficient and covering only a limited interval.

As a result, diversion techniques are developed to increase stimulation coverage and therefore maximize wellbore-reservoir contact for increased production. However, effective stimulation of long producing intervals (more than 100 ft) in vertical wells has been challenging. Sand plugs, bridge plugs, CoilFRAC and other limited-entry techniques have long been used in vertical wells. However, these methods can be time-consuming, and they increase completion costs.

Consequently, various multiple-stage isolation techniques are currently being utilized. To enable extending the interval length and increasing effectively stimulated rock volume, a new Broadband Sequenced fracturing technique was developed and successfully tested by Schlumberger. This chapter will discuss the mechanism of this diversion technique and compare it with a mechanical diversion from operational and economic aspects.

III-2- Introduction to Multistage Fracturing:

Multistage hydraulic fracturing is one of the key methods for effective stimulation of reservoirs, whether in horizontal or vertical wells. Therefore, it comes to studying the complex formations and extreme conditions in order to stimulate and frack the individual zones to increase the contact area between the reservoir and the wellbore. This technology is performed by increasing the pressure in the well with multiple perforations and forcing significant fractures from all perforations. **[27]**

However, Multi-stage fracturing leaves sections under-stimulated. Hence, the introduction of new diversion techniques to stimulate every cluster and increase stimulation coverage. Thereby maximizing wellbore-reservoir contact for increased production. There are two main ways of performing multistage hydraulic fracturing selected depending on the well design and completions.

III-3-Diverter Concept

Diverters help ensure that the entire interval is stimulated. When a diversion is not considered, there is a significant reduction in the assurance of complete zonal coverage. In fact, depending on other variable such as the permeability and porosity heterogeneity along the interval, it should be recommended that diversion always be recommended to maximize the potential for success. **[17]**

Diverters can be separated into two broad categories, mechanical and chemical:

III-3-1-Mechanical diversion

There are many mechanical options used to divert reservoir treatments to the target zone; such as sand plug technique and CoilFRAC. However, the Plug and Perf technique is the mostly used.

III-3-1-1-Sand Plug technique

It is a treatment diversion technique using Proppant, sand, or gravel to plug back a previously-fractured zone prior to perforating and fracturing the next zone higher the wellbore. The lower interval can be perforated and fracture treated. Then a sand plug is placed over the first zone and the sand is allowed to settle by gravity. After the sand plug has been pressure tested, the second interval can be perforated and fracture stimulated. And the process will be repeated for the rest of the stages. After the last fracture treatment, the wellbore can be cleaned out with coiled tubing or a conventional workover rig. **[13]**

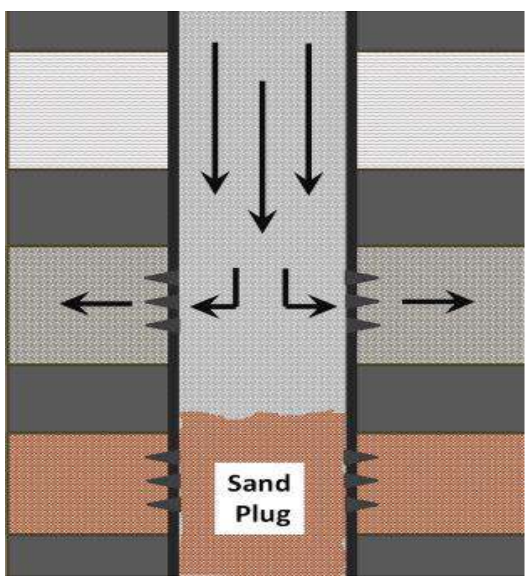


Fig III- 1: Sand Plug technique in a vertical well [13]

III-3-1-2-CoilFRAC technique:

The CoilFRAC service combines CT and selective fracturing technology enabling multiple zones to be treated in a single trip. In new wells, each zone is perforated conventionally in one wellsite visit. CT is then run in hole with a straddle tool BHA. The bottom zone is straddled, and the fracture stimulation is pumped through the CT string. Residual proppant is reverse-circulated out of the wellbore, and the straddle tool is moved to the next zone, where the process is repeated. Each layer is individually stimulated using only one run into the wellbore. **[30]**

III-3-1-3-Plug and Perf technique

The plug method is one of the mechanical diversion options that can be applied for both horizontal and vertical wells. It is employed as mechanical isolation between fracturing stages. Consequently, the ability to stimulate each perforation cluster becomes uncertain, and prior evaluation has indicated that a significant fraction of these clusters do not ultimately contribute to production. Access and diversion is accomplished by pumping down a bridge plug along with the perforating guns through cables. **[21]**

A plug is a downhole tool that is located and set into position to isolate the lower part of the wellbore from a treatment conducted on an upper zone. A typical treatment using this method involves perforating a lower zone, performing a fracture treatment, setting a plug above that particular interval, and then perforating and treating the next zone up the wellbore. This process is then repeated for the number of planned stimulation desired for the wellbore. And the final phase is to remove the plugs and flow back the well. **[21]**

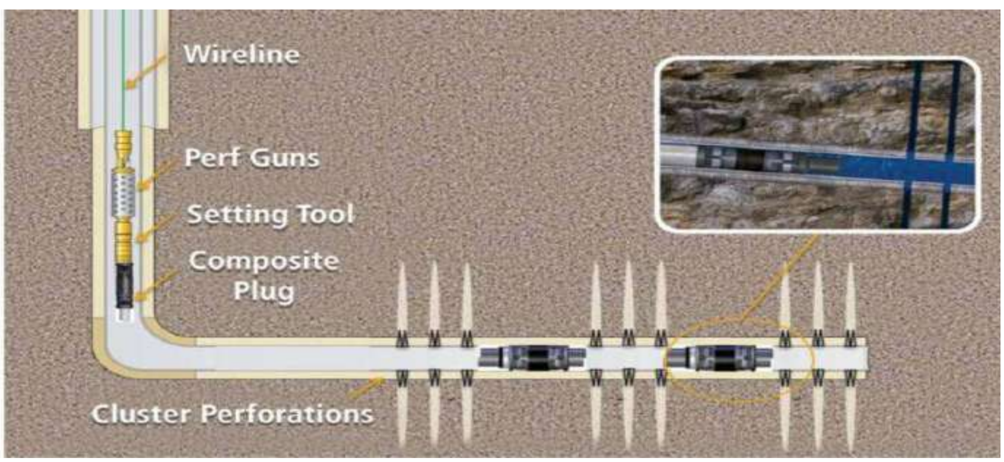


Fig III- 2 : Wellbore diagram of a Plug and Perf completion system [26]

- **Limitations:**

Due to the different isolation methods and pipe string structure, perf-and-plug multistage fracturing presents many limitations which are:

- Repeated WL or CT interventions as a result, more operational risk and high-cost.
- Long time between fracturing stages to set bridge plugs and perforate the next zone.
- Cementing can impair and plug natural fractures in the horizontal section.
- Mechanical problems can occur with the retrievable bridge plugs used for isolation.
- Formation damage (water block-water sensitive clays or other saturation change) can be caused by long shut in times.

Fig III- 3 : Plug and Perf Technique [24]

III-3-2-Chemical Diversion:

Chemical diversion uses a chemical diverter agent to achieve diversion during the stimulation of multi-stage hydraulic fracturing. This technique carries less risk because it does not have to run the tubing, packers and other mechanical equipment that can become stuck in the wellbore. One of the best examples of chemical Diversion is the new BroadBand Sequence fracturing technique.

III-4-BroadBand Sequence technique:

III-4-1-Definition:

The Broadband Sequence fracturing technique is a stimulation diversion technology that was executed in Algeria for the first time in 2019 by Schlumberger. It increases operational efficiency, productivity, and potentially estimated ultimate recovery with a reduced time and cost by using a chemical diverter that consists of a degradable blend of particles and fibers made of polymers that degrades without leaving any residue.

This chemical diverter offers a temporary near-wellbore isolation of the zones that have the lower fracture pressures and divert the fracturing fluid injection to the zones that have the higher fracturing pressures. Therefore, it will increase the fracture stimulation of the entire interval. Diversion can occur inside the pipe at the perforations, in a channel in the casing/formation annulus or in the fracture itself.

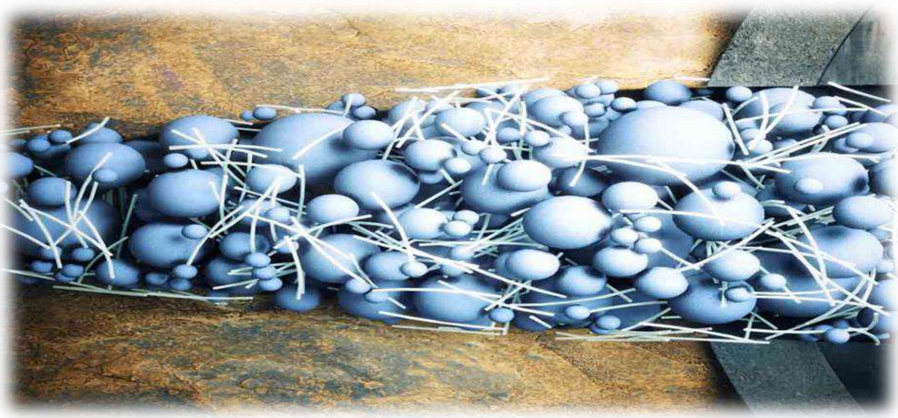


Fig III- 4 : Conceptual view of diversion at the fracture face [24]

III-4-2-Objective:

The primary objective of BroadBand sequence technology is to assure that every separate formation interval is fractured and stimulated. It is used in fracturing to increase contact with the reservoir and to extend the interval lengths to be stimulated, or both. This technique can also be used as an alternative solution for mechanical diversion options as it reduces completion cost and operation time; therefore, it will help in improving resource utilization in new wells.

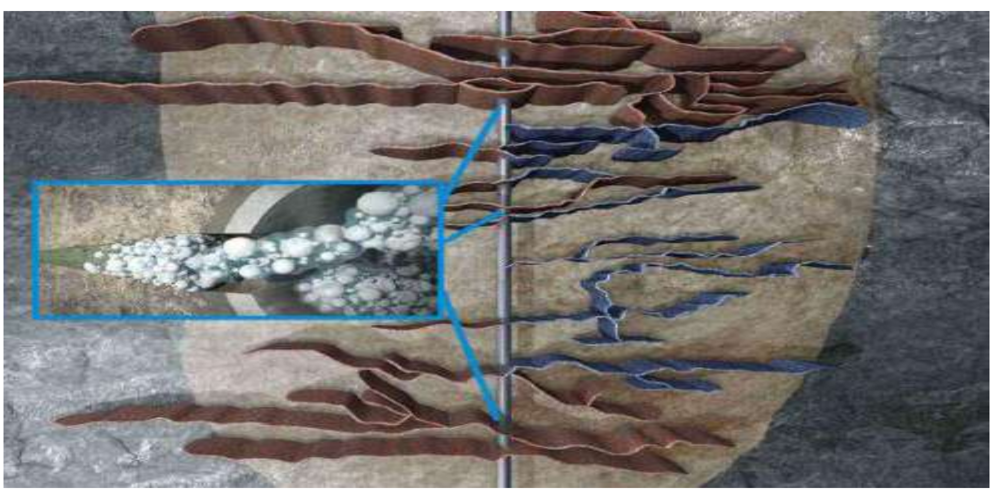


Fig III- 5 : Chemical Diversion Function in Multistage Fracturing [24]

III-4-3 Features:

- ✓ Enhanced near-wellbore conductivity and superior diversion with partially degradable pills
- ✓ Ability to reduce the number of bridge plugs used per completion
- ✓ Degradable without inducing formation damage
- ✓ Small volume of material is used
- ✓ Fast operation: no pumping slow-down, simplicity on surface
- ✓ No restriction in the wellbore
- ✓ Reduced time and cost **[22]**

III-4-4 Applications:

- ➢ Conventional and unconventional formations
- ➢ Vertical and horizontal wells
- ➢ New completions
- ➢ Re-fracturing operations
- ➢ 100°F<BHST<400°F **[22]**

III-4-5-Candidate selection:

The success or failure of a hydraulic fracture treatment often depends on the quality of the candidate well selected for the treatment. Choosing an excellent candidate for stimulation often ensures success, while choosing a poor candidate normally results in economic failure.

The best candidate wells for hydraulic fracturing have a substantial volume of hydrocarbons in place and need to increase the productivity index. Such reservoirs have a thick pay zone, sufficient reservoir pressure, in-situ stress barriers to minimize vertical height growth and either a low permeability reservoir (Less than 10 mD) or a damaged reservoir (positive skin factor). **[8]**

However, the well conditions which may require BBS diversion treatment include:

- ➢ Multiple sets of perforations (clusters)
- ➢ Thick, massive formations
- ➢ Cemented, cased and perforated wells
- ➢ Formation’s BHST above 90°F (32°C°xk
- ➢ Long lateral intervals in horizontal well

- High stress or permeability contrasts between multiple zones of interest
- Small tubulars which require lower injection rates
- Horizontal fractures

III-4-6-Description of BroadBand Sequence Stimulation:

The diverter is injected right at the end of the conventional hydraulic fracturing treatment to basically provide temporary isolation in the fractures that have been stimulated and divert the fracturing fluid into the under-stimulated zones of interest.

III-4-6-1-BroadBand Sequence Operation:

A BroadBand treatment consists of a three-step sequence:

- **First Spacer:** In BroadBand treatment, Spacers are a combination of the base fluid (linear gel) and fiber. A spacer is pumped before and after the composite pill to keep the Broadband composite pill integrity and to avoid mixing with the other fracturing stages.
- **Diversion pill:** the composite pill is a mixture of linear gel, degradable particles and fibers. So, by temporarily locking and unlocking perforation clusters, this composite pill diverts fluid to higher stress regions for increased fracture stimulation within each stage. Particles and fibers completely degrade after few hours with a degradation triggered by bottom-hole temperature; there is no additional intervention to put the well back in production, ensuring that all the intervals are available to contribute.
- **Second Spacer:** Another spacer (linear gel with fiber) is pumped after the composite pill to flush the dedicated diversion.

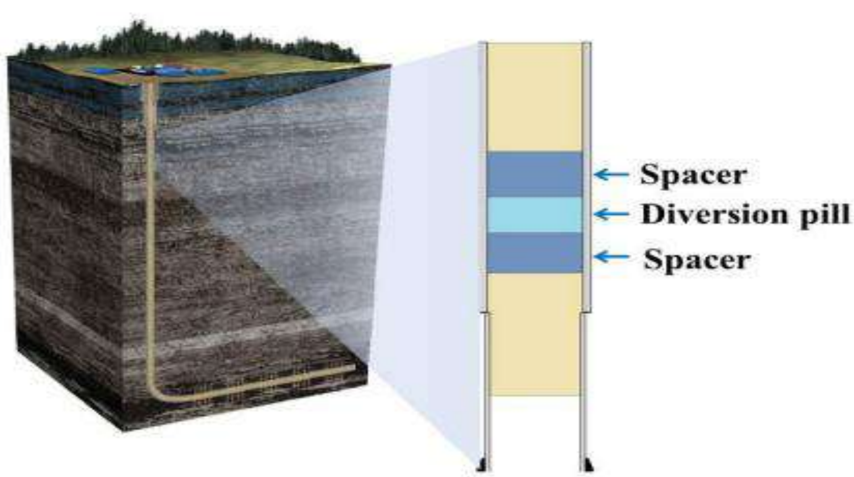


Fig III- 6 : Illustration of a BroadBand Composite pill [13]

III-4-7-Broadband Composite pill:

The most useful type of BBS composite pill in Schlumberger- Algeria is the enhanced-conductivity pill. It is an engineered slurry consisting of partially degradable particles of highly conductive ceramic spheres chosen to enhance diversion strength and ensure near-wellbore conductivity. **[24]**

Fig III- 7 : Enhanced Conductivity BBS Composite Pill [24]

The degradable nature of both the fiber and diverting materials ensures that no residue remains in the wellbore after the hydraulic fracturing treatment. Hence, all treated intervals are then available to contribute to production.

Concepts:

- Composite Pill = slurry containing linear gel + fibers + particles
- Stage = each Proppant - laden schedule pumped in a wellbore
- Interval = each segment in a wellbore isolated by plugs

The figure below shows samples of degradable particles the most useful in Algeria:

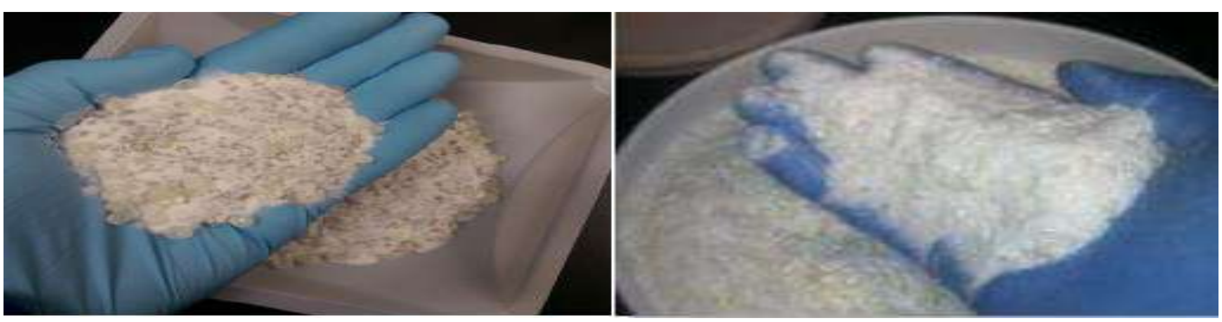


Fig III- 8 : Samples of degradable particles and Fiber (Composite Pill) [13]

III-4-7-1-Diverting Agent Selection:

The diverting agent must be selected based on:

-The Bottom hole static temperature

-Formation permeability

-The desired degradation rate and time for effective diversion.

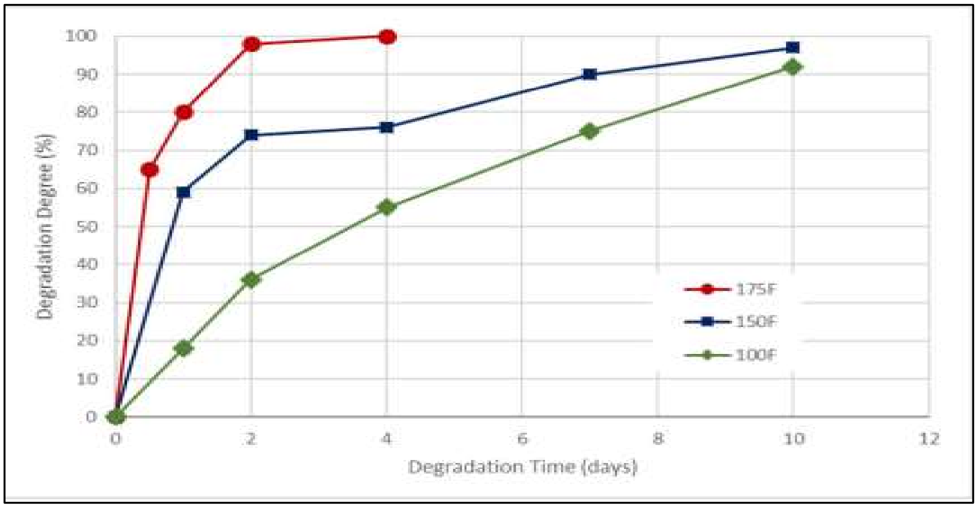


Fig III- 9 : BBS Pill degradation time [23]

The figure shows that at higher temperature of degradation, 175°F, the BBS Pill degrades 100% in a shorter time (4 days). While, at temperatures of 150°F and 100°F, the degradation of the Pill will take longer (10 days). Thus, we conclude that the diverter agent is selected based on the Bottom hole static temperature that will define the degree and time of degradation of the Pill.

III-4-8-Mechanism of Action:

The principle of this diversion relies on particulate-based diverting materials used to effectively create multiple fractures during one continuous fracturing operation. This typically involves multistage fracturing treatments where each zone receives its own pad volume and graduated Proppant schedule. At the end of each stage, enough diverter is injected to either cover the perforations of the zone being treated or bridge in the fractures, effectively diverting the next stage into other perforations. The mechanism is described below:

- The size distribution and amount of components of the degradable diversion blend are optimized to create a low permeable plug with a minimum amount of material. The pill is designed so that the large particles accumulate at the fracture entrance, bridging the fracture face, and the smaller particles reduce permeability to create temporary isolation.

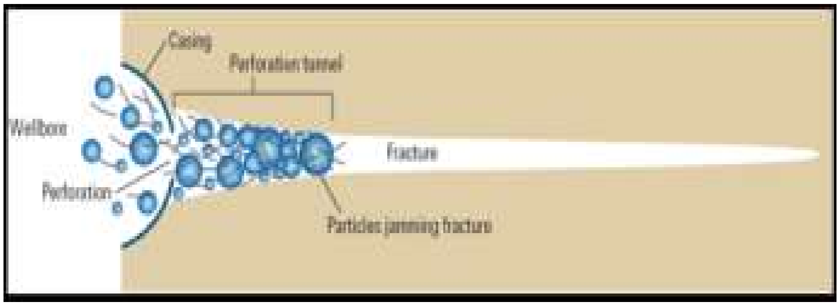
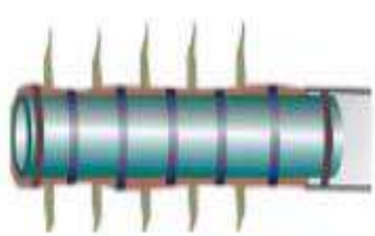


Fig III- 10 : Mechanism of action of chemical diversion pills during HF [28]

- Fibers are used to ensure the integrity of the blend from the surface to the near-wellbore area, helping to mitigate pill dispersion and particle settling and also enhancing the bridging mechanism.
- The diverter is then followed by the pad volume to initiate the fracture in the next zone and the process is repeated. There is no need for a diverter at the end of the final stage.
- After the fracturing treatment has been completed, the material degrades completely leaving no residue or fracture conductivity damage and therefore opening the zone for production. **[24]**

III-4-9-Technical comparative study:

Table III- 1 : Difference between BroadBand Sequence and plug & Perf

Method	Image	Description
BroadBand Sequence Fracturing		- Chemical diversion - The use of a chemical diverter to plug fractures or perforations - Small volume of material is used - Cheap and safe - Minimized operational time
Fracturing using Plug and Perf		- Mechanical diversion - The use of bridge plugs to isolate clusters - High risk and completion cost - Long operational time

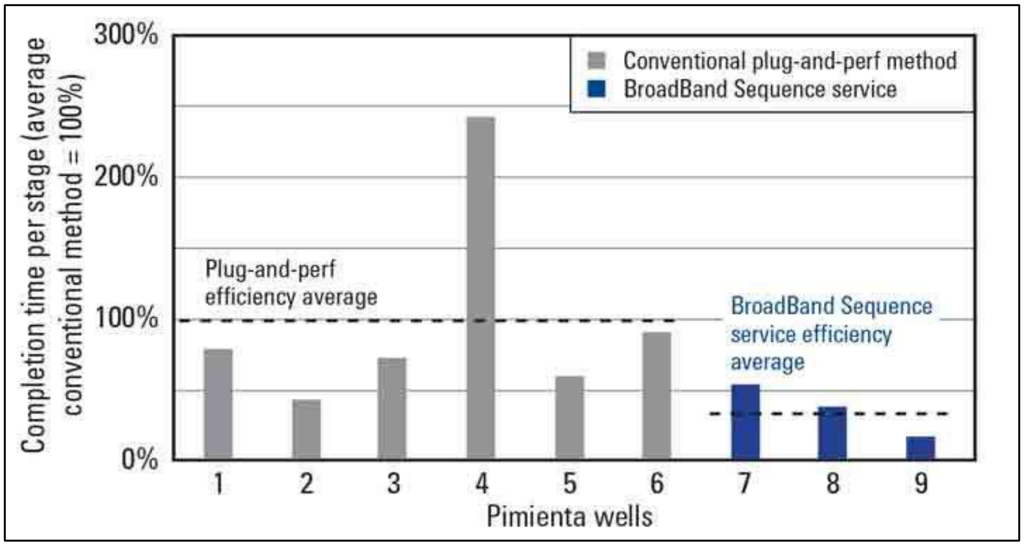


Fig III- 11 : Comparison between completion time of Plug-and-Perf and BBS [29]

III-4-10-Broadband Sequence equipment:

The Broadband sequence treatment is pumped in parallel to conventional hydraulic fracturing job. However, due to the large size of some components of the BroadBand composite pill and to avoid contamination of the manifold trailer and the main pumps, it requires extra dedicated equipment which are added specifically for composite pill mixing and pumping.

1- BroadBand Blender:

The pill is prepared by batch mixing, this requires BroadBand blender where the linear gel, Fibers and degradable particles get mixed to form a composite pill.

Fig III- 12 : BroadBand Blender [13]

2- BroadBand Pump:

The dedicated pump is used to pump the BBS composite pill downhole. Only triplex pumps can be used, therefore bigger plungers are desirable.

Fig III- 13 : BroadBand Pump [13]

III-4-11-Impact on Production:

As seen in the figure below, BroadBand well outperformed offset well based on normalized production data. The Cumulative oil production increased and we conclude that the BroadBand Sequence technique delivers Higher Production.

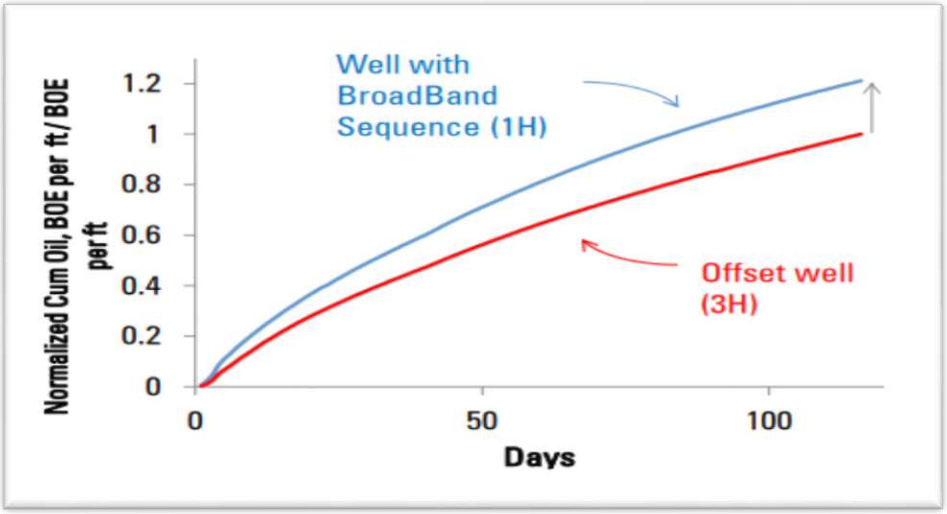


Fig III- 14 : Cumulative Oil in a well with BBS vs an offset well [13]

III-4-12-Stimulation effectiveness of Broadband Sequence:

III-4-12-1-Sequenced stimulation for optimal reservoir contact:

The BroadBand Sequence fracturing service reliably provides temporary isolation on demand and thus stimulates more perforations. It increases contact with the reservoir and enables the extension of the interval lengths to be stimulated. It can also be used as an alternative option to bridge plugs in situations where a bridge plug cannot be used. **[22]**

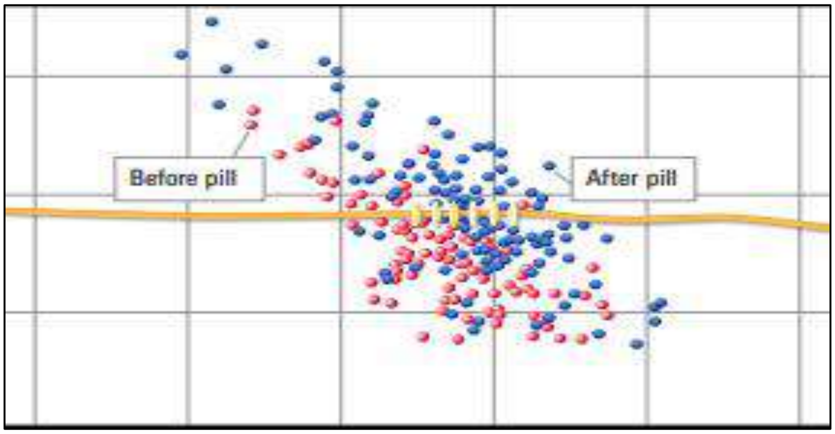


Fig III- 15 : The distribution of micro-seismic events in the fractured zone [22]

Interpretation: The distribution of micro-seismic events demonstrates the effectiveness of the BroadBand Sequence service (in blue) in a previously unstimulated zone (in red). In addition, it showed that after using the BBS Pill, the number of micro-seismic events increased, which means the pill was successfully diverted to inaccessible well intervals and the initiation of new fractures.

III-4-12-2-Step change in completion efficiency:

When using the BBS service, the stimulation treatment for each interval consists of multiple stages of Proppant separated by pills of composite fluid that consists of degradable fibers and particles. Longer intervals can be treated effectively by increasing the number of stimulation stages and pills without requiring additional bridge plugs, saving operational time and costs. **[22]**

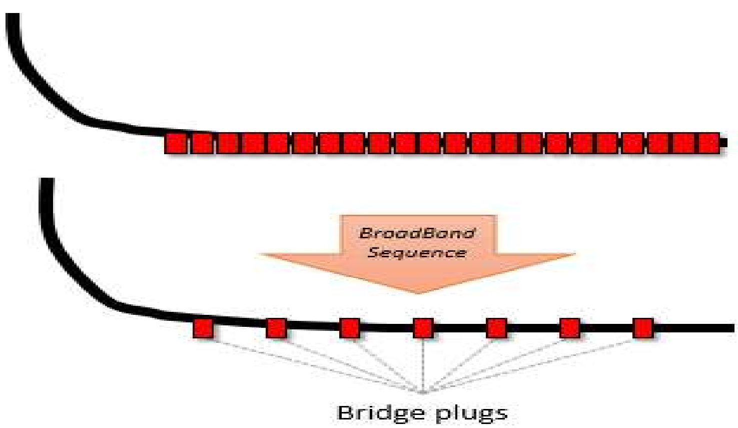


Fig III- 16 : Broadband Sequence reducing the number of bridge plugs [13]

III-4-13-Economics

Introduction:

Each oilfield operation must be provided with economic support that will contribute to evaluating the efficiency of that operation. An economic evaluation involves considering the price of the transaction, adding to this any preliminary preparations to prepare the field, as well as those related to "Post-job" rehabilitation or happening as a direct consequence in order to complete the job.

At the most basic level, hydraulic fracturing is about time and money "economics" that provide the final design for the treatment. The operating costs of Conventional hydraulic fracturing job with Multistage Broadband Sequence include:

- **The products used:**
  - Cost of the fracturing fluid and the Proppant used.
  - Cost of the Broadband composite pill and Fiber.
- **Job Execution:**
  - Cost of rental equipment and personnel.

A hydraulic fracturing job should use the most cost-effective solution or the solution that yields the highest return on investment. As a result, the Broadband Sequence fracturing was used because it offers an enhanced production with a reduced cost. However, this technology also has operational costs that will be studied in the case study section.

Conclusion:

In conclusion, during a fracturing job, Broadband Sequence Technology is used to ensure that the fracturing fluid penetrates all perforations so that after the treatment, the entire productivity of the well can be recovered. It is a chemical diversion that has been developed and successfully tested to enable sequential stimulation of perforated clusters or open hole intervals, maximizing wellbore coverage and reservoir contact.

It increases operational efficiency, productivity, and potentially estimated ultimate recovery compared to Plug and Perf mechanical diversion, which presents higher risk, completion cost, and additional operation time. However, the efficiency of this technology depends on the effectiveness of the chemical diverter used, which will be conducted in the following case study chapter.

Chapter IV:

Case Study and Simulation results with Petrel

IV-1-Introduction:

This chapter presents a hydraulic fracturing job using Broadband Sequence technique that was performed the first time in Algeria in 2019. It includes the well history and formation data, well completion data, the design of broadband sequence fracturing treatment and the software used.

This case study is conducted to prove the efficiency of BBS Composite Pill on the well X that showed the effectiveness of this technology to achieve a successful diversion stimulation.

IV-2-Overview of Hassi Messaoud field:

HMD field is in the eastern part of the Algerian Sahara Desert discovered in the late fifties. It had an elevated reservoir pressure of 450 kg/cm^2. Along with production, the pressure declined and today, most of the zones in the field are water or gas injection wells for pressure maintenance. It produces 375,000 bbl/day, or about 40 percent of Algeria's production. The oil is produced from a Cambrian sandstone reservoir in a large dome with a productive area of around 1,300 km^2.

The HMD field is a very thick sandstone reservoir, covering an area of 2500 km^2. It is a flattened anticline formed by a sequence of Horsts and Grabens contained by faults. These faults are oriented and cover all the layers of the producing reservoir (Cambro-Ordovicien). This field consists of 25 separate zones that have distinct petro physical properties. All the wells existing outside these zones are known as boundaries.

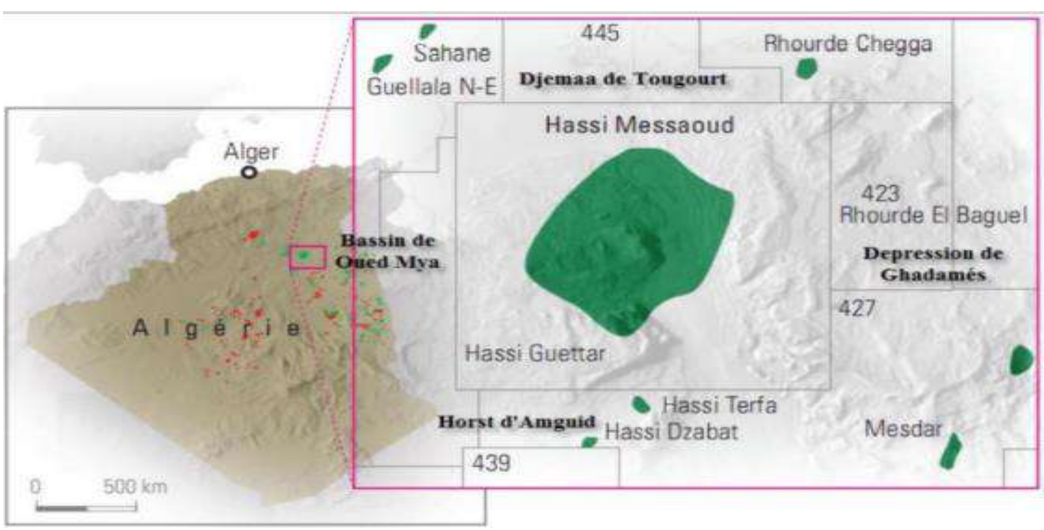


Fig IV- 1 : Hassi Messaoud field location map, Algeria.

IV-2-1 Reservoir description:

Hassi Messaoud reservoir occurs in a depth varies between 3100m and 3380m. Its thickness goes up to 200m and consists of four different formations in addition to an alteration zone. Each formation is subdivided into drains that are characterized by variable petro-physical properties.

The different parts of this reservoir are:

R3: This zone has 300 m, composed of coarse sandstones and conglomerates with cement made of clay (illites) and dolomites, it is divided into two sub levels; R2c and R2ab.

R2: is made of sandstones which are coarse but smaller size grains than these in R3. The cement is argillaceous (Kaolinite). The average thickness of this zone is 80 m.

Ra: Anisometric zone with average thickness of 120 m, composed of sandstone clay cement from medium to coarse grains. It is subdivided into drains from bottom to top: D1, ID, D2, D3, D4.

Ri: Is made of fine rounded, isometric sandstone with considerable development of quartzite. It has a thickness of 45 m mainly quartzite with fine grains. It corresponds to the drain D5.

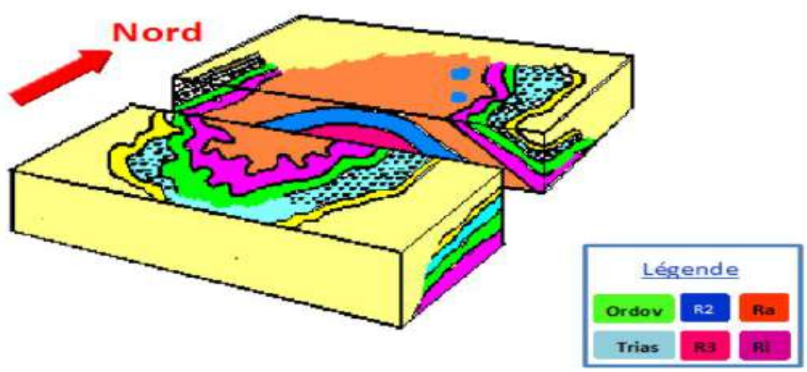


Fig IV- 2 : Diagram block of the geological crust under the Hercynian discordance. [25]

IV-2-2 Field Stratigraphy:

The figure below represents the composition of Hassi Messaoud reservoir from the top to the bottom:

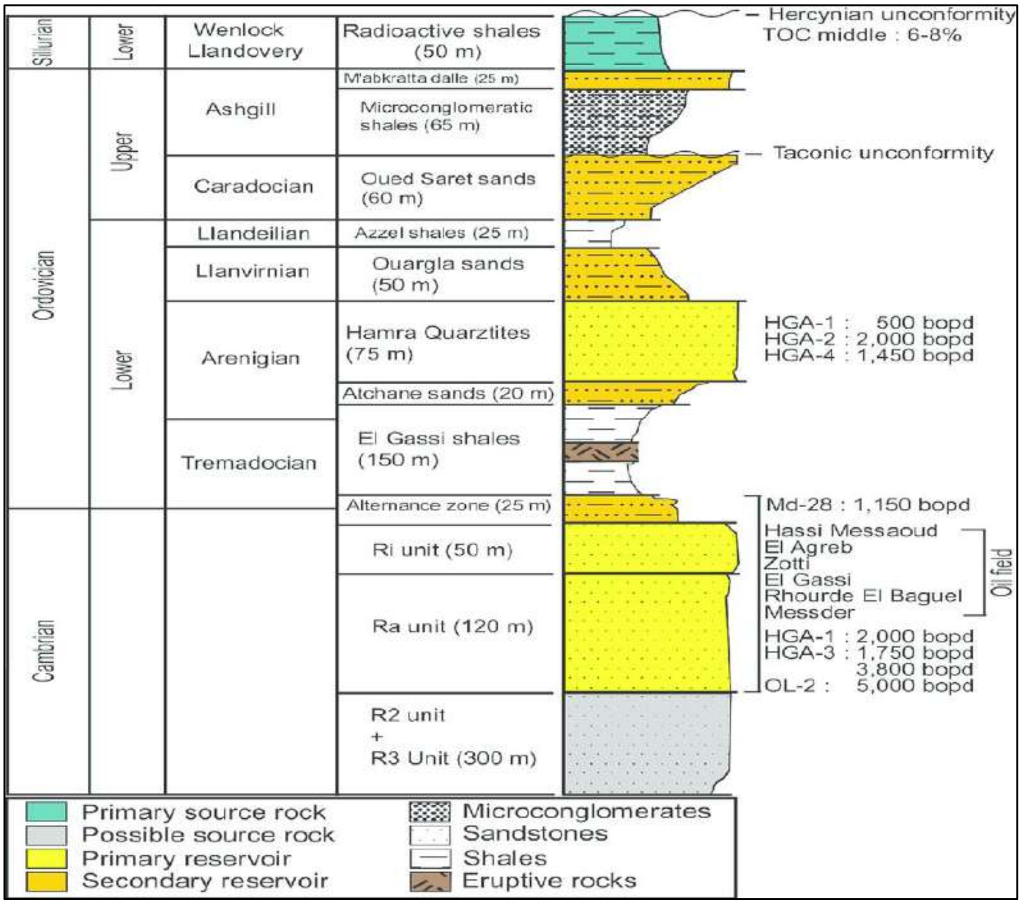


Fig IV- 3 : Stratigraphic section of Hassi Messaoud reservoir

IV-2-3 Average Petro physical characteristics of Cambrian reservoir:

Table IV- 1 : Petro Physical Characteristics of Cambrian reservoir [25]

Reservoir	K min (md)	K moy (md)	K max (md)	Φ min (%)	Φmoy (%)	Φ max (%)	S wi (%)	Vshmoy (%)
Ri	**0.3**	**1**	**2**	**6**	**7**	**8**	**17**	**15**
Ra	**2**	**15**	**100**	**6**	**8**	**10**	**10**	**7**
R2	**1**	**2.5**	**7**		**10**		**17**	**20**
R3		**<1**			**0.11**		**0.17**	**30**

IV-2-4 Fluid characteristics:

The oil is under saturated and light. Some of the oil and gas properties of HMD field are represented in the table below:

Table IV- 2 : Fluid properties of Hassi Messaoud Field [25]

Oil	**Density**	**Light: 0,8 (API = 45.4)**
	Reservoir pressure	**Varies from 400 to 120 kg/cm2**
	Reservoir temperature	**118°C**
	GOR	**219 m3 /m3**
	Average porosity	**Low: 5 to 10%**
	Average permeability	**Relatively low: 2 md to 100 md**
	Oil viscosity	**0,2 Cp**
	Oil FVF	**1,7**
	Bubble point	**160 kg/cm2**
Associated Gas	**Gas viscosity**	**0.02 Cp**
	Gas compressibility	**0.8 bar^{-1}**

NB: Due to the confidentiality of the data in Schlumberger, the well name and field were not mentioned. As well as the name of products used.

IV-2-5 History of the well X:

- The well X was the first application using a Broadband Sequence fracturing technique in a vertical well located in southern Algeria. It was an oil producer, then turned into water injector supporting two oil producer wells Y and Z.
- The well was drilled and completed in **21 October *2002.***
- **In Jan 2011**, the formations U1 and M1 were fractured in the intervals **(2808-2823m and 2833-2851m)**
- **In 2019,** Broadband Sequence Fracturing treatment on the M1 sand **(2831-2852m)** is needed to increase WI rates. And the U sand does not need to be re-stimulated.

IV-2-6 Overview:

The sonic logs were used to build the stress profile; both shear and compressional and shear waves were available in log data used to calculate the Poisson's ratio and the minimum horizontal stress. Fluid efficiency and Friction Pressures used in the model are based on the previous Frac performed on this region. DataFRAC evaluation will be used to confirm and adjust their values, allowing redesigning of the optimum treatment for the main fracturing job.

The well X was fractured, but there were some non-stimulated zones. Therefore, the BBS Composite Pill will be performed in this well in order to stimulate the lower zone and isolate the upper zone while it is opened and already fractured. In addition, this well would benefit from stimulation on the lower interval to improve drainage in this region and thus enhance recovery.

- **Objective**:
  - Broadband Sequence fracturing treatment to increase injection rate in the lower perforations.

Fig IV- 4: Placement of the Well X

IV-3-Production history:

Table IV- 3: MPLT obtained in July 2014

Zones (m)	Qt res (B/D)	Production %	W O G
Inflow 0 (2808-2823)	-7366.48	79.32	
Inflow 1 (2833-2851)	-1920.37	20.68	

Table IV- 4 : MPLT obtained in Sep 2015

Zones (m)	Qt res (B/D)	Production %	W O G
Inflow 0 (2808-2823)	-5546.38	-73.02	
Inflow 1 (2833-2851)	-2049.66	-26.98	

Interpretation:

The Memory Production Logging Tool (MPLT) provides advanced measurements of the downhole fluid flow properties and well conditions that will be monitored to evaluate production and injection performance**. [2]**

The MPLT in 2014 shows that the first interval (2808-2823), which represents the upper perforations, had a higher injection rate compared to the second interval (2833-2851), which represents the lower perforations. However, the MPLT recently showed a little improvement in injectivity on the lower perfs against the upper perfs compared to the previous MPLT.

NB: Post-treatment production expectations were obtained and confirmed with a long-term well test which was a confidential data of Schlumberger.

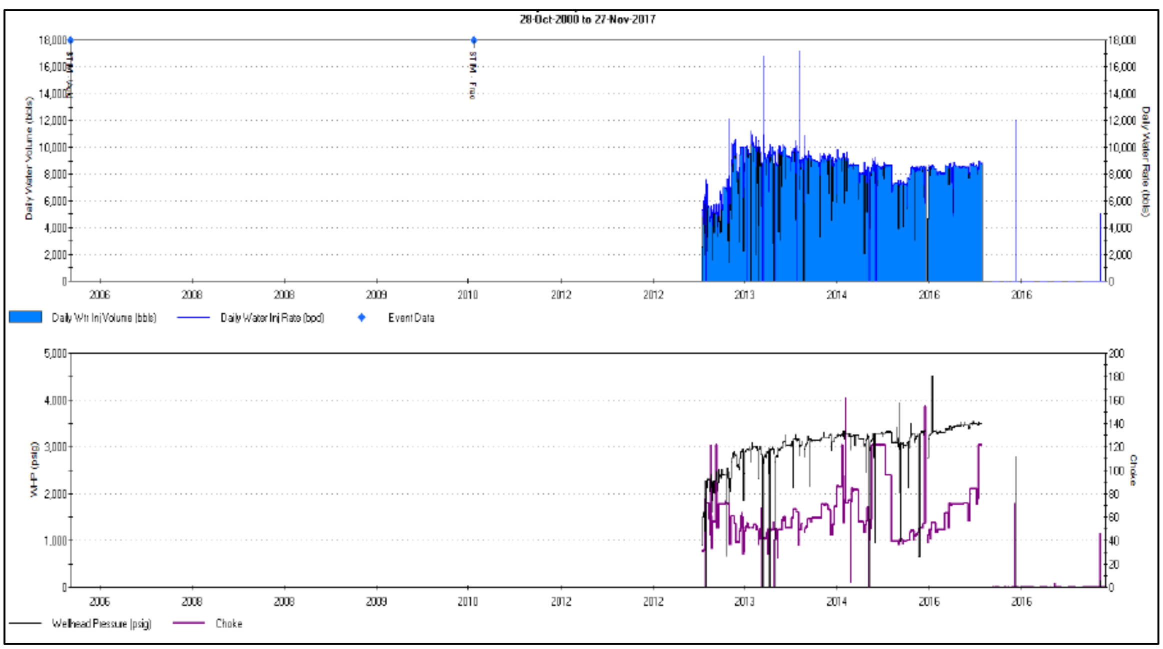


Fig IV- 5 : Production History Data of the well X

IV-4-Perforation history

Table IV- 5 Perforation history

Sand Sub Group	Perforated From (m)	Perforated To (m)	Perforation Date	Service Company	Gun Type	Gun OD	SPF	Charge Type	Comments
U1	2808.00	2817.00	01-Jul-2003						
U1	2808.00	2814.00	01-Nov-2002						
U1M1	2811.00	2823.00	12-Feb-2010	Baker		3.125	6		New Perf
U1M1	2833.00	2839.00	12-Feb-2010	Baker		3.125	6		New Perf
M1	2833.00	2840.00	26-Sep-2017	HESP	HSC, phasin	3.125	6		Reperf
U1M1	2839.00	2851.00	12-Feb-2010						
M1	2840.00	2852.00	23-Sep-2017	HESP	HSC, phasin	3.125	6		Reperf

IV-5-Well completion data:

Table IV- 6 : Well Completion Summary

Well Depth	3,597	m
Deviation	Vertical	-
Casing OD	7	in
Tubing OD	4 ½	in
Tubing Weight	12.6	Lb/ft
Bottom of Tubing	2432.26	m
Perforation	2808-2817 m 2811-2823 m 2833-2851 m	m

IV-5-1-Reservoir description:

The reservoir “A” is a laminated quartz sandstone with porosity of 14.7 %. It is a heterogeneous rock showing a large stress contrast between layers. Petro physical interpretation suggested two main target intervals U and M which were designed to be stimulated by the BBS diversion method.

Table IV- 7 : Field overview and Reservoir Properties

Well type	Water injector
Production	Oil
Reservoir name	A
Target formation	U sand, M sand
Rock type	Sandstone
Initial reservoir pressure	5600 Psi
Average porosity	14.7 %
Average permeability	176 mD
Average water saturation	0.28
Hydrocarbon pore volume (metres)	1.48
Field WOC (mtvdss)	-2596 FWL
Poisson's ratio	0.2-0.35
Young's Modulus	4-8 Mpsi
Bottom hole temperature at the mid perforation (BHST)	100 degC
Gross Thickness	84.4 m
Net Thickness	52.1 m

IV-6-Stress profile

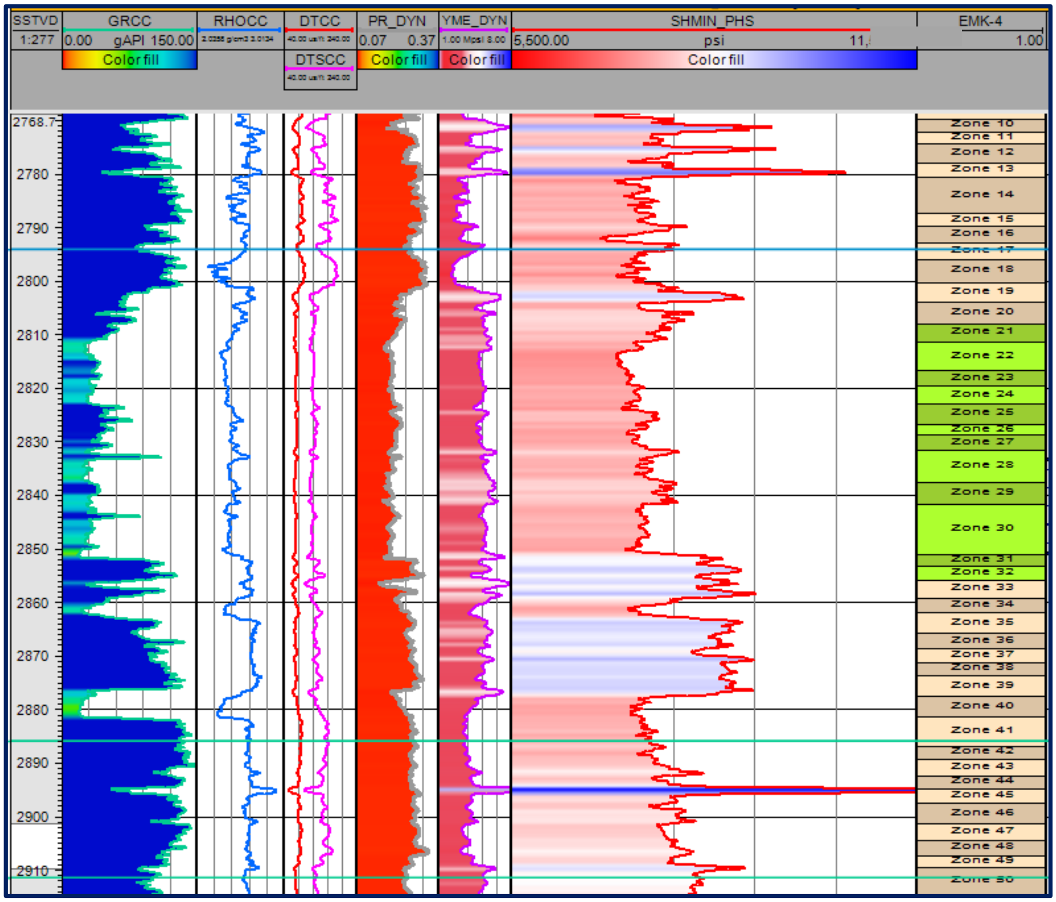


Figure IV- 8: Reservoir mechanical properties

Interpretation:

After filling the software with the coordinates of the well (pressure, strain...), Petrel generated the profiles of Young's modulus, Poisson ratio, and stress between the different layers (zones).

The figure below shows low stress in the upper zone and high stress in the lower zones; while the fractures was in the intervals from: **(2808-2823m and 2833-2851m).**

- **Petro physical Properties:**

The figure below shows the results of Gamma ray, porosity, Resistivity, saturation measurement for the different layers of the reservoir at reservoir depth. It shows high saturation in the previously fractured zones from **(2808-2823) and (2833-2851)** indicating the presence of the fracturing fluid in these zones.

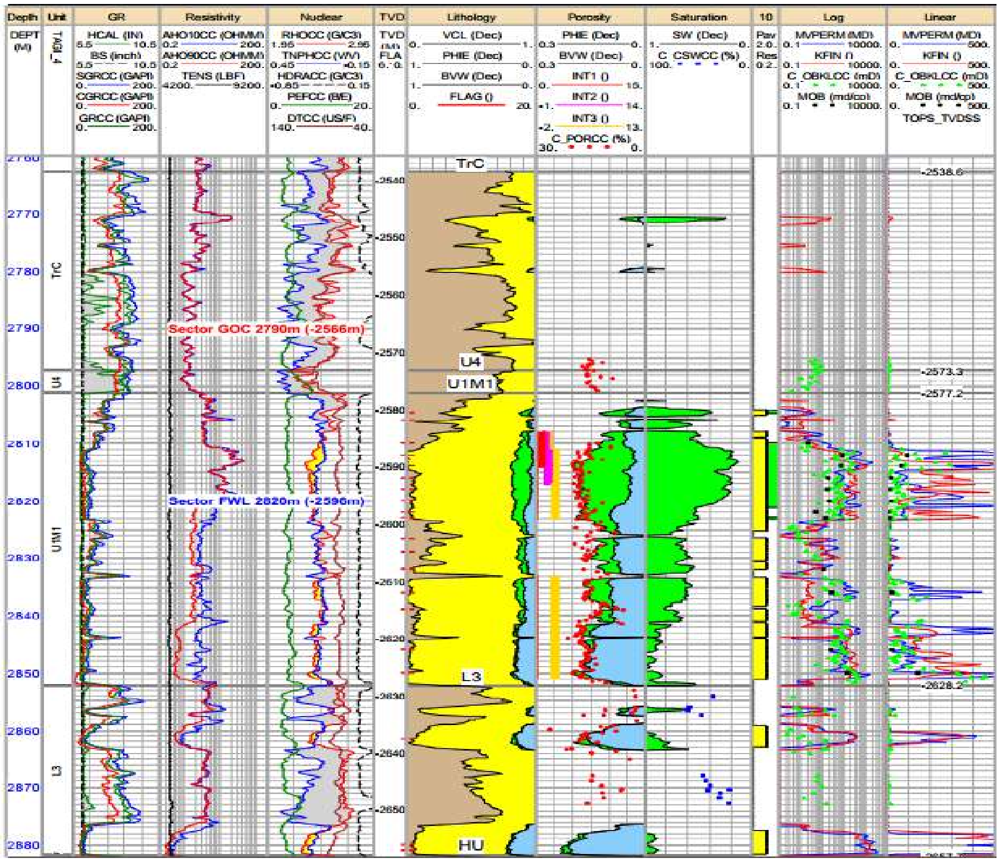


Figure IV- 9 : Reservoir Petro physical parameters

IV-7-Job preparation:

IV-7-1-Broadband Operational Requirement:

1- **Equipment:**

- Broadband blender
- Broadband pump
- Additional equipment (hose covers, flapper check valve, 2x2 valves, pressure gauge).

2- **Chemicals:**

- Degradable particles
- Fibers

3- **Personnel**

IV-7-2-Selection of the fracturing fluid:

The fracturing fluid must have specific proprieties. Therefore, it is necessary to select the appropriate fluid according to the operating conditions (BHST Temperature).

The fracturing fluid used in this operation is **YF135FlexD** at the BHST of 100°C (212 °F) to provide fluid stability and proppant carrying abilities. In addition, the BroadBand additives have been chosen based on the BHST and well conditions.

IV-7-2-1 Fluid QA/QC

The lab test will be performed using the wellsite X water source sampled from frac tanks; to measure and assure the quality of this fluid starting from water analysis; which is a broad description for various procedures used to analyze water source quality (means Common analyses identified in water samples include barium, bicarbonate, boron, calcium, carbonate, chloride, hydroxide, iron, magnesium, silica and sulfate should be controlled).

IV-7-2-2 Fluid System Composition

The fracturing fluid used in this treatment is a water-based fluid and its additives are shown in the tables below:

Table IV- 10 : Cross-linked Gel Composition

YF135FlexD Formulations	
Additive Function	**Concentration per 1000 gal**
Field Mixing Water	1000 gal
Bactericide	0.5 lb
Guar Gelling Agent	35 lb
Clay Stabilizer & Surfactant	3 gal
Cross linker Formulation	
Activator	2.2 gal
Cross linker	2.2 lb
Breakers	
EC-LT-Breaker	3 gal
Live-LT-Breaker	1 gal
BroadBand Additives	
Fiber	TBD
BroadBand Pill	TBD

IV-7-3-Selection of Proppant:

Proppant should be selected based on in-situ stress conditions as well as their availability.

The proppant used in our job are:

- **MaxPROP HSP:**

IV-7-3-1-Technical Data Sheet

Trade Name: MaxPROP HSP

Size: 20/40

Proppant Type: HSP

Manfacturing Date: 24/03/2018

Fig: Proppant MaxPROP HSP

Proprieties:

Table IV- 11 : MaxPROP HSP Proprieties

Absolute Density, g/cm³	3.51
Bulk Density, g/cm³	2.04
Roundness	0.80
Sphericity	0.90
GSD, In Size wt%	99.63
Acid solubility, %	5.17
Turbidity, NTU	65.30
Mass Absorption Coefficient, cm³/g	0.07560

IV-7-3-2-Conductivity and Permeability

Table IV- 12: MaxPROP HSP Conductivity and permeability Test

Stress, Psi	Conductivity, md-ft	Permeability, md
2000	5878	417
4000	5172	370
6000	4570	331
8000	3763	276
10000	2781	209
12000	1896	147
14000	1225	97

IV-7-3-3-Crush Test

Stress, Psi	Fines, wt%
15000	**7.16**

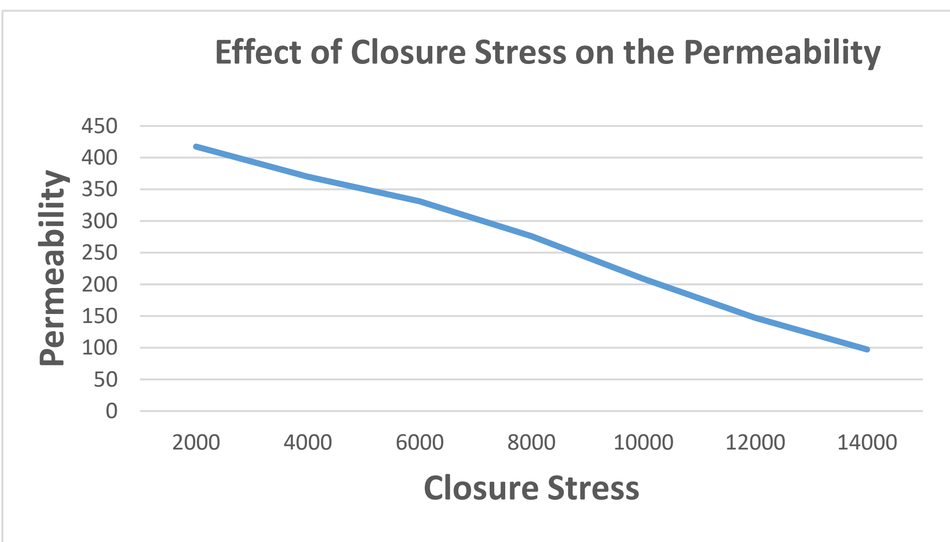


Fig IV- 6 : Effect of closure stress on the permeability of MaxPROP HSP

-SinterBall Bauxite:

- **Technical Data sheet:**

Trade Name: SinterBall Bauxite

Size: 16/30

Proppant Type: HSP

Manfacturing Date: 07/07/2017

Fig: Proppant SinterBall Bauxite

- **Proprieties:**

Table IV- 12 : SinterBall Bauxite HSP Proprieties

Absolute Density, g/cm^3	**3.63**
Bulk Density, g/cm^3	2.09
Roundness	0.80
Sphericity	0.90
GSD, In Size wt%	99.50
Acid solubility, %	4.98
Turbidity, NTU	110.00
Mass Absorption Coefficient, cm^3/g	0.07560

- **Conductivity and Permeability:**

Table IV- 13 : SinterBall Bauxite HSP conductivity and permeability

Stress, Psi	Conductivity, md-ft	Permeability, md
2000	15904	1084
4000	12217	849
6000	9040	642
8000	5199	381
10000	3939	296
12000	2527	196
14000	1621	129

Table IV- 14 : Effect of closure stress on the permeability of SinterBall Bauxite HSP

- **Crush Test:**

Stress, Psi	Fines, wt%
12500	**4.82**

IV-7-4-Broadband Pill mixing procedure:

The BBS Pill is prepared by batch mixing in the Broadband blender. The pill will be prepared not more than 1 to 2 hours before pumping the BroadBand.

- Pill mixing will start around 30 minutes before the end of stage.
- Both displacement tanks and the mixing tub will be filled with linear gel from PCM
- Fiber will be added to the mixing tub
- Particles to be added in the mix as per the designed concentration.

IV-7-5-BroadBand Sequence Rip up Layout:

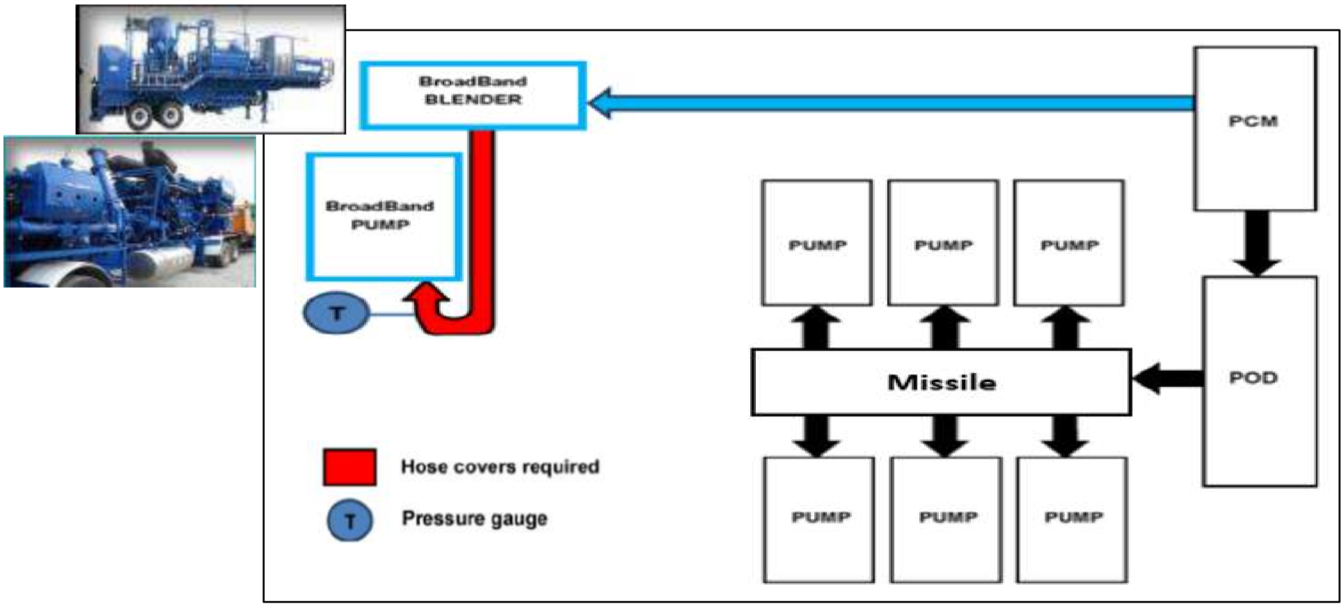


Fig IV- 7 : BroadBand Sequence Job Layout

NB: In addition to the conventional hydraulic fracturing equipment, there are extra equipment to pump the BBS. The linear gel comes from the hydration unit (PCM) and get mixed with the degradable particles and fiber in the Broadband blender, then pumped to the wellbore by a Broadband pump. The hose covers are required to pump the composite pill from the BroadBand blender to the pump.

IV-8-Job execution:

IV-8-1-Function test:

This test is required before starting any operation to test the state of the equipment.

IV-8-2-Prime up pumps:

Pump priming is a process by which air present in a pump and its suction line is removed by filling liquid. the pumps are filled with water from the blender while the BroadBand pump gets filled from the BroadBand blender to the open-top tank, and that liquid forces to remove the air, gas, or vapor present. This will reduce the risk of pumps damage and cavitation during start-up.

Pressure test:

performed to ensure the safety, reliability, and leak tightness of pressure systems (the pumps and the treating line). The process starts by Appling a pressure of 500 Psi on the line up for 3 minutes. If there is no leak, slowly increase the pressure gradually to the test pressure and finish it with a bleed-off from the line.

Fig IV- 8 : Broadband Sequence Job On-site

IV-8-3-Injection & Calibration Test:

In 06 July 2019, an injection breakdown was performed with treated water to identify the breakdown pressure which is considered as the upper bound of the closure.

During the DataFRAC, a total PAD volume of **20,000 gallons** of **YF135HTD** to be injected into the formation, then over flushed by additional **5bbl** to the displacement volume with linear gel.

The results obtained from this test include:

- Closure Pressure Pc.
- Instantaneous Shut-In Pressure (ISIP).
- Fluid efficiency.
- Last Pumping Pressure (LPP).
- Net Pressure.
- Frictions

The table below summarizes the pump schedule of DataFRAC steps with the total fluid volumes during the job:

Table IV- 15 : Designed Pump Schedule of DataFRAC & Injection

Step	Step Name	Slurry Volume (bbl)	Pump Rate (bbl/min)	Pump Time (min)	Fluid Name	Fluid Volume (gal)
1	Breakdown/Injection	182.8	15.0	12.2	Treated WATER	7678
2	Pre-Pad	23.8	15.0	1.6	WF130	1000
3	PAD	214.3	15.0	14.3	YF130HTD	9000
4	Flush	152.8	15.0	10.2	WF130	6418

Table IV- 16 : DataFRAC volume totals

Slurry (bbl)	Pump Time (min)	Clean Fluid (gal)	Proppant (lb)
567.0	42.2	23802	0

IV-8-3-1-Evolution of Surface and BHP during Injection & DataFRAC Test:

The Evolution curves of the surface and bottom hole pressures and rate are represented by the tables and the charts below**:**

Table IV- 17 : Stage Pressure & Rates of DataFRAC & Injection

Stage Pressures & Rates						
Step #	**Step Name**	**Average Slurry Rate (bbl/min)**	**Maximum Slurry Rate (bbl/min)**	**Average Treating Pressure (psi)**	**Maximum Treating Pressure (psi)**	**Minimum Treating Pressure (psi)**
1	BD/INJ	16.1	20.4	2270	2950	881
2	Pre-Pad	13.4	15.2	1933	2097	1133
3	PAD	15.1	15.3	2299	2803	2101
4	Flush	15.0	15.1	3008	3106	1339

IV-8-3-2-Injection test treatment Plot:

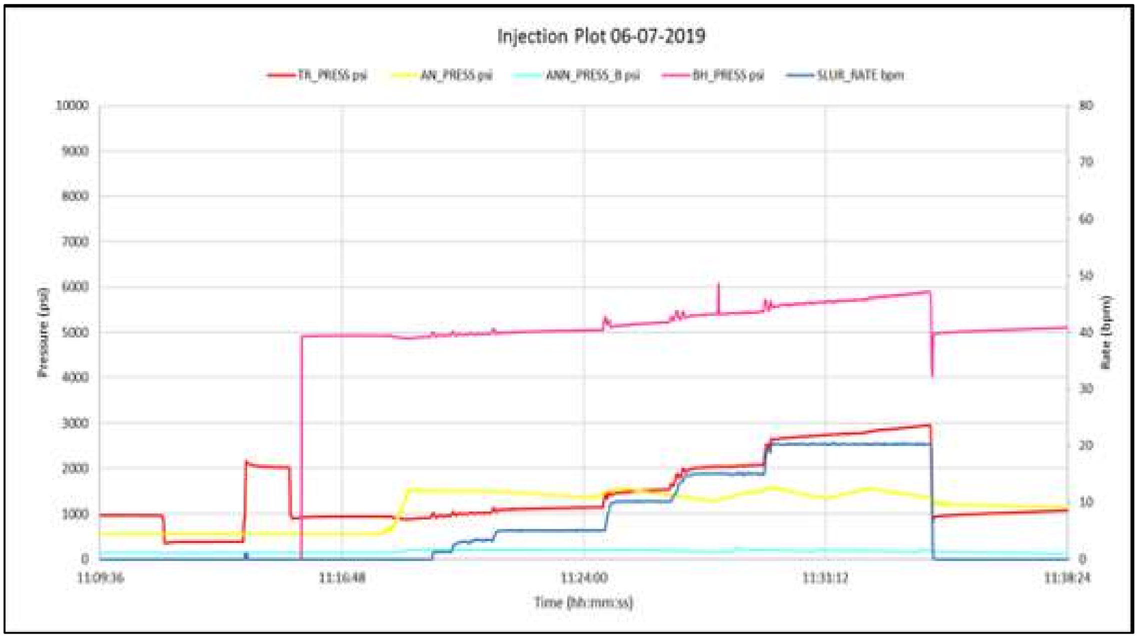


Fig IV- 9 : Injection Test Treatment Plot

Matching the parameters of main Frac without diagnostic injection data offers little value; The Analysis of the injection test gave these results:

Table IV- 18 : Injection Test Analysis

Pressure Parameter	Pressure Value (psi)
LPP (BH)*	5,880
ISIP (BH)	4,994
LPP (surface) Last Pumping Pressure	2,935
ISIP(Surface) (psi) (instantaneous Shut in Pressure)	938
Tubing Friction	1,111
NWB Friction -Treated Water @ 15 bpm	886
Total Friction-Treated Water @ 15 bpm	1,997

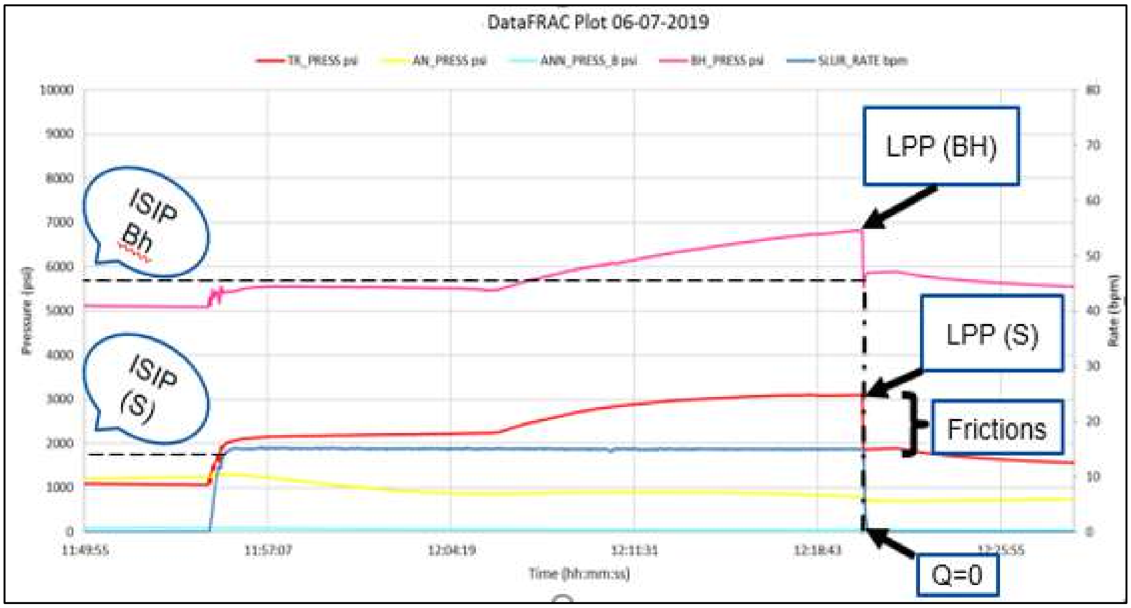


Fig IV- 10: DataFRAC treatment plot

IV-8-3-4-ISIP determination

Instantaneous Shut-In Pressure (ISIP) is defined as the pressure when the flow rate is equal to Zero (End pumping). In order to determine the ISIP, a vertical line is drawn from the point corresponding to the time of end pumping then the stabilized pressure drop line is extrapolated to the (Y-axis) corresponds to ISIP.

From this graph generated by the Petrel software we got:

ISIP (Bottom hole) = 5875 Psi

ISIP (Surface) = 1838 Psi

SLPP (Surface) = 3104 Psi

LPP (Bottom hole) = 6813 Psi

IV-8-3-5-Frictions determination

After the end of pumping, the pressure decreases due to frictions. This last is expressed by:

Frictions = LPP (surface) – ISIP (Surface)

Total Frictions = 3104 – 1838 = 1266 Psi

Table IV- 19 : DataFRAC analysis

Pressure Parameter	Pressure Value (psi)
LPP (BH)	6,813
ISIP (BH)	5,875
LPP (surface) Last Pumping Pressure	3,104
ISIP(Surface) (psi) (instantaneous Shut in Pressure)	1,838
Tubing Friction*	328
NWB Friction* WF130 @ 15 BPM	938
Total Friction WF130 @ 15 BPM	1,266

IV-8-3-6-G Function Analysis

G-function is a variable related to time. G-function (*x*-axis) versus BHP (*y*-axis) can be plotted to determine various fracture and formation properties such as fracture closure, fluid efficiency, effective permeability, and leak-off mechanism.

IV-8-3-7-Estimation of fracture closure pressure

The calculation of this essential parameter is done by the G-function plot below:

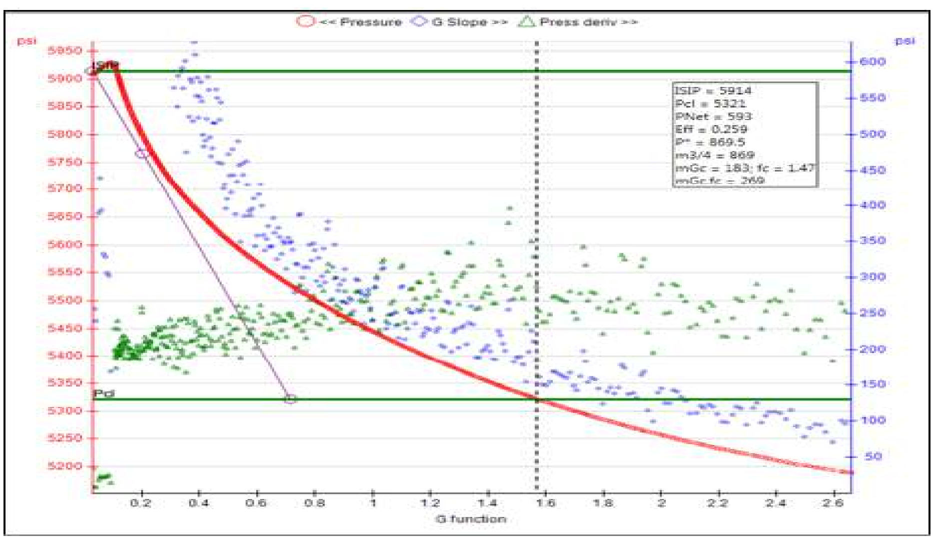


Fig IV- 10 : G-Function analysis.

The analysis of the G Function gave:

Table IV- 20 : G Function Analysis

Key Parameters	**Value**
ISIP	7176 psi
Closure Pressure	6207 psi
FG	0.64 psi/ Ft
Net Pressure	969 psi
Fluid efficiency	15.17%

IV-8-3-8-Net pressure determination

Another parameter can be determined from the G-Function Analysis which is the **pressure net (the additional pressure to keep the fractures open).**

Δp net= ISIP – Pc

Δp net = **969 Psi**

IV-8-3-9-Fracture gradient determination

$$\mathbf{FG} = \frac{ISIP\ (Surface) + Ph}{TVD\ Midperf}$$

$ISIP_{Surface}$ = **1838 Psi**

TVD MidPerf = **9239 ft**

Ph= Fluid SG * 8.34 * TVD MidPerf * 0.052

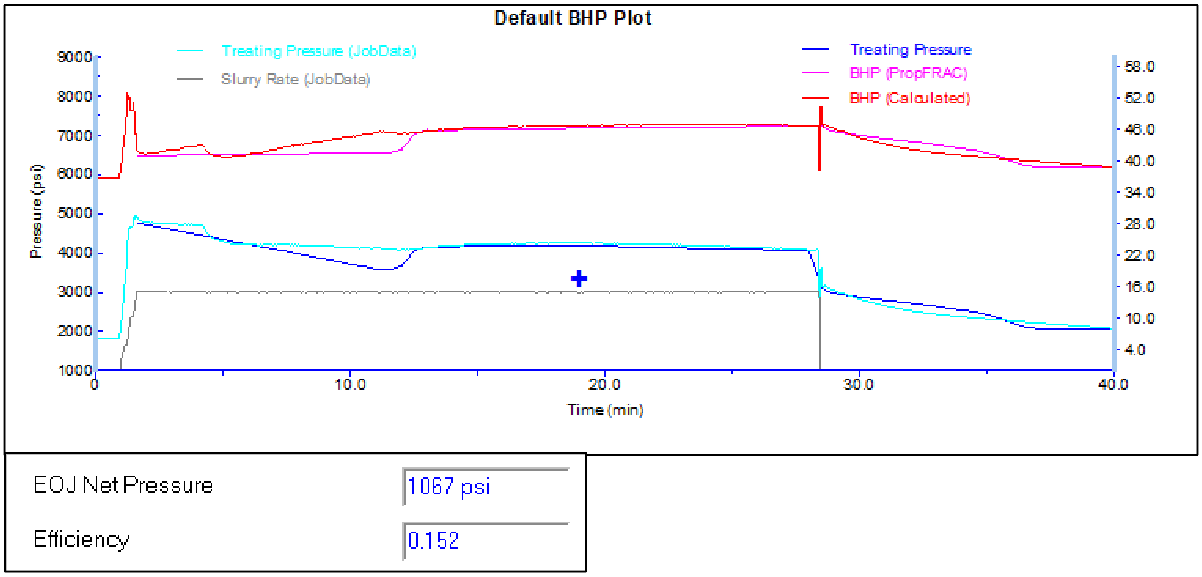
Ph= 1.01 * 8.34 * 9239* 0.052= **4047 Psi**

$$\mathbf{FG} = \frac{4047+1838}{9239} = \mathbf{0.64\ Psi/ft}$$

IV-8-3-10-DataFRAC Pressure match results:

After the DataFRAC, a pressure match was performed to calibrate the mechanical formation properties in order to re-design an optimized treatment. The Fracturing engineer aims to find a reservoir description that minimizes and calibrates the difference between the observed performance during the job and the simulator.

Fig IV- 11 : DataFRAC pressure match plot



IV-8-4-Main Frac treatment:

IV-8-4-1-Pre- Designed treatment schedule

The closest designed job scenario prepared before the main frac was a:

Total treatment size was **97 klbs** at a rate of **20 bpm** in order to stimulate the lower zone by isolating the upper zone using the BroadBand Sequence technique.

IV-8-4-2-Simulation results with PETREL:

IV-8-4-3-Petrel Software

Petrel is a software platform developed by Schlumberger and used in the exploration and production sector of the petroleum industry. It considers one of the simulation tools in the market.

Petrel software is used to:

- ✓ Determine the geometry of the fracture by simulation the data.
- ✓ Allow the user to interpret seismic data and perform well correlation.

- ✓ Build reservoir models.
- ✓ Produces maps and design development strategies to maximize reservoir exploitation.
- ✓ Visualize reservoir simulation results.

Simulation results with Petrel

The simulation with PETREL estimated the geometry of the fracture and many other parameters shown below:

Table IV- 21 : MainFRAC Simulation results of the Well X

Simulation Results	
Type of fluid	YF135FlexD-BBS
Total Proppant mass (lbs)	97k
Fracture gradient (Psi/ft)	0.60
Prop. Frac half length Xf (m)	28.84
EOJ Hyd Height at Well Hf (m)	43.07
Prop. width at well bore Wf (in)	0.40
Avg. Prop. Width (in)	0.40
Effective conductivity (md.ft)	14,729
Maximum surface pressure (Psi)	4,950
Pumping rate (bpm)	20
EOJ Net pressure (Psi)	562
Fluid efficiency (%)	23

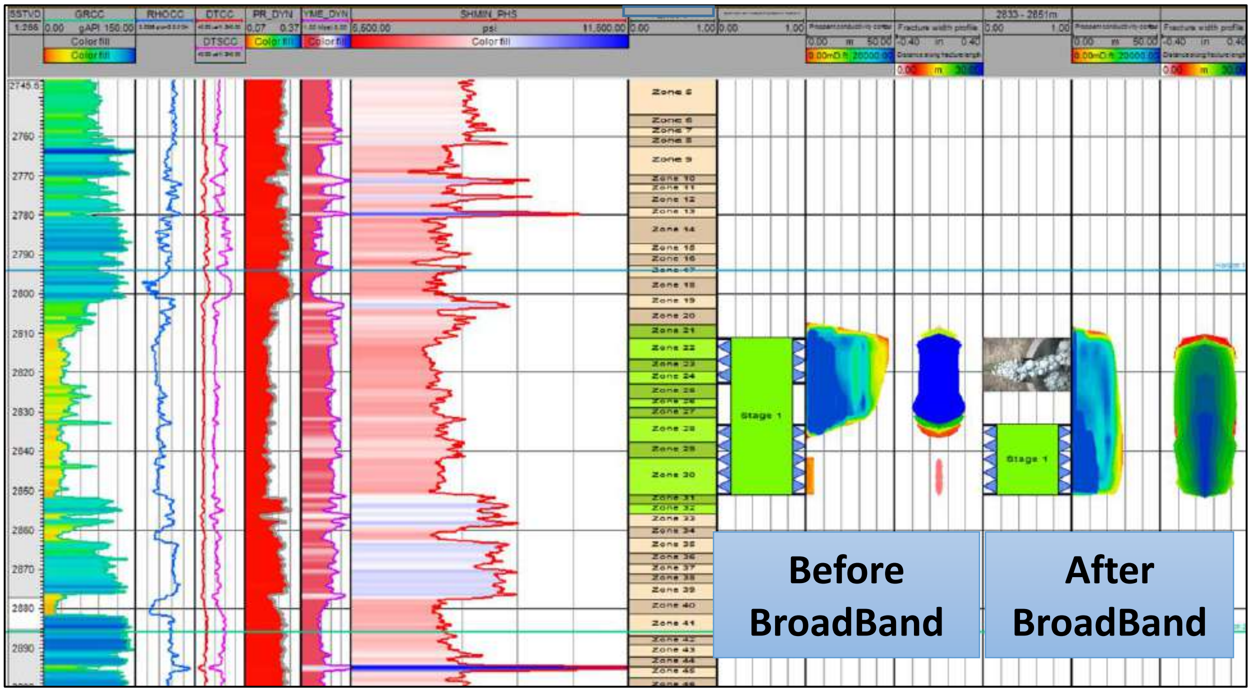


Fig IV- 12 : Simulation results of the well X before and after BBS

From the Figure:

Before the BroadBand Sequence Technology, the lower zone was not stimulated. As a result, the BBS was executed to increase contact with the reservoir and extend the lower zone's interval lengths to be stimulated. The simulator showed the initiation of new fractures in the lower zone; as a result, successful diversion of the treatment to the upper formation and enhance the productivity of the supported well.

IV-8-4-4-Measured pump schedule

BroadBand sequence Composite Pill was performed during this step to isolate the upper perforations and stimulate the lower zone of interest.

- Spacer to keep the Broadband composite pill integrity.
- BBS Pill to divert fluid to high stress.
- Pad to create the geometry of the fracture.
- Slurry to keep the fracture open.
- Flush to displace the slurry.

Table IV- 22 : Pump schedule of MainFRAC

Step	Step Name	Slurry volume (bbl)	Slurry rate (bbl/min)	Fluid Name	Fluid volume (gal)	Proppant Name	Max prop conc (PPA)	Prop conc (PPA)	Prop Mass (lb)
1	Pre-pad	92.3	22.3	WF130	3873		0.0	0.0	0
2	spacer	8.6	5.9	WF130	360		0.0	0.0	0
3	BBS pill	8.8	6.0	WF130	370		0.0	0.0	0
4	Spacer	10.4	6.0	WF130	438		0.0	0.0	0
5	Flush	140.3	6.0	WF130	5908		0.0	0.0	0
6	Pre-Pad	28.5	16.1	WF130	1186		0.0	0.0	0
7	Pad	472.1	25.1	WF130	19835		0.0	0.0	0
8	1.0 PPA	61.5	25.2	YF130HTD	2509	20/40 HSP	1.0	0.9	2317
9	2.0 PPA	63.4	25.2	YF130HTD	2506	20/40 HSP	2.1	1.9	4788
10	3.0 PPA	65.3	25.2	YF130HTD	2506	20/40 HSP	3.1	2.9	7304
11	4.0 PPA	67.3	25.2	YF130HTD	2505	20/40 HSP	4.1	3.9	9816
12	5.0 PPA	69.2	25.2	YF130HTD	2505	20/40 HSP	5.1	4.9	12324
13	6.0 PPA	71.2	25.2	YF130HTD	2505	20/40 HSP	6.1	5.9	14830
14	7.0 PPA	29.2	25.2	YF130HTD	1006	20/40 HSP	7.0	6.8	6817
15	8.0 PPA	30.0	25.2	YF130HTD	1004	20/40 HSP	8.1	7.8	7871
16	9.0 PPA	56.9	25.2	YF130HTD	1854	20/40 HSP	9.2	8.9	16459
17	10.0 PPA	31.7	24.3	YF130HTD	1006	16/30 HSP	10.8	9.7	9788
18	11.0 PPA	42.6	25.1	YF130HTD	1317	16/30 HSP	12.6	10.6	13930
19	Flush	144.5	22.9	WF130	6090		4.9	0.0	0

IV-8-5-Evolution of Surface and BHPs during Main Frac Test:

The Main Frac Plot is represented by the table and graph below during the job:

Table IV- 23 : Stages Pressures & Rates of the MainFRAC job

Step	Step Name	Average slurry rate (bbl/min)	Maximum slurry rate (bbl/min)	Average treating pressure (psi)	Maximum treating pressure (psi)	Minimum treating pressure
1	Pre-pad	22.3	25.3	3278	3657	944
2	Spacer	5.9	5.9	1906	2046	1712
3	BBS Pill	6.0	6.0	1761	1832	1726
4	Spacer	6.0	6.0	1772	1790	1735
5	Flush	6.0	6.5	2219	3877	1090
6	PrePad	16.1	25.8	3307	3965	1192
7	PAD	25.1	25.8	4062	4307	3839
8	1.0 PPA	25.2	25.2	4107	4193	4010
9	2.0 PPA	25.2	25.2	3796	4009	3650
10	3.0 PPA	25.2	25.2	3505	3639	3383
11	4.0 PPA	25.2	25.2	3252	3379	3136
12	5.0 PPA	25.2	25.2	3012	3136	2902
13	6.0 PPA	25.2	25.2	2826	2915	2749
14	7.0 PPA	25.2	25.2	2720	2750	2678
15	8.0 PPA	25.2	25.2	2674	2717	2622
16	9.0 PPA	25.2	25.2	2519	2644	2312
17	10.0 PPA	24.3	25.7	2408	2543	2218
18	11.0 PPA	25.1	26.0	2367	2433	2282
19	Flush	22.9	29.7	3339	4187	1901

Table IV- 24 : Measured Totals Volume

As Measured Totals			
Slurry(bbl)	**Pump Time**(min)	**Clean Fluid**(gal)	**Proppant**(lb)
1493.7	87.3	59282	106245

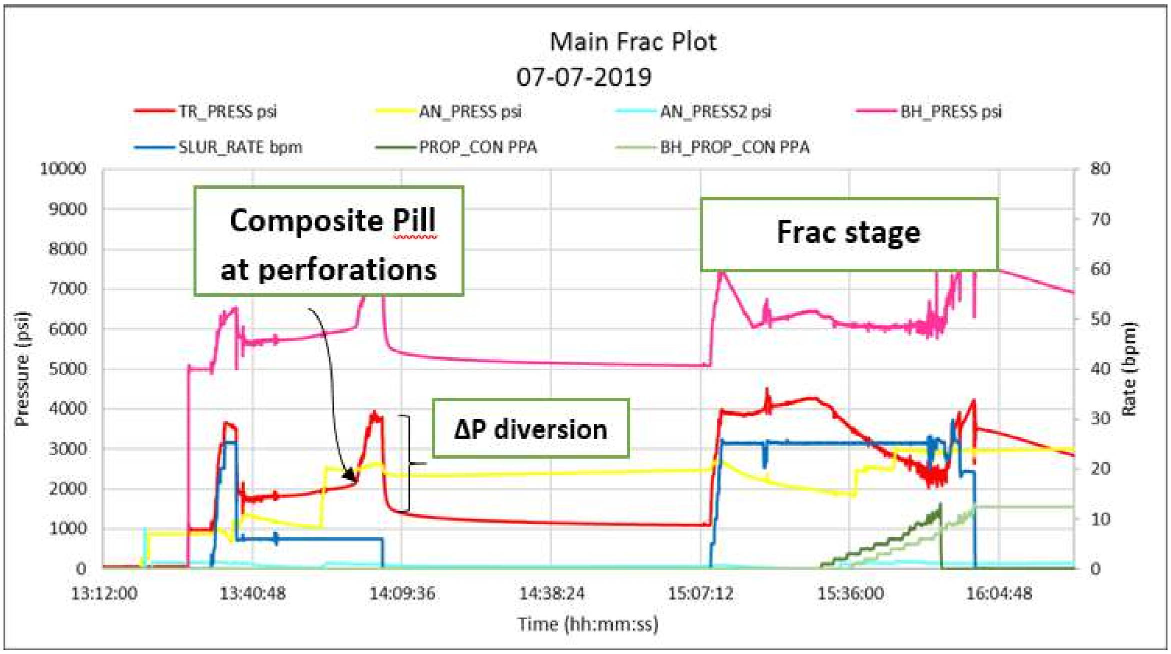


Fig IV- 13 : Main Frac Plot

Interpretation:

-Diagnostic Diversion:

The first fracture was successful in 2011; so to avoid re-stimulating the same section, a diverter composite pill was typically pumped at a reduced pump rate (6 Bpm) to allow better determination of the associated pressure increase, increasing the chances of bridging fractures which are wider than the particle size and affects fluid distribution in the clusters.

A pressure increase (ΔP diversion) was generated once the pill landed and plugged the perforation (squeezed). It is the pressure increase at the rate at which the composite pill is squeezed through the perforations, as shown in the plot above.

When the diversion pill had been pumped into the formation, the pumps were shut down for a short time to obtain an instantaneous shut-in pressure (ISIP) measurement for evaluation purposes and have better control when the pill entered the formation.

Then, it was decided to pump the frac stage with Pad at 25 Bpm to create the fracture of the upper zone, followed by pumping different concentrations of proppant at 25 Bpm until 11 PPA. Once the Proppant stage has been ended, the pumps were shut down to obtain a final ISIP.

IV-8-6-Effectiveness of the Broadband composite pill:

With Petrel Software, we obtained a simulation on fracture geometry shown in the figure
The efficiency of the BBS pill on the well X is studied below:

1- Interpret Diversion from ΔP diversion:

At first, the diverter is displaced in the wellbore (but not squeezed into the perforation) at **6 bpm. At 13:55,** the pressure started increasing to **3956 Psi;** this represents the complete plugging of perforations in the upper zone by the Broadband pill.

In other terms, this diverter systematically generated a significant ΔP diversion that is strongly influenced by the plugging efficiency of the composite pill, which is defined as the amount of diverter required to plug one perforation. However, it is impossible to only refer to ΔP diversion to say that the increase in pressure means a new fracture is initiated. This is why assessing diversion requires measuring ISIP.

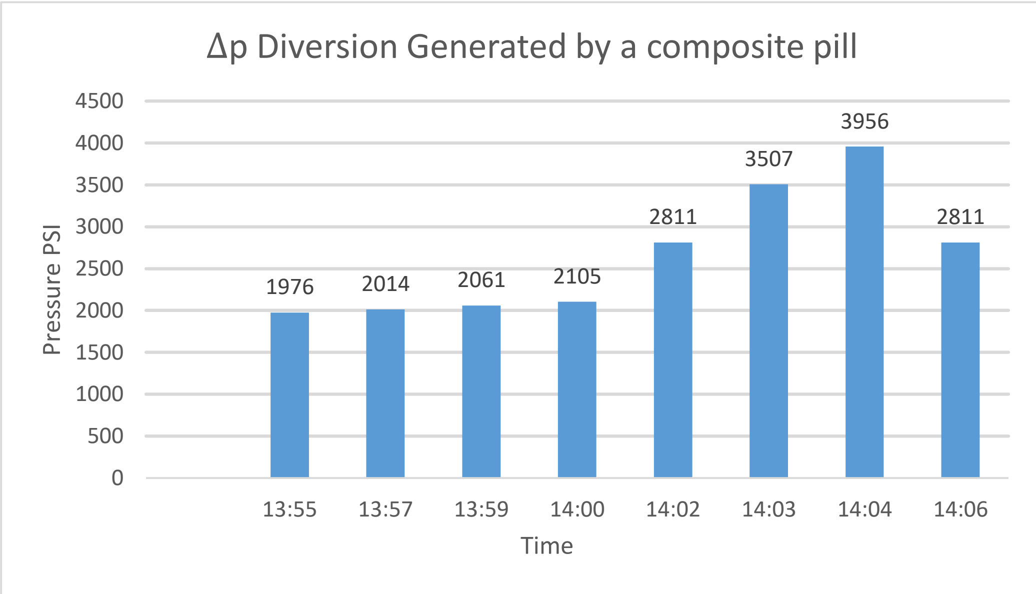


Fig IV- 14 : ΔP diversion generated by a composite pill.

2- Interpret Diversion from the Pressure ISIP:

Evaluation of the ISIP trend indicates that the shut-in pressures consistently increase throughout the treatment. The Plot below indicates the ISIP reading before and after the Pill.

Logically, perforation clusters located in areas with the lowest stress are likely to initiate first, so the Increasing ISIP values till 3100 Psi after the pill are taken evidence that these initial zones were successfully diverted which means a sufficient quantity of pill plugged the perforations of the upper zone; thus accelerating the diversion of treating fluid into the highest-stress area (lower zone) of the well (the initiation of new fractures).

ΔISIP 1, 2 > 0 → it reflects the initiation of new fractures in the highest stress zones (lower zone of interest). In Our case study from the plot below:

ΔISIP 1, 2 = 3100 – 1838 = 1262 >0

ΔISIP 1, 2 = 0 → means no new cluster is being stimulated, or the fluid has been diverted to regions with high fracture initiation pressure (upper zone).

ISIP 1: Instantaneous shut-in pressures at the beginning of the job (before diversion).

ISIP 2: Instantaneous shut-in pressures after diversion.

ΔISIP 1, 2: the difference between the ISIP 1 and ISIP 2.

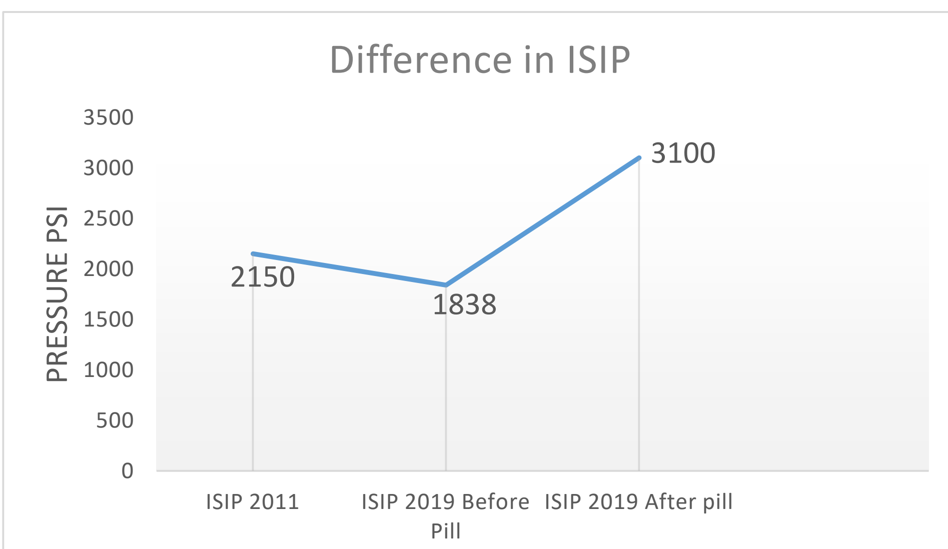


Fig IV- 15 : ISIP Evolution before and after the Pill.

IV-8-7-The success of Broadband fracturing job:

From the previous interpretations, we concluded that the success of the BBS pill was confirmed by the plugging of fractures and perforations of the upper zone and the diversion of the treating fluids into the highest stress zones of the wellbore. In addition, inconclusive pressure indications of bridging were observed when the composite pill was placed.

This was indicated by:

1- An increased ΔP diversion when the pill reaches and starts plugging the perforations.
2- An increased ISIP during the treatment indicates that the highest stress zone was fractured.

IV-8-7-1-Post Skin estimation

The formula of calculating the Skin in this case is:

$$S_f = 1.6 - \text{Ln}\left(\frac{Xf}{rw}\right)$$

From the table (Scenario); **X_f = 28.24 m** and from completion history: **rw= 6in = 0.1524 m**

$$Sf = 1.6 - \text{Ln}\left(\frac{28.24}{0.1524}\right)$$

Sf= -3.64

The negative value of the skin confirms the success of this operation for this well X.

IV-8-8-Economical Study

The nature of formations being stimulated mostly all around the world with its heterogeneities and complexity because of the rock properties and formation weaknesses as result, the fractures will grow to the path of least resistance and leave the rest of the well relatively unstimulated which is the lower zone in this case study.

In the well X, the challenge is to stimulate the lower intervals to improve drainage in those regions while the upper zone is opened and already fractured. Several different mechanical diversions have been proposed such as (CoilFRAC) but it had:

- long time compared to the chemical diversion.
- High cost and more operational risk.
- There is a high rate in the fracturing job performed on the well X due to the high velocity and consequently, a risk of erosion and failure of CoilFRAC.

BroadBand Sequence has been identified as the cheapest and safest technology. It provided **70%** saving in completion time and **55%** saving in operating cost compared to the mechanical options suggested. Furthermore, it provided **50%** extra gain compared to the conventional operations helping the client achieve a higher rate of return.

Conclusion

In this last chapter, we studied the case of the well X fractured with BroadBand Sequence technology. Moreover, the results obtained confirmed the success of this operation by achieving a successful diversion of the treatment to the upper formation, as a result; increasing the water injection rate and enhancing the productivity of the supported wells. Furthermore, implementing this technology showed clear evidence of the possibility of exploiting the under stimulated zones for conventional fracturing while reducing the extra cost and operation time.

Conclusion & Recommendations:

This thesis targeted the first application of the new Broadband Sequence Fracturing technique in Algeria performed by Schlumberger in 2019. The objective of this project was to determine and prove the efficiency of this technique used with conventional multi-stage hydraulic fracturing. Detailed feasibility was demonstrated in the case study On the well X, which was the right candidate for the BBS treatment from technical and economic aspects.

The implementation of this technology showed clear evidence of the possibility of exploiting the under stimulated zones for conventional fracturing compared to mechanical diverters. This makes the chemical diversion a practical, efficient, and cost-effective preferred solution for diversion stimulations.

Based on the sequenced cluster stimulation results that have been performed on the well X; the following can be concluded:

- The BroadBand sequence provides a viable and best solution alternative to stimulate inaccessible well intervals.
- BBS treatment assures successful treatment diversion by temporarily blocking the upper formation and diverting the treating fluids into the lower zone of interest while delivering production performance and an extra gain of up to 50% compared to offsets.
- BBS diverter pills improve operational efficiency in fractures and reduce job time.
- The success of the BBS job is confirmed by an increase in both ΔP diversion and ISIP between fracturing stages. In addition to a good conductivity and a negative skin.
- The steady increase in ISIP treatment indicates that post-diversion treatment stimulates higher-stressed zones.

Conclusion

Finally, the efficiency of the Broadband pill was confirmed by inconclusive pressure indications of bridging when the composite pill was placed in the lower perforation. The early diagnostic data from wells completed with this technology demonstrate that diversion was achieved and reservoir contact improved. In addition, the water injection rate of well X was increased and thus enhanced the productivity of the supported wells Y and Z.

However, implementing this technology will open several opportunities since there are many cases where the lower zones are not stimulated using conventional fracturing. And although the success of the first execution of the Broadband fracturing job in Algeria;

Will there be any other application and candidate wells for selective diversion using BBS fracturing treatment with other customers in Algeria?

Recommendations:

1- Run a temperature log right after the DataFRAC test to estimate the fracture height.
2- Clean out with Coiled Tubing is recommended before any hydraulic fracturing job.
3- The Broadband Sequence fracturing treatment is highly recommended in multistage fracturing wells where the lower zone needs a diversion stimulation while the upper zone is opened and already fractured.
4- The BBS diversion has been developed and successfully tested to ensure the even penetrations in all perforations and to guide the flow to the target area by diverting treating fluid to the under stimulated regions of the wellbore.
5- The use of the Broadband pill is required in the treatment. This will be an alternative solution for mechanical diversion tools such as Plug and Perf technique, by reducing the number of bridge plugs, completion cost and time will be minimized.

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Appendix

Depth m	String	Description	O.D. ins	I.D. ins	Drift ins	Length m
		Rig Floor - Tie-down Bolts Elevation (ENTP-162)				7.36
7.58		Vetco T / H 4.1/2" N / V Box x 4 7/8" Acme Box (Top End)	10.875	3.980	3.833	0.22
9.21		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.900	3.958	3.833	1.63
22.81		4.1/2" 12.6 lb/ft New Vam Joint # 258	4.900	3.958	3.833	13.60
36.42		4.1/2" 12.6 lb/ft New Vam Joint # 256	4.900	3.958	3.833	13.61
38.31		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.898	3.940	3.833	1.89
40.04		4.1/2" New Vam Flow Coupling	4.896	3.946	3.833	1.73
42.19		**4.1/2" TUSME SCSSV ('BR' Profile) Assy No:829**	5.983	3.813	3.813	2.15
43.93		4.1/2" New Vam Flow Coupling	4.897	3.948	3.833	1.74
45.81		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.899	3.941	3.833	1.88
2273.04		4 1/2" 12.6# lb/ft New Vam Tubing 181 Joints.	4.900	3.958	3.833	2227.23
		NOTE: 117 joints R-2 on top. (1116m) 90 joints R-3 tubing below. (1207m)				
2274.93		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.905	3.955	3.833	1.89
2276.67		4.1/2" New Vam Flow Coupling	4.905	3.955	3.833	1.74
2278.82		**Baker -Gas Lift Mandrel Assy No 895 (PSI Model)**	5.990	3.850	3.833	2.15
2280.56		4.1/2" New Vam Flow Coupling	4.895	3.950	3.833	1.74
2282.44		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.910	3.955	3.833	1.88
2296.03		4.1/2" 12.6 lb/ft New Vam **Joint # 8**	4.900	3.958	3.833	13.59
2309.61		4.1/2" 12.6 lb/ft New Vam **Joint # 7**	4.900	3.958	3.833	13.58
2311.50		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.938	3.935	3.833	1.89
2313.24		4.1/2" New Vam Flow Coupling	4.939	3.938	3.833	1.74
2315.41		**Baker - Gas Lift Mandrel Assy No 876 (PSI Model)**	5.975	3.860	3.833	2.17
2317.15		4.1/2" New Vam Flow Coupling	4.932	3.936	3.833	1.74
2319.03		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.941	3.940	3.833	1.88
2332.58		4.1/2" 12.6 lb/ft New Vam **Joints #6**	4.900	3.958	3.833	13.55
2345.60		4.1/2" 12.6 lb/ft New Vam **Joints # 5**	4.900	3.958	3.833	13.02
2347.48		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.905	3.950	3.833	1.88
2349.22		4.1/2" New Vam Flow Coupling	4.900	3.940	3.833	1.74
2349.68		**4.1/2" x 3.813" Baker 'BR' Nipple Assy No 871**	4.920	3.813	3.813	0.46
2351.42		4.1/2" New Vam Flow Coupling	4.900	3.937	3.833	1.74
2353.31		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.920	3.965	3.833	1.89
2366.76		4.1/2" 12.6 lb/ft New Vam **Joint # 4**	4.900	3.958	3.833	13.45
2368.64		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.915	3.945	3.833	1.88
2370.37		4.1/2" New Vam Flow Coupling	4.900	3.940	3.833	1.73
2371.14		KC-22 Anchor Seal Unit	5.500	3.880	3.833	0.77
2372.62		**Baker 'SABL-3' 85-47X38 Packer Assy No 876**	5.875	3.875	3.833	1.48
2374.21		5" New Vam Millout Extension	5.030	4.410	3.833	1.59
2374.50		5" New Vam x 4.1/2" 12.6 lb/ft New Vam Crossover	5.584	3.960	3.833	0.29
2376.24		4.1/2" New Vam Flow Coupling	4.910	3.925	3.833	1.74
2378.13		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.910	3.942	3.833	1.89
2391.71		4.1/2" 12.6 lb/ft New Vam **Joint # 3**	4.900	3.958	3.833	13.58
2405.29		4.1/2" 12.6 lb/ft New Vam **Joint # 2**	4.900	3.958	3.833	13.58
2407.18		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.910	3.960	3.833	1.89
2408.92		4.1/2" New Vam Flow Coupling	4.900	3.940	3.833	1.74
2409.38		**4.1/2" x 3.813" Baker 'BR' Nipple Assy No 869**	4.910	3.813	3.813	0.46
2411.12		4.1/2" New Vam Flow Coupling	4.905	3.945	3.833	1.74
2412.99		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.900	3.955	3.833	1.87
2426.58		4.1/2" 12.6 lb/ft New Vam **Joint # 1**	4.900	3.958	3.833	13.59
2428.46		4.1/2" 12.6 lb/ft New Vam Pup Joint	4.885	3.960	3.833	1.88
2430.20		4.1/2" New Vam Flow Coupling	4.890	3.950	3.833	1.74
2432.26		**4.1/2" Tie Back Seal Assy (No Seals) No 881**	5.730	3.970	3.833	2.06
2432.26						

Top of 4.1/2" Liner-2428 m Drillers Depth
Bottom of tie back - 1.70 m inside PBR
7" Casing Shoe @ 2729,5 m Drillers Depth
Radio Active Pip Tag @ 2786.83m

Upper Baker DIPS Assy # 851 @ 2788.70m

Perfs: 2808 – 2817 m AIT, using 2 ¾" Predator, 6 SPF, 60 Deg Phasing.
Re - Perfors : TAGI U/M Sand : Perfs: 2,811.0 m - 2,823.0 m m AIT, with 3 1/8"Predator HSC, 6 SPF, 60° Phasing
Add - Perfors : TAGI U/M Sand : Perfs: 2,833.0 m - 2,851.0 m m AIT, with 3 1/8"Predator HSC, 6 SPF, 60° Phasing
On 12/02/2010 Reperforate: 2,811.0 m - 2,823.0 m & 2,833.0 m - 2,851.0 m AIT, with 3 1/8"Predator HSC, 6 SPF, 60° Phasing

Lower Baker DIPS Assy # 850 @ 2914.76 m
HUD-3,567m RT S/L Depth.
Landing Collar @ 3566.93m Drillers Depth.
TD 3,597m Drillers Depth.

Figure: Well X Schematic (last updated on 22-07-2018)

	Step name	Pump rate (bbl/min)	Fluid name	Fluid volume (gal)	Proppant	Prop. conc (PPA)	Prop. mass (lb)	Slurry volume (bbl)	Pump time (min)
1	Pad	20.00	YF135FlexD	20000.00	None	0.00	0.00	476.19	23.81
2	1 PPA	20.00	YF135FlexD	2500.00	20/40 HSP Ceramic	1.00	2500.00	61.59	3.08
3	2 PPA	20.00	YF135FlexD	2500.00	20/40 HSP Ceramic	2.00	5000.00	63.66	3.18
4	3 PPA	20.00	YF135FlexD	2500.00	20/40 HSP Ceramic	3.00	7500.00	65.73	3.29
5	4 PPA	20.00	YF135FlexD	2500.00	20/40 HSP Ceramic	4.00	10000.00	67.79	3.39
6	5 PPA	20.00	YF135FlexD	2500.00	20/40 HSP Ceramic	5.00	12500.00	69.86	3.49
7	6 PPA	20.00	YF135FlexD	2500.00	20/40 HSP Ceramic	6.00	15000.00	71.93	3.60
8	7 PPA	20.00	YF135FlexD	1000.00	20/40 HSP Ceramic	7.00	7000.00	29.60	1.48
9	8 PPA	20.00	YF135FlexD	1000.00	20/40 HSP Ceramic	8.00	8000.00	30.43	1.52
10	9 PPA	20.00	YF135FlexD	1000.00	20/40 HSP Ceramic	9.00	9000.00	31.25	1.56
11	10 PPA	20.00	YF135FlexD	1000.00	16/30 HSP Ceramic	10.00	10000.00	31.67	1.58
12	11 PPA	20.00	YF135FlexD	1000.00	16/30 HSP Ceramic	11.00	11000.00	32.46	1.62
	Flush	20.00	WF135	2730.91	133.74	5.00		6.69	

	Fluid volume (gal)	Prop. mass (lb)	Slurry volume (bbl)	Pump time (min)
Total	40000.00	97499.99	1032.15	51.61

% Pad clean: 50.00 %

% Pad dirty: 46.00 %

Fig IV- 16 : Input Preliminary design schedule performed with Petrel

Hydraulic Geometry	
Max hydraulic frac half-length:	29.05 m
EOJ hydraulic frac half-length:	20.75 m
EOJ hydraulic height at well:	43.07 m
EOJ hydraulic width at well:	0.86 in
Propped/Conductivity	
Propped frac half-length:	28.84 m
Propped width at well:	0.40 in
Average propped width:	0.40 in
Effective conductivity:	14729.81 mD.ft
Average gel concentration:	690.64 lb/mgal
Effective FCD:	1557.97
Pressure/Efficiency	
EOJ net pressure:	562 psi
Efficiency:	23.00 %
Max surface pressure:	4950 psi
Estimated closure time:	17.81 min

Fig IV- 17 : Simulation Results with Petrel Software