SAND CONTROL TECHNIQUES IN OIL & GAS WELLS AND DESIGN OF GRAVEL PACK

Major Project By

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CERTIFICATE

This is to certify that the project work entitled "*Sand Control Techniques in Oil & Gas Wells and Design of Gravel Pack*" has been carried out by *Mehul Chopda & Vaibhav Suresh* ,in partial fulfillment of the requirements for the award of the degree of Bachelor of Technology in Applied Petroleum Engineering, University of Petroleum & Energy Studies, Dehradun, under the supervision and guidance of the undersigned, during the academic session 2010-2011.

The results obtained in the work have not been submitted to any other University or institute for the award of any other degree or diploma.

06/05/11

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(May 2011)

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ABSTRACT

Sand influx into producing wells causes a multitude of operating problems, many of which cannot be tolerated for safe and economic field operations. These problems include erosion of down hole tubulars and casing that can lead to the need for premature and costly workovers. It is clearly necessary to assure limiting the sand free production rates by the most cost effective method.

The day to day challenges in a well be it offshore or onshore makes the selection, implementation of sand completion a very critical operation. With a view of understanding critical parameters and their consequence in designing of the sand control set up for various cases, case studies are being examined.

With more and more experience boosted by growing technology, conventional gravel pack techniques are no longer used in field. Instead, we have advanced packing methods that help us in better sand control without affecting the deliverability of the well.

The results of the project are aimed at designing a gravel pack to efficiently overcoming the problem of sand production and still ensuring an efficient check on the sand production rates. The sizing, selection, placement and evaluation of a gravel pack completion and the related factors has been incorporated.

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1. INTRODUCTION

1.1.Project Background

Sand control is one of the oldest problems in the petroleum industry. Sand production erodes hardware, blocks tubular, creates downhole cavities (collapse of the formation), gets accumulated in the surface equipment. These effects can cause multitude of inconveniences , production losses, and serious well damage.

Various methods have been developed time to time to tackle these problems. These methods utilize one or more mechanisms like reducing drag forces, increasing formation strength etc. Commonly used sand control techniques are use of prepacked screens or slotted liner, plastic consolidation technique and Gravel pack. Of these, Gravel pack is the most commonly used technique.

In highly unconsolidated formations, the production of formation fluid will probably be associated with the production of formation sand. In some cases , small quantities of sand is produced with no significant adverse effect ,however in most of the cases, sand production leads to reduction in productivity and excessive maintenance to both downhole and surface equipment. Sufficient sand production may cause premature failure of the wellbore and the well equipment.

1.2.Aim of the Project

Sand production is one of the most recurring menace of the oil and gas industry. Even with the advent of technology, sand continues to trouble the operators leading to reduced productivity or expensive remedial actions all leading to uneconomical operation. The project aims at understanding various aspects of sand production and control in wells. The analysis and evaluation of a gravel pack is also done in order to establish the effectiveness of the job. Sand prediction and sand management are gaining in importance.

1.3.Project Objectives

As the value of non renewable hydrocarbon reserves and the cost of remedial work increase, a renewed emphasis is being placed on proper well completion techniques. Maximum reliability and productivity are essential. The objective is to understand what are the different causes of sand production and the techniques used in sand control and apply them in completing oil and gas wells in unconsolidated sandstone reservoirs with new methods and new technologies so as to maximize well productivity and prevents the well from damaging.

Various methods have been developed time to time to tackle this problem. These methods utilize one or more mechanisms like reducing drag forces, increasing formation strength etc. Commonly used sand control techniques are use of slotted liner or prepacked screens, plastic consolidation technique and Gravel pack. Of these, Gravel pack is the most commonly used technique. Designing of gravel pack depends on various factors. A technique used successfully in one well may be of no use in the other well. We have to consider whether it is an open hole or cased hole completion. The well bore diameter also plays a major role. The success of gravel pack depends on selection of proper gravel size, proper screen slot size and the placement of gravel at the proper location and then holding it in place for the life of the well. A major challenge faced by gravel pack technique is in its application in highly deviated and horizontal wells due to non-uniform packing of grains brought about by gravity and creation of voids. To overcome these challenges is the main objective of designing an efficient gravel pack.

1.4.Scope of the Project

The business of completing oil and gas wells in unconsolidated sand reservoirs is continuously changing with new challenges, new methods and new technologies. Sand when produced along with hydrocarbons and water from most wells, represents a costly problem for operators.

Solutions for controlling sand production are many ranging from stand alone screens to frac packs or more. Most often operators elect to employ various sand exclusion techniques when completing a well. In some areas, it may be more economical to employ sand management techniques in an attempt to delay or minimise expected problems such as formation erosion, sand fill, production interruptions or even eventual bore hole collapse.

1.5.Project Methodology

Considering the wide array of issues posed by the production of sand during oil and gas production preventive as well as corrective measures have become the state of the art affair. In the literature review to the report, an attempt has to be understand the various methods that can be employed to minimise sand in pumping lines and tubulars. The candidate selection of methods against operating parameters is also done.

Gravel pack continues to be the most reliable of methods for achieving sand control. An in depth analysis of gravel packing solutions is thereby followed with special ficus on the sizing and selection of gravel sizes to be used which is largely dependent on formation characteristics.

A case study to design a gravel packing for a 100 ft interval at the bottom of a well 10,500 ft total depth has been taken up to enhance the understanding of the process.

It is also important to evaluate the efficiency with which the sand control technique employed is reacting. Evaluation methods and thereafter numerical simulator methods have taken into consideration.

1.6.Project Limitations

There are several techniques for controlling sand production in oil and gas wells, these can range from simple restrictions on the speed of production and changes in operational practices, to the use of expensive equipment completion, all with the purpose of controlling the movement of particle formation to the wellhead. Most operations in oil and gas sector are economics driven. The limitations of economic criteria play a major role in determining the feasibility of an operation. However, the economic aspect of sand control has not been covered up in this project.

Successful gravel packed sand screen well completions require the knowledge of sand as well as gravel textural properties. These completion methods keep sand and fine from entering the well bore, so the long term production capacity of the well is ensured. Accuracy of results of formation sampling and related experiences have a direct effect on the efficiency if a design plan. Data has been carefully assumed at certain points due to the limitations of adherence to security policies. Also, the effectiveness of a completion job is governed by run time parameters like extent of filter cake removal, fluid interactions etc. which have not been considered in the scope of this project.

2.1. Introduction

Sand control is one of the oldest problems of the oilfield. Sand production erodes hardware, creates downhole cavities, blocks tubulars, and must be separated and disposed of on surface. Completion methods that allow sand prone reservoirs to be exploited often severely reduce production efficiency. The challenge is to complete wells to keep formation sand in place without unduly restricting productivity.

Sand problem is generally associated with shallow formations of Tertiary Age; but in some areas sand problems may be encountered to depths of 12000 feet or more. Unconsolidated reservoirs with permeability 0.5 to 8darcies are more susceptible to sand production, which may start during first flow or later when reservoir pressure has fallen or water breaks through.

It has been said that the best technique of sand control is "no sand control". This means that well completion practices are a critical consideration in zones where there is a tendency for sand production. Often sand production problems are created by less-than-adequate completion practices. Sometimes, even continuous sand production is even tolerated. But this option may lead to a well becoming seriously damaged, production being killed or surface equipment being disabled. What constitutes an acceptable level of sand production depends on operational constraints like resistance to erosion, separator capacity, ease of sand disposal and capability of artificial lift equipment to remove sand laden from fluid from the well.

In considering sand control or "formation solids" control, it is necessary to differentiate between load bearing solids and fine solids associated with the formation fluids which are not part of the mechanical structure of the formation.

2.2. Causes of Sand Production

Conditions that can cause sand production and the probable condition of the formation outside of the casing after the sand is produced can be determined by the factors that affect the beginning of sand production. These factors must determine the nature of the formation material and the forces that causes the formation structure to fail.

Sand grains are stabilized by or the strength of sandstone is controlled by:

- Amount and type of cementation material holding the individual sand grains together
- Frictional forces between grains
- Fluid pressures within the pores of the rock
- Capillary pressure forces

Shear failure of the sandstone will occur when the compressive strength of the rock is exceeded. The solid material produced from the well can consist of both formation fines(usually not considered part of the formation's mechanical framework) and the load bearing sands. The production of fines cannot normally be prevented and is actually beneficial, since if fines are free to move, and if they are not produced, they along with other fines moving in behind must eventually block the flow channel.

The critical factor in assessing the risk of sand production is whether or not the production of load bearing sands can be maintained below an acceptable level at anticipated flow rates and conditions of production.

The factors that influence the tendency of a well to produce sand are the:

- Degree of formation consolidation
- Reduction in pore pressure throughout the life of the well
- Production rate
- Reservoir fluid viscosity
- Increase of water production throughout the life of the well

In totally unconsolidated formations, sand production may be triggered during the first flow of formation fluid due to drag from the fluid or gas turbulence. Drag forces of formation fluid increases with higher flow rates and higher viscosity of the fluid. The fluid flow causes the sand grains to detach and carry them in to the perforations. High pressure differential also increases sanding.

In better cemented formations, sanding may be caused by incidents in well's productive life, for example, fluctuations in production rate, onset of water production, changes in gas/liquid ratio, reduced reservoir pressure.

Increase of water production severely limits the stability of the Sand Arch around a perforation resulting in initiation of sand production. Secondly, as the water cut increases the relative permeability to oil decreases. This results in increase in pressure differential being required to produce oil at the same rate which creates a greater shear force across the formation sand grains. This greater shear force is the reason of the instability of the Sand Arch.

Reduction in formation strength often associated with water production due to dissolving of cementing materials, or a reduction in capillary forces with increasing water saturation.

2.3. Sanding Mechanism

The mechanical failure of the unconsolidated rock surrounding a perforation is analogous to the failure of a loose material surrounding a tunnel in soft earth. After some sand is produced from around a perforation tunnel, an arch is formed that has the sufficient strength to support the weight of the surrounding material. Limited production of formation sand can be tolerated to allow an arch to develop, after which the production of formation sand ceases; however the stability of the arch is complicated by the fact that the state of stress surrounding the perforation is constantly changing due to changes in flow rate, reservoir pressure, producing water cut, etc.

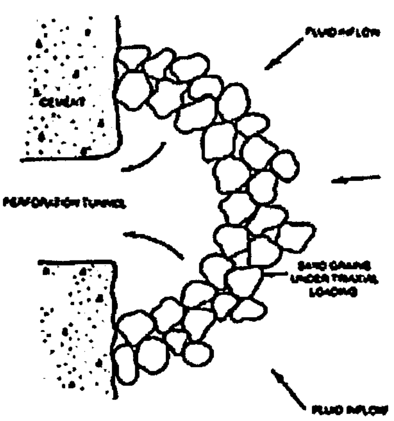

Fig.2.1. Geometry of a stable arch surrounding a perforation

2.4. Effects of sand production

The effects of sand production are always detrimental to the short or long term productivity of the well. While some wells routinely experience "manageable" sand production, these wells are the exception not the rule. The following are the effects:

- Accumulation in the surface equipment
- Accumulation downhole
- Erosion of downhole and surface and downhole equipment
- Collapse of the formation

2.4.1. Accumulation in Surface Equipment

If the production velocity is great enough to carry sand up the tubing, the sand may become trapped in the separator, heater treater, or production pipeline. Cleaning will be required for the efficient production of the well ,for which well has to be shut in and equipment has to be opened and the sand has to be manually removed. In addition to the clean out cost, the cost of deferred production must also be considered. Also the capacity of the separator to handle oil, gas and water is reduced, if it is partially filled with sand.

2.4.2. Accumulation Downhole

If the production velocity is not great enough to carry sand to the surface, the sand may bridge off in the tubing or fall and begin to fill the inside of the casing. Eventually, the producing interval may be completely covered with sand. In both the cases, the production rate declines until the well is completely filled with sand and the production ceases. Remedial operations or clean out techniques such as running a 'bailer' or running a 'coiled tubing' are used to clean the well and restore the production.

2.4.3. Erosion of Downhole and Surface Equipment.

In highly productive wells, fluids flowing at high velocity and carrying sand can produce excessive erosion of both downhole and surface equipment leading to frequent maintenance and replacement of the damaged equipment. It results in critical safety and environmental problems as well as deferred production.

2.4.4. Collapse of the Formation

Due to the void or the empty area developed behind the casing, if the rate of sand production is very large and continues for a sufficient period of time. This void continues to grow larger as more sand is produced. When this void becomes large enough the overlying shale or formation sand above the void may collapse into the void due to a lack of material to provide support. This will be especially true for formation sand with a high clay content or wide range of grain sizes.

WELL TYPE	EFFECT OF SAND
Gas wells	Unacceptable in most
HPHT	Unacceptable
Sub sea	Unacceptable in most
Horizontal wells	Depends on completion
Injection wells	Depends on completion
Oil wells	May be beneficial
Heavy oil	Usually beneficial
Damaged wells	Usually beneficial

Table 2.1. Sanding impact in various well environments

2.5. Sand Control Mechanism

- **Reducing Drag Forces**: This is one of the cheapest and easy method of sand control. It is always considered along with some other sand control method. It often is the natural outcome of a proper well completion.
- **Mechanical Method**: It is the oldest method and has a wide application. It is difficult to apply in multiple zones or small diameter wells.
- **Increasing Formation Strength**: This is done by consolidation of sand by some special resins/chemicals. It has specialized application- it leaves a full open well bore and can be used in small diameter casing.

2.5.1. Reduction of Drag Forces

Reducing drag or frictional forces is often the most effective and the simplest means of controlling sand. Fluid production rate causing sand movement must be considered as a rate-per- unit area of permeable formation.

Increasing Flow Area:-

The first thing to reduce drag force is to increase flow area. For a fixed production rate flow area can be increased by:

1. Providing clean large perforations through the existing production section.
2. Increasing perforation density.
3. Opening increased length of section.
4. Creating a conductive path some distance into the reservoir by means of a packed fracture.

Restricting Production Rate:-

Where reservoir consideration and market demand will support higher production rates, determining the maximum rate or the critical producing rate above which sand production becomes excessive is an important economic question.

2.6. Predicting Sanding Potential

By understanding reservoir, it may be possible to predict whether a well will produce fluids without producing sand or predicting that some type of sand control will be required. No technique has been found to be universally acceptable or completely accurate. Until better prediction techniques are available, the best way of determining the need for sand control in a particular well is to perform an extended production test with a conventional completion and observe if sand production occurs. Any reservoir data should be correlated with available open-hole logs and formation core sample data as they form the foundation for understanding any reservoir.

The indicators for predicting sanding potential are:

Formation strength

Determine the hardness of the formation rock (i.e., the rock's compressive strength). Studies shows that rock failed and began to produce sand when the drawdown pressure is 1.7 times the compressive strength. As an example, formation sand with a compressive strength of 1000 psi would not fail or begin to produce sand until the drawdown was about 1700 psi.

Sonic Log

The sonic log can be used as a way of addressing the sand production potential of wells. The sonic log records the time required for sound waves to travel through the formation in microseconds. The porosity is related to the sonic travel time. Short travel times, (for example, 50 microseconds) are indicative of low porosity and hard, dense rock; while long travel times (for example, 95 microseconds or higher) are associated with softer, lower density, higher porosity rock. A common technique used for determining if sand control is required in a given geologic area is to correlate incidences of sand production with the sonic log readings.

Formation Properties Log

Certain well logs such as the sonic, density and neutron devices are indicators of porosity and formation hardness. For a particular formation, a low density reading is indicative of a high porosity. The neutron logs are primarily an indicator of porosity. Additionally, formation properties log is being offered by several Wireline logging companies that performs a calculation using the results of the sonic, density, and neutron logs to determine the likelihood of whether a formation will or will not produce formation material at certain levels of pressure drawdown. This calculation identifies which intervals are stronger and which are weaker and more prone to produce formation material.

Porosity

Porosity is related to the degree of cementation present in a formation. It can be used as a guideline for the need for sand control. If the porosity of the formation is higher than 30%, the probability of a requirement for sand control is higher. Conversely, if the porosity is less than 20%, the need for sand control will probably be less. The porosity range amid 20% to 30% is where uncertainty usually exists. Porosity can be derived from well logs or laboratory core analysis.

Drawdown

The Pressure drawdown associated with production may be an indicator of potential formation sand production. No sand production may occur with low pressure drawdown around the well whereas excessive pressure drawdown can cause formation sand to be produced at unacceptable levels. The amount of pressure drawdown is normally associated with the permeability of the formation and the viscosity of the produced fluids. Fluids with low viscosity such as gas experience small drawdown pressures as opposed to the drawdown that would be associated with a 1,000 cp (highly viscous) fluid produced from the same interval. Hence, higher sand production is usually associated with viscous fluids.

Finite Elemental Analysis

It is the most sophisticated approach to understanding the reservoir and predicting sand production is the use of geomechanical numerical models developed to analyze fluid flow through the reservoir in relation to the formation strength. The effects of formation stress associated with fluid flow in the immediate region around the wellbore are concurrently computed with finite elemental analysis. This method is by far the most rigorous; it requires an accurate knowledge of the strength of the formation both in the elastic and the plastic regions where the formation begins to fail.

Multiphase Flow

The initiation of multiphase fluid flow, primarily oil and water, can also cause sand production. Many cases can be cited where wells produced sand free until water production began, but produced unacceptable amounts of formation sand subsequent to the onset of water production. The reasons for the increased sand production are caused by two primary phenomena: relative permeability effects and the movement of water-wet fines. Most formation fines are water wet and as a result are immobile when a hydrocarbon phase is the sole produced fluid because hydrocarbons occupy the majority of the pore space. On the other hand , when the water saturation is increased to the point that it also becomes mobile, the formation fines begin the move with the wetting phase (water) which creates localized plugging in the pore throats of the porous media. Moreover, if two-phase flow occurs, increase in pressure drawdown experienced as a consequence of relative permeability effects and increases the pressure drop around the well by as much as a factor of 4 to 5. The result of fines migration, plugging, and reduced relative permeability around the well increases the drawdown to the point that it may exceed the formation strength. The consequences may be excessive sand production.

2.7. Sand Management Techniques

The technique of Sand Management is an operating concept where traditional sand control means are not applied and production is managed through examining and control of well pressures, fluid rates and sand influx. In the recent past, Sand Management in conventional oil and gas production has been implemented on a large number of wells in the Gulf of Mexico and elsewhere. In all the cases it has proved to be feasible and has led to the generation of highly approving well skins because of the self-cleanup. These low skins have led to higher productivity indexes (PIs), and each of the wells where sand management has been successful has displayed increased oil or gas production rates. Moreover, expensive sand control devices are avoided and the viability of possible future well interventions is guaranteed. Sand Management leads to low cost solutions, but it also involves high risk management.

Effective Risk management requires a reliable analysis of the Life cycle of sand, with predicting formation conditions conducive to sanding, and ending with ultimate disposal of the produced material at the surface. These techniques are based on:

- Extensive field data acquisition campaign
- Theoretical Modeling of the involved physical processes
- Active Monitoring and follow-up on production data
- Well testing to optimize production rates

These techniques will help the production engineer in:

- Optimization of completion design
- Assessing Risk throughout the well's production life.

Phases in the Life Cycle of sand include sand transport, sand detachment, sand erosion and surface sand deposition.

2.8. Well Management Optimization with Sanding Risks

With a reliable Sand Management analysis it is possible to define safe limits within which production rates should be kept. This information allows designing and managing the well so as to extend these limits and even increase well productivity. Some examples are as follows:

2.8.1. Rate Exclusion

Reduction in production rates will reduce the drag forces and drawdown to provide reduced risk of sand production. The procedure is to slowly increase rate until sand production begins to increase, and then, successively reduce flow rate until the sand production declines to an acceptable level. The objective is to establish a maximum flow rate in conjunction with the stable-arch concept.

2.8.2. Selective Perforating Practices

Once the characteristics of the formation are known, perforation strategies can be evaluated. If possible, only intervals which are of high strength can be perforated. For high rate wells, this will require a high shot density to prevent additional pressure drop and associated sand production. On the other hand, high density can lead to perforation interaction, which also promotes sand production.

2.8.3. Perforating for Sand Prevention

Space the Perforation far enough apart to prevent failed zone interactions. It is being suggested the best technique to limit sand production and also the technique to minimize entry hole diameter. Phasing of the perforation can be optimized to provide the least amount of interaction with greater shot density. Also, perforating into breakouts should be avoided.

2.8.4. Oriented Perforating

It has been shown in the past from laboratory tests that the mechanical stability of perforation cavities depends on perforation direction relative to the in situ stress field. This has led to the idea of oriented perforating so that shear stresses acting at the wall of perforation cavities can be minimized.

2.9. Completion Options

When considering wells for sand control option, the issue of productivity is especially important. Gravel-Packed wells are particularly sensitive to the problems of poor productivity if improper completion techniques are used. But if the techniques are best implemented it can result in an acceptable productivity from gravel-packed and nongravel-packed wells.

Once it has been established that at planned production rate, sand is likely to be produced, the next step is to choose a completion strategy to limit sanding. A first option is to treat the well with 'tender loving care', minimizing shock to the reservoir by changing drawdown and production rate slowly and in small increment. Production rate may be reduced to ensure that drawdown is below the point at which the formation grains become detached.

Sand control methods have become more varied in recent years. Since the early application of gravel packing, there have been several new processes introduced with varying results. Many of these innovations were introduced in the U.S. Gulf Coast Area, North Sea because, historically, gravel packing provided poor results in formation sands there. Results from these new methods varied quickly, so the industry moved rapidly from one process to another, but most often returned to gravel packing. In recent years, there have been continuous improvements in gravel pack completions. Therefore, gravel packing has maintained industry dominance and many alternative methods have been abandoned or their use diminished greatly.

Factors considered in selection and design of a particular technique in a particular field or well are listed below:

- Initial cost of sand control
- Expected reliability
- Effect on Productivity
- Completion repair cost
- Formation sand quality
- Presence of thin multiple, thin productive sections
- Exclusion of inter-bedded gas or water
- Presence of undesirable shale streaks
- Level of reservoir pressure depletion
- History of sand production

Commonly used sand control techniques used in petroleum industry are:-

- Chemical consolidation
- Mechanical control

    1. Screens(including expandable screens)
    2. Slotted liners
    3. Special filters

- Inside casing gravel packing
- Open-hole gravel packing
- Propped fracturing including frac packing, gas propellant fracturing and use of resin coated sand
- Selective and oriented perforating
- Production rate control

In the following section, we shall take up each of the mentioned sand control methods in detail and focus on the underlying working principles and mechanisms.

2.9.1. Chemical Consolidation

Sometimes chemical techniques are employed for sand control. These processes are designed such that it produces chemical reaction with the formation sand for the purpose of restraining its mobility. Two techniques are used, resin consolidation and steam consolidation.

2.9.1.1. Resin consolidation

This technique involves injecting chemicals (resins) into the unconsolidated formation to provide grain to grain cementation. The basic objective of plastic sand consolidation is to increase the strength of the formation sand around the well bore such that sand grains are not dislodged by the drag forces of the flowing fluids at the desired production rate.

Resin, attracted to the sand contacts, hardens to form a consolidated mass having a compressive strength of the order of 3000 psi. Subsequent flushes displaces excess resins material further into the formation to clear the pore spaces between grains, allowing the best possible permeability for oil and gas to flow. Resin consolidation system helps control sand without the use of mechanical screening devices. This system is ideal for dual-zone completion; these systems permit access to lower zone without disturbing the upper zone.

Advantages

Properly applied under the right conditions resin consolidation has inherent advantages:

- Suitable for through tubing application.
- Applicable in small diameter casing.
- Leaves full open well bore.
- Suitable for multi reservoir completions.
- Can be applied readily in abnormal pressure wells
- Works well in fine sands difficult to control with gravel packing

Problems

- The basic problem is to increase the strength of the formation uniformly through the completion zone without excessive reduction in permeability.
- Treatments are generally more expensive on a per foot basis than gravel pack
- Uniform coverage of each perforation is a critical requirement. Fingering of one fluid through another must be controlled by low injection rates, and by designing each fluid so that its viscosity is similar or slightly greater than the fluid it displaces.
- Low fluid viscosities are desirable so that reasonable injection can be obtained at low injection pressures.
- Most materials used are toxic and highly inflammable.
- Interval length is limited to 15 ft at a time
- Resins are very expensive.

In field applications, it is difficult to consistently obtain successful plastic treatments. Not only is proper placement of the materials critical to success, but the material must be injected into all perforations in the correct sequence: first the preflush and conditioning fluids, then resin, overflushes and activating agents.

Types of Resin Consolidation Systems:

1. **Phase separation system.**
2. **Overflush system**

1. **Phase separation system:**

It consists of 15 to 25 % active resin which, properly attracted to grain contact points, hardens to form the consolidation. The remaining inert material fills the center portion of the pore space to insure that permeability is retained. Curing agent or catalyst is added at the surface with the amount added depends on formation temperature. Very accurate control of displacement is required to place the resin through the perforations, but without over displacement.

2. **Overflush system:**

In an Overflush system the resin solution contains a high percentage of active material. Thus, in the initial step, active resin occupies most of the pore space. Permeability must be re-established by displacing further into the formation all but residual resin saturation. This, with proper sand wettability, remains at the sand grain contacts. Curing agent is usually contained in the Overflush fluid, but can be added to the initial resin solution. Accurate control of displacement is not as critical but all sections not overflushed will be plugged.

Sands containing more than about 10 % clay present a problem to phase-separation systems, since these systems have only a small percentage of active material in the resin solution. The much higher surface area of dirty sands robs the sand-grain contacts and reduces the strength of consolidation. Most commercially available system employs phenolic, furan or epoxy resins.

2.9.1.2. Steam consolidation

This technique of using hot alkaline/steam sand-consolidation to complete wells is based on the geochemical bonding. In this method, unconsolidated formation sand grains are bonded with a lattice of primarily high-temperature, complex synthetic silicate cements and possibly other lower-temperature precipitates, such as silica cements and carbonate scales. By high-temperature, high-alkaline pH steam condensate, complex silicate cements and other mineral precipitates are created. This condensate preferentially dissolves sand grains. The injected fluids rapidly lose heat to the formation and various cement precipitates with changes in temperature, alkalinity and contact time.

In addition, this method significantly lowers drilling and completion costs. It improves fluid entry, provides a low cost means of eliminating unwanted completion intervals, and provides flexibility to use wells interchangeably as producers or injectors.

2.9.2. Mechanical control

Slotted pipes, screens and prepacked screens offer the lowest-cost downhole filtering. Slotted liners have the largest holes, wire wrapped screens have smaller openings, while screen prepacked with resin-coated sand offer the finest filtering. Each part can be run as part of the completion string and are particularly suited for high angle wells, which cannot be easily completed otherwise.

Slots are typically sized to cause bridging of the largest 10 % of the formation particles, filling the annulus between the screen and the casing, or open hole, with formation sand creating a filter for remaining particles. However, production can be restricted by this relatively low-permeability, sand-packed annulus. Also, production of even a small amount of fines can plug many screens, particularly prepacked screens, within a few hours of installation.

Slotted liners and screens are best suited to formations that are friable rather than completely unconsolidated. They are used mostly in California, USA and some Gulf of Mexico, USA fields where permeabilities are greater than 1 Darcy. Slotted liners and prepacked screens are used in only about 5 % of sand-control completion.

Slotted liners are used in gravel packed completions to prevent the production of gravel pack sand or can be used in stand-alone service when the formation grain size is large. While the slotted liners are usually less costly than wire-wrapped screens, they have a smaller inflow area and experience higher pressure drops during production. Slotted liners also plug more readily than screens and are used where well productivity is low and economics cannot support the use of screens. The single slot staggered pattern is generally preferred because a greater portion of the original strength of the pipe is preserved. The staggered pattern also gives a more uniform distribution of slots over the surface area of the pipe. The single slot staggered pattern is slotted with an even number of rows around the pipe.

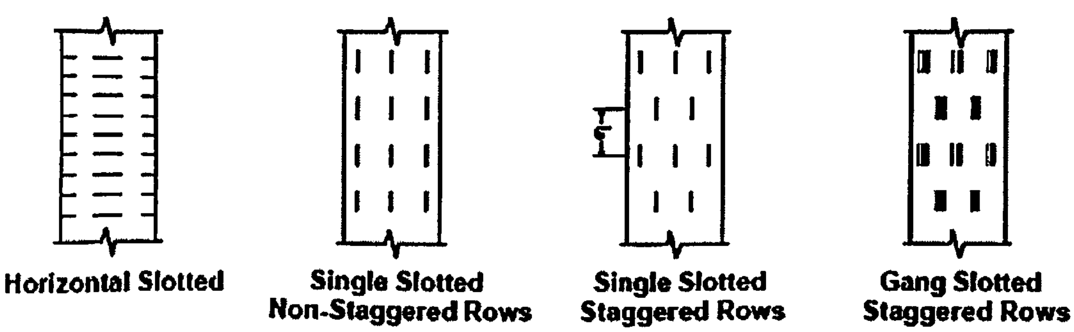

Fig 2.2. Slotted liner geometry

In some cases slotted liners or screens are used alone to control the formation sand in open-hole completions. These exclusion devices actually function as filters. Unless the formation, sand is clean with a large grain size and is well-sorted, this type of completion may have an unacceptably short producing life before the slotted liner or screen plugs. Consequently, a hot spot may develop on the interface between the formation and screen causing potential erosion and screen failure.

Opening size (in.)	Opening size (micron)	Particle size required to bridge(μm)
0.020	508.0	169.3
0.012	304.8	101.6
0.008	203.2	67.7

Table 2.2. opening sizes and bridging particle requirements for slotted liners and screens.

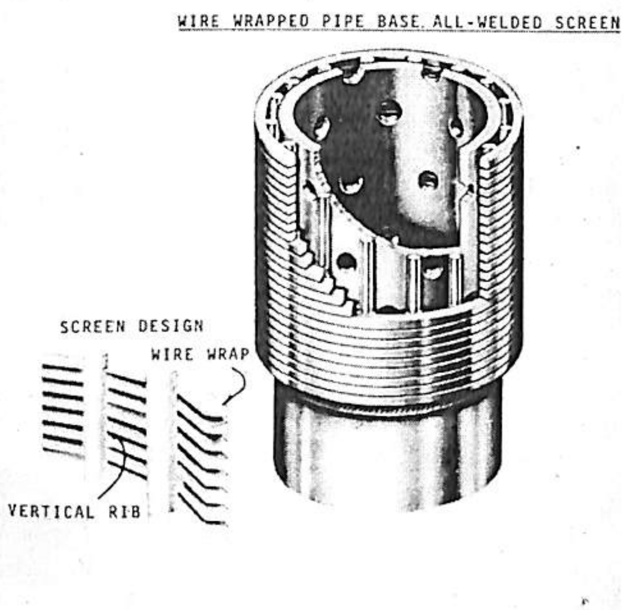

Fig2.3. All welded, wire wrapped screen on base pipe

Various types of screens are used: wire wrapped, pre-packed, premium screens.

Wire wrapped screens offer an alternative for retaining the gravel in an annular ring between the screen and the formation. The advantage of a wire-wrapped screen over a slotted liner is substantially more inflow area as Figure illustrates.

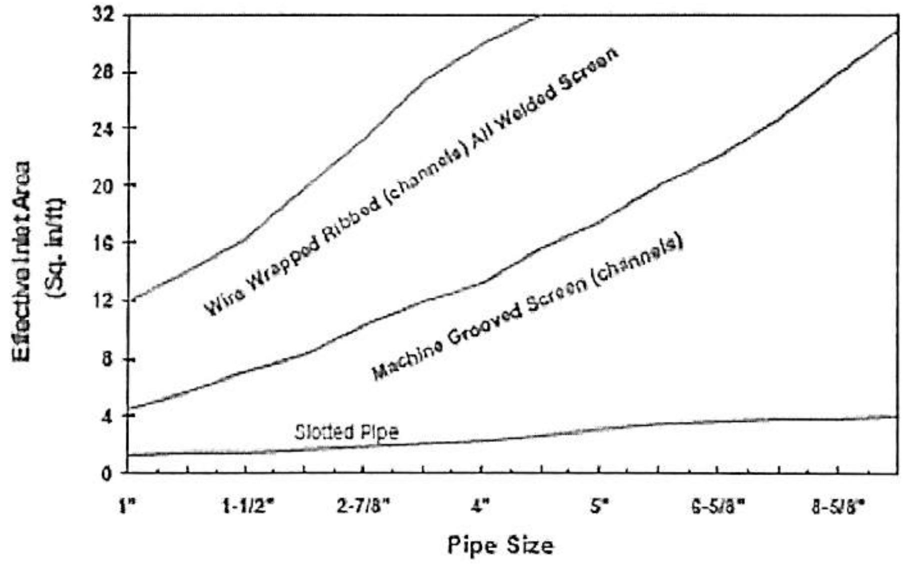

Fig.2.4. Comparison of effective inlet areas

The screen consists of an outer jacket which is fabricated on special wrapping machines that is similar to a lathe. The wire wrap is simultaneously wrapped and welded to longitudinal rods to form a single helical slot. The jacket is then placed over and welded at each end to a supporting pipe base to provide structural support.

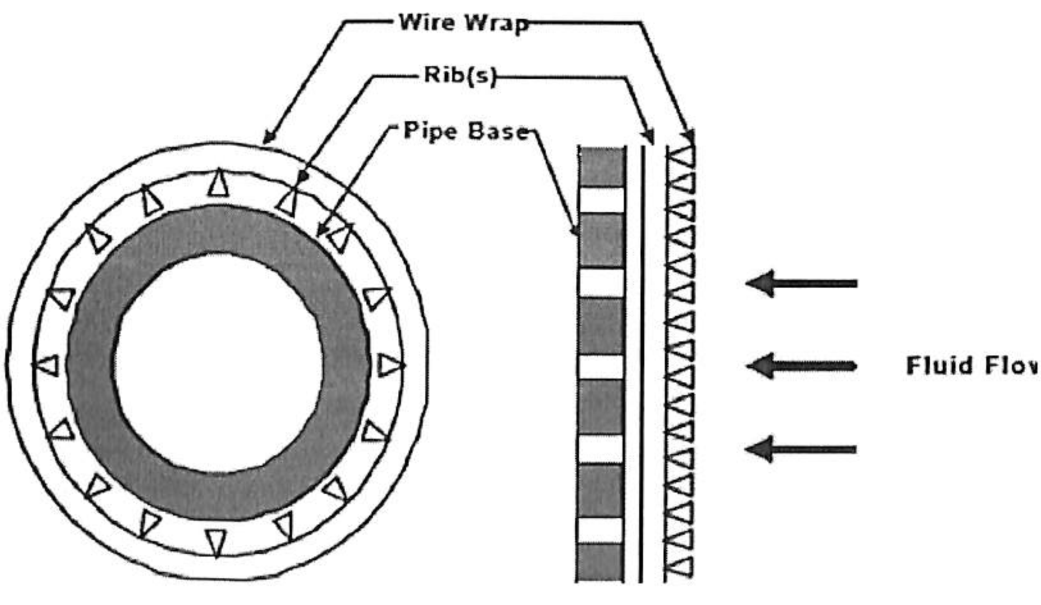

Fig.2.5. Construction schematic of wire wrapped screen

These screens are more erosion and corrosion resistant than slotted liners.

2.9.3. Resin-Coated Gravel without Screen

Resin-coated gravel may be used as a downhole filter without installing a screen. The gravel is circulated into position as slurry, either inside casing or open hole and then squeezed to form a plug across the production zone. The bottomhole temperature of the well or injection of steam causes the resin to cure into a consolidated pack. Adjacent particles are bonded together by the resin, strengthening the pack

In cased hole, the plug may be completely drilled out to leave gravel filled perforations. Alternatively, the pack may be drilled out to the top of the perforations/open hole so that the hydrocarbons are produced through the pack. A narrow hole can be drilled through the pack to provide a conduit to reduce drawdown through the pack. This can be achieved using coiled tubing if a conventional rig is not available.

Resin-coated gravel has the advantage of needing no special hardware. But the pack creates significant additional drawdown that may affect the productivity. If the drillout technique is employed to reduce drawdown, all perforation must be evenly packed and the resulting pack may be fragile. Complete coverage of intervals longer than 20 ft (6m) is difficult to achieve. The technique represents about 5% of sand-control treatments, mainly concentrated on low-cost onshore markets.

2.9.4. Frac Packing

Frac-Packing has been a popular technique for sand control since the early 1990's and provides high reliability completions aimed at enhancing productivity of gravel packed wells. Frac packing is a process that involves pumping gravel or proppant into the formation at rates and pressures that exceed the fracturing pressure of the formation. The intention is to by-pass any near well bore damage remaining from the drilling or perforating phase of the operation. The technique incorporates a 'tip screen out' hydraulic fracturing treatment as a part of the gravel packing procedure, thus stimulating the well. The tip screen out method provides a high contrast between fracture permeability and formation permeability and is essential to ensure that the fracture width and proppant concentrations are adequate to efficiently connect the reservoir to the well bore.

Frac-Packing should be considered as an alternative during development planning for fields that are predicted to produce sand. Usually poorly consolidated, moderate to high permeability sandstone reservoirs are susceptible to sand production. Sometimes, traditional techniques to control the sand influx typically result in the decreased productivity of the well. To solve this production decrease problem, operators have found that performing a fracturing job combined with a sand control gravel pack enhances well productivity and mitigates the tendency of the stand-alone screen or gravel pack to cause a decrease in production.

As a percentage of sand control treatments and in terms of jobs per year, frac –packing is growing steadily- from a fewer than hundred it has gone up to a current of around 1000 jobs per year. Since the beginning of its increased attractiveness, almost all frac-pack treatments have been done performed in cased holes. Advances in stimulation design, well completion equipments, treatment fluids and proppants continue to differentiate frac-packing from conventional gravel packing and fracturing.

The major benefit of the frac-pack is the formation of a high conductivity path through the 'critically' damaged zone. The fracture does more stimulation of low permeability formations than high permeability formations. Major assumptions to the enhanced effectiveness of frac-pack operations are: (1) has no restriction to flow through the fracture, (2) causes no further damage to the formation, (3) allows production to be in non-turbulent flow through the propped fracture.

Means of controlling sand may be different significantly than in a gravel pack. This is because formation sand movement in frac-packs may be due to the reduction in fluid flux into the propped fracture, while in a gravel pack must physically barricade the produced sand. Formation sand may not enter the fracture if the velocity of the produced velocity flowing from the formation into the proppant is low enough to restrict the fluidisation of sand.

Comparing an ideal gravel pack with a frac pack indicates that there might not be much difference in productivity results. Wider frac widths and longer frac lengths will theoretically increase results of the frac pack, but increased removal of formation damage replaced by increased volumes gravel packed outside of a cased hole will theoretically improve the results of a gravel pack also.

Candidate selection:

Good candidates for frac-pack include wells with the following characteristics:

- High permeability, easily damaged reservoirs
- Near well bore damage
- Low permeability reservoirs and formations with fines migration problems
- Formation sanding potential
- Productive layers not connected to the well bore
- Laminated sand/shale sequences
- Poor productivity expected after gravel pack installation
- Low pressure and depleted reservoirs

Advantages of a frac-pack operation

There are several factors that are advantageous in considering frac pack as a completion method for sand control including:

- By passes near well bore formation damage
- Accelerates production through increased sand face area

- Connects thin sand layers
- Stimulates low permeability formations
- Reduces potential scale problems
- Reduces potential fines migration

Disadvantages of a frac-pack operation

Conversely there are several factors that do not favour frac-pack completions including:

- Fractures growing out of the zone (water/ oil, water/ gas, gas/ oil)
- Fracturing in a high angle well bore interferes with packing of gravel over the entire completion interval
- More difficult to do remedial work such as shutting-off water or gas
- Higher cost than gravel pack
- Higher injection pressures and rates are required, especially in long completion intervals
- Small casing and tubing restricts pump rates during treatment
- Higher strength casing, tubing, screen, liners are required to reduce the risk of collapse due to high pressure
- Special stimulation needed for off-shore locations

Frac packing may also be uneconomical for low rate wells, water source or injection wells that do not produce revenue directly, and reservoirs with limited reserves or homogenous thick zones where horizontal gravel packing in open hole is more appropriate.

2.10. GRAVEL PACKING

2.10.1. Introduction

Gravel packing has been used by oil industry since the 1930s. Today it is most widely used sand control measure, accounting for about three-quarter of treatments. A slurry of accurately sized gravel in a carrier fluid is pumped in to the annular space between a centralized screen and either perforated casing or open hole. The gravel also enters perforations if a cased-hole gravel pack is being performed. As pumping continues, carrier fluid leaks off in to the formation or through the screen and back to the surface. The gravel pack creates a granular filter with very high permeability- about 120 Darcies- but prevent formation sand entering the well.

Gravel pack technique like any other also has some disadvantages. During installation carrier fluid is injected in to the formation which may damage the reservoir permeability and restrict production. The pack then tends to trap the damage in the perforations, preventing clean up. Once in place, the pack in perforation tunnel increases drawdown which may seriously damage productivity. Gravel packs reduce the operating well bore diameter, usually necessitating artificial lift equipment to be set above the zone. Completing multiple zones with gravel packs is difficult, and almost all well repairs involve the removal of the screen and pack.

The technique is also an expensive completion method. A sophisticated way of establishing the viability of a gravel pack is to construct well performance curves for a range of completion method using a reservoir simulator and predictions of sand movement and how this affects drawdown. Although gravel packing has these drawbacks, it is the most effective method of stopping sand movement and permitting production, albeit at a reduced rate. Because of this, gravel packing is predominant method in use today and warrants a detailed examination.

Though the industry kept moving from one methodology to another in search of the most optimum sand control technique, gravel packing maintained its industry dominance.

2.10.2. Open-Hole Gravel Packing

A gravel pack is a simple down hole filter which is designed to prevent the production of unwanted formation sand. The formation sand is held in place by a properly sized gravel pack sand which in turn is held in place with the help of a properly sized screen.

Open-hole gravel pack is a common completion technique in many parts of the world such as California, Bolivia, Venezuela, China, Indonesia, Gulf of Mexico and the North Sea. However, there are advantages and disadvantages of open hole gravel packing completion and it is important to understand these factors in order to be able to make the choice where possible.

Advantages:

- Easiest gravel packing method because of large availability of annular space between the screen and the formation. It also presents the least difficulty in transportation of gravel since the gravel does not have to be carried into the perforations.
- Highest theoretical productivity because there is no restriction to flow in perforation tunnels.
- Lowest possible velocity for produced fluids flowing through the gravel pack
- Less expensive as the casing and cementing costs are eliminated

Disadvantages:

- It is more difficult to control unwanted water and gas production, or injection into thief zones
- Hole stability poses a problem during placement in case annulus is sand filled the gravel is placed
- Screen is more easily plugged as against a cased hole
- Generally limited to a bottom interval in case of multiple zone completions

Most open hole completions require under reaming before they are packed with gravel. Under reaming increases the diameter of the open hole to about twice the casing ID. Usually casing is set above the productive zone, but sometimes it is set through all productive intervals. Then, a window is milled out through the zones to be gravel packed.

To prevent a weak formation from collapsing during under reaming operations, a formation compatible Drill-in-Fluid must be properly employed to control fluid loss. As gravel is being circulated into an open hole, the formation sand is disturbed much more easily than in a cased hole completion. This can cause the formation sand to be fluidized and plug the slotted liners or screens. Any subsequent stimulation in this case would preferentially flow into the upper part of the gravel pack. Once the pack is damaged, achieving diversion becomes

2.10.3. Cased Hole Gravel Packing

There are no special requirements for a cased hole gravel pack. The casing is cemented conventionally at the total depth. Next step then is to perforate the completion interval with high density, large diameters perforations which are capable of penetrating the damaged zone. The perforation damage induced is cleaned out behind the pipe by back flushing, under balanced perforating and perforation washing.

The screen is run and the gravel pumped into the perforation tunnels and casing/screen annular area. The key to success is the criterion of a high permeability path through the casing, cement and damaged zone to permit effective packing out against the native formation.

In theory open hole gravel packs are found to result in a better productivity cased hole gravel packs particularly at higher rates or for viscous fluids. At the same time, they are difficult to plan and install. Cased hole packing offers more flexibility, selectivity, planning time and cost/rig time savings.

Cased hole gravel packs are widely used to control production of formation sand in oil and gas wells. Cased hole completions are more popular than open hole completions for several reasons. First, if operator if the operator has not predicted the need for sand control during the drilling phase, a perforated casing completion with gravel pack may be installed. Secondly, the cased hole gravel pack does not require very special DIFs for operation. Thirdly, the issue of well bore stability is comprehensively dealt with. One negative point of the cased hole completion is low productivity unless the gravel is placed through and outside the perforations properly.

A successful cased hole gravel pack requires that the perforations or fractures extending beyond any near well bore damage be tightly packed with gravel. The likely hood of incomplete perforation packing via a single placement process is foreseen, cased hole gravel packing is done as a two stage process. The first stage is packing the perforation tunnels with gravel, termed as perforation pre-pack. The second stage comprises packing the annulus between the screen and the casing ID with the same gravel.

2.10.4. Designing Gravel Pack

Basic design parameters include:

1. Optimum gravel size in relation to formation sand size.
2. Optimum screen slot width to retain the gravel, or if no gravel, the formation sand.
3. An effective placement technique-perhaps most important.

To determine what gravel pack sand size is required, formation sand samples needs to be evaluated to determine the median grain size diameter and the distribution of sand grains. With this information available, gravel pack sand can be selected using the technique outlined by Saucier. The quality of sand is as important as the proper sizing.

The first step is getting representative samples. Sand-grain size distribution often varies through a particular sand body and certainly from one generic zone to another. Thus for a representative measurement a no. of samples are needed.

2.10.4.1. Formation Sand Sampling

Improper formation sand sampling techniques can lead to gravel packs which fail due to plugging of the pack or the production of sand. As the formation sand size is very important, the technique used to obtain a formation sample is also important. Without sampling of formation sand from the formation the following items cannot be determined and they are at best a guess:-

- Proper gravel size, screen or slot spacing to stop formation sand while keeping up the productivity
- Degree of clay stabilization required
- Benefits or hazards of acidizing
- Filtering of fluids required to avoid damaging the formation

The samples should be taken at each lithology change or every two to three feet. As most pay zones have different permeabilities, average grain sizes, porosities and strengths. These parameters may change quickly in an interval.

Samples only from one well in a field is not considered adequate as sandstone formations also vary across the reservoir. Continuous coring technology has been developed for coring long horizontal and high-angle wells. The classification of formation sands include:

- Quick Sand (completely unconsolidated)
- Partially consolidated
- Friable sands (well cemented)

Different sampling techniques include:

Produced Samples

In wells producing sand, a sample of the formation sand is easily obtained at the surface. Although such a sample can be analyzed and used for gravel pack sand size determination, produced samples will usually contain only the smaller sand grains. The flow rate, produced fluid characteristics and completion tubular design will influence whether a particular size of formation sand grain is produced to surface or settles to the bottom of the well. In most of the cases, the larger sand grains settle to the bottom, so that a sample that is produced to the surface has a higher proportion of the smaller size of sand grains.

Samples taken at different on the surface (sand trap, well head, heater treater, etc.) will indicate a variation in sand size distribution. This variation in sand size makes it difficult for the operate to decide which sample to use.

Bailed Samples

Samples obtained from bailing operations or from circulation of fill off bottom will generally include the larger grain sizes sand from some of the intervals opened to production. Wireline Bailers are used to collect these samples. Bailed samples of formation should never be used for designing sand control treatments as this may result in design of larger than required gravel pack sand which results in sand production or plugging of the formation.

Sidewall Cores

If full cores of the formation are not available, the next best samples are sidewall cores. In some measure, they are less expensive than full conventional cores, sidewall cores are frequently the only types of core available from most sandstone formations.

Sidewall core samples are obtained by shooting hollow projectiles from a gun lowered into the well on an electric line to the desired depth. The projectiles remain attached to the gun via steel cables, so that when pulling the gun out of the well, the projectiles are retrieved with a small formation sample inside. When the projectiles strike the face of the formation, localized crushing of the sand grains occurs, producing broken sand grains and generating more fine particles. These are the most widely used sample type for gravel pack sand design. Sidewall cores are small and often contain mud cake or invaded mud particles i.e., they can also give misleading results. However, they are more representative of the formation sand than produced or bailed sands.

Conventional Core Barrel

The most representative formation sample is obtained from conventional cores. These are used to recover samples of friable and partially consolidated formations. In case of alternating consolidated and unconsolidated formations, considerations should be given to using double tube core barrel for total recovery. Although conventional cores are the most desirable formation sample, they are not readily available in most cases due to the cost of coring operations.

2.10.4.2. Conventional Core, Unconsolidated Core and Sieve analysis

After the completion of data acquisition of formation through sampling, its analysis is done in the laboratory, aid in the proper design of (1) drilling fluid, (2) DIFs, (3) completion fluids, (4) stimulation treatments and (5) sand control installations. Three basic type of laboratory analysis is performed:

Conventional core analysis: This analysis includes porosity, horizontal permeability, grain density, a lithologic description and fluid saturations. Routine core analysis often includes measurements of vertical permeability. Measurements are made at room temperature and at atmospheric confining pressure, formation confining pressure or both.

Unconsolidated core analysis: Unconsolidated core samples can be easily damaged and therefore it requires special equipments for safe acquisition and transportation. Various tests can be performed on these samples and it includes:

- Sample selection and treatment using spectral core gamma, CT scanning and mineralogy screening.
- Poro-perm to determine porosity, gas permeability, and klinkenberg corrected permeability.
- Resination to preserve core integrity after slabbing.
- Profile Acoustic to evaluate sanding potential and borehole stability models.
- Photography to reveal fluorescing hydrocarbons and minerals.
- High resolution digital core imaging to provide detailed sedimentary information.

Sieve Analysis

Sieve analysis provides grain size distribution on percentile basis. But sieve analysis techniques have not been standardized for the oil industry. Normally for oil field work U.S. Standard Sieve Series is used, and sieve analysis is reported in inches or millimetres.

Sieve analysis consists of placing a formation sample at the top of a series of screens, which have gradually smaller mesh sizes. The sand grains in the original well sample will fall through the screens until it comes across a screen through which that grains size cannot pass because the openings in the screen are too small. By weighing the screens before and after sieving, the weight of formation sample engaged by each size screen can be determined. The cumulative weight percent of each sample retained can be plotted as a comparison of screen mesh size on semi-log coordinates to obtain a sand size distribution plot as shown in Figure. Reading the graph at the 50 percent cumulative weight gives the median formation grain size diameter. This grain size, often referred to as D50, is the basis of gravel pack sand size selection procedures.

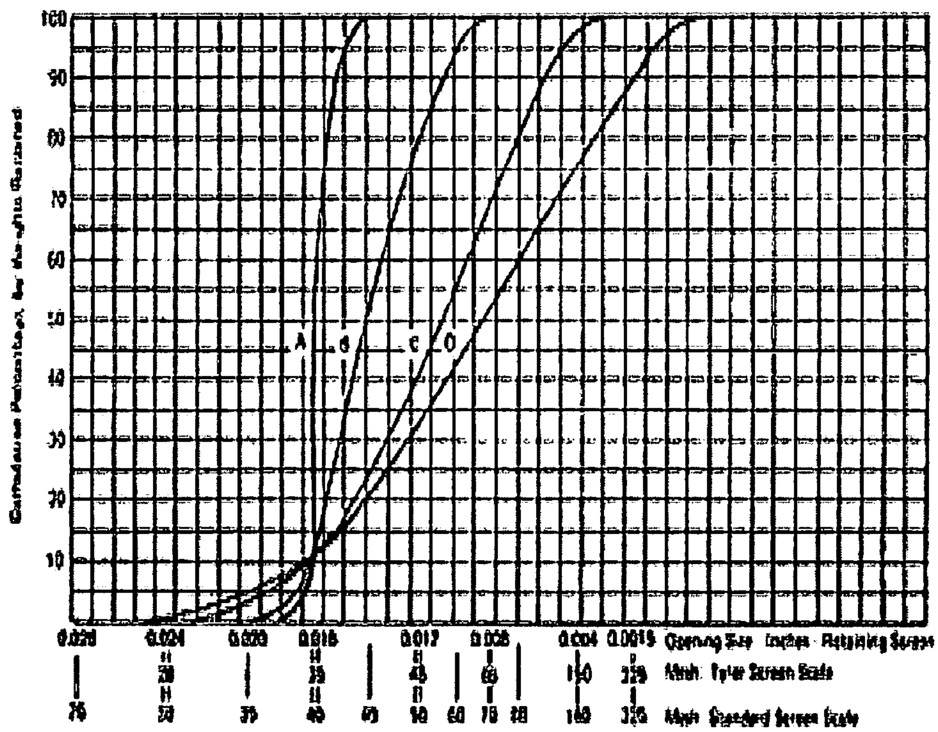

Fig.2.6. sieve Analysis of uniform and non-uniform formation sand.

Ten percentile sand size is defined as the point on the distribution scale where 10% by weight of the sand is of larger size and 90% of smaller size. Grain size distributions around the world vary considerably, both in average size and uniformity. A specific size is needed to describe the distribution curve. It is convenient to describe the grain size distribution curve by the size at a specific percentile point. Several points on the percentile scale are used:

- 10 percentile – typical of Gulf Coast
- 50 percentile – Karpoff-Saucier-Halliburton
- 10, 40 or 70 depending on slope- Schwartz

Table below shows various mesh sizes versus sieve openings

US Series Mesh	Sieve Openings (in)	Sieve Openings (mm)
2.5	0.3150	8.000
3	0.2650	6.730
4	0.2230	5.660
5	0.1870	4.760
6	0.1570	4.000
7	0.1320	3.360
8	0.1110	2.830
10	0.0937	2.380
12	0.0787	2.000
14	0.0661	1.680
16	0.0555	1.410
18	0.0469	1.000
20	0.0394	0.840
25	0.0331	0.710
30	0.0280	0.589
35	0.0232	0.500
40	0.0197	0.420
45	0.0165	0.351
50	0.0138	0.297
60	0.0117	0.250
70	0.0098	0.210
80	0.0083	0.177
90	0.0070	0.149
100	0.0059	0.124
120	0.0049	0.104
140	0.0041	0.088
170	0.0035	0.074
200	0.0029	0.062
230	0.0024	0.053
270	0.0021	0.044
325	0.0017	0.037

Table 2.3. Standard Sieve Openings

2.10.4.3. Gravel Size Determination

Early work by Coberly in defining gravel sand size ratios considered only the problem of preventing movement of sand into the well bore, and not the permeability of the gravel pack. This led to rather large gravel sand ratios. Later it became clear that for maximum productivity the formation sand must be stopped at the outer face of the gravel pack. If sand bridges occur within the gravel pack itself, permeability is significant reduced. This thinking started the current industry trend towards the lower G-S ratios. The term "gravel-sand size ratio" has not been standardized. Early investigators Coberly, Hill, Wagner, and Gumpertz meant:

G-S ratio = Largest gravel size / 10 percentile sand size

Schwartz means:

G-S ratio = 10 percentile gravel / 10 percentile sand

or

40 percentile gravel / 40 percentile sand

Maly means:

G-S ratio = Smallest gravel size / 10 percentile sand

There are several methods for the selection of gravel-pack sand size to control the production of formation sand. The technique most widely used today was developed by Saucier. The basic premise of Saucier's work is that optimum sand control is achieved when the median grain size of the gravel pack sand is no more than six times larger than the median grain size of the formation sand.

The effect of G-S ratio on gravel pack permeability is best shown by lab work by Saucier. Using the results of saucier's experiments; optimization of gravel pack sand size can be accomplished using the following guidelines:

When:- $D_{50}/d_{50} < 5$

Then, there is good sand control but restricted flow due to low gravel pack permeability.

When:- $5 < D_{50}/d_{50} < 7$

Then, there is good sand control and maximum pack permeability.

When:- $7 < D_{50}/d_{50} < 9$

Then, there is good sand control but restricted sand flow due to formation sand invasion of gravel-pack sand.

When:- / > 9

Then, there is no sand control and the formation passes through the gravel-pack sand.

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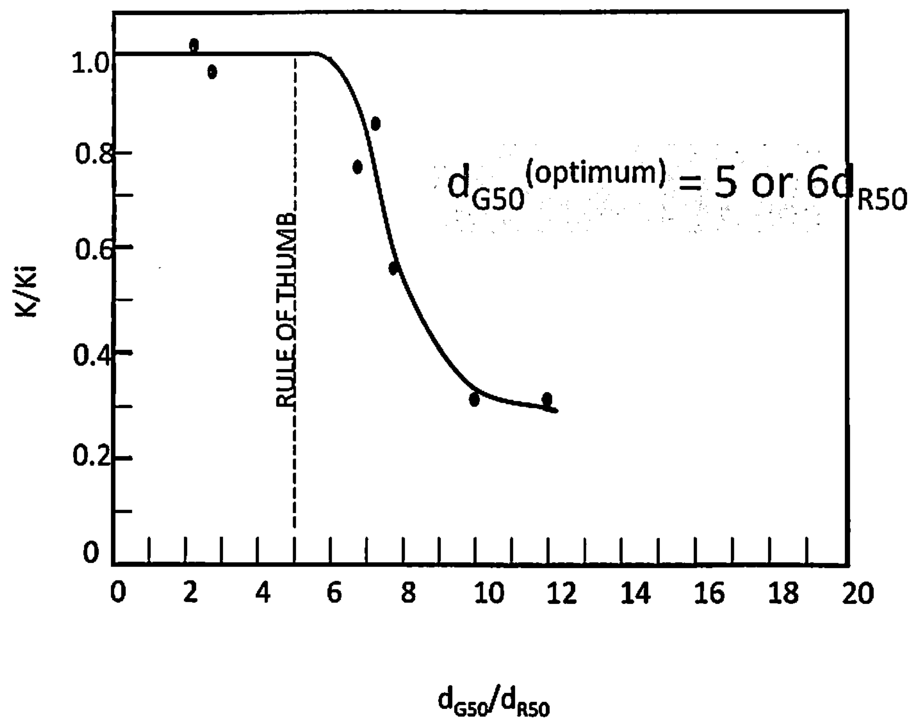

Fig.2.7. Results of Saucier's gravel size experiments

Saucier's technique is based solely on the median grain size of the formation sand with no consideration given to the range of sand grain diameters or the degree of sorting present in the formation. The sieve analysis plot discussed earlier can be used to establish an indication of the degree of sorting in a formation sample. A near vertical sieve analysis plot represents a high degree of sorting versus a more horizontal plot which indicates poorer sorting. A sorting factor can be calculated as:-

= /

Where, =sorting factor

=grain size at the 40% cumulative level from sieve analysis plot

=grain size at the 90% cumulative level from sieve analysis plot

The value of should not be greater than 5, if it is then sand is considered to be poorly sorted.

2.10.4.4. Gravel Pack Sand and its thickness

Gravel pack well productivity is sensitive to the permeability of the gravel pack sand. To ensure maximum well productivity only high quality gravel pack sand should be used. The API Recommended practices 58 establish rigid specifications for acceptable properties of sands used for gravel packing. Only a few naturally occurring sands arc capable of meeting the API specifications without excessive processing. These sands are characterized by their high quartz content and consistency in grain size. A majority of the gravel pack sand used in the world is mined from the Ottawa formation in the Northern United States.

With the practical problem of placing gravel, and with fluctuating flow velocities, a 3-in thickness of gravel is considered minimum. This means that open hole must be under-reamed to provide 3 in. on the radius between the screens and the formation. In perforated casing gravel must be placed through the perforation tunnel and outside the casing. Thicker ravel packs permit higher production rate. Either a sharp increase or a sharp decrease in flow rate through a 3-in. gravel pack caused a temporary increase in sand production. If the flow rate was held uniform after the change, sand production decreased, apparently indicating re-establishment of bridging effects. Gas evolution had a significant effect in increasing sand production. Results of the tests conducted by Saucier indicate that rate changes are more important than the magnitude of the flow rate. These tests also showed that gravel-sand ratios must be less than 6 to minimize sand production under disturbed flow conditions, or under high velocity conditions.

2.10.4.5. Gravel Pack Sand substitutes

Although naturally occurring quartz sand is the most common gravel pack material used, a number of alternative materials for gravel pack applications exist. These alternative materials include resin coated sand, garnet, glass beads, and aluminium oxides. Each of these materials offers specific properties that are beneficial for given applications and well conditions. The cost of the materials will range from 2 to 3 times the price of common quartz sand. Resin coated gravel pack sand consist of standard gravel pack sand coated with a thin layer of resin. When exposed to high temperatures, the resin cures resulting in a consolidated sand pack.

Practical Consideration in Gravel Packing

- Selecting gravel of proper size and quality.
- Placing the gravel without contamination, at the proper location, as tightly as possible- then holding it in place for the life of the well.

The crux of the problem is to control the load bearing solids without excessive loss of productivity. When reservoir conditions are such that high production rates can be sustained, every trick must be employed to maximize productivity and reduce flow velocity per unit area. An open gravel pack provides maximum productivity. The much greater area open to flow of fluids into the wellbore, and the corresponding reduction in flow velocity for an open hole gravel pack allows some margin for error compared with the inside casing pack.

Based on tremendous PI advantage, an open hole gravel pack should always be selected when the open hole is compatible with other completion considerations. Control of extraneous water or gas in the subsequent life of the well may, however, rule in favour of the perforated casing or inside casing gravel pack.

Suitability of particular gravel depends on:

- Roundness: Krumblein scale of 0.6 or better. Flat or angular grains should be avoided.
- Grain strength: depends on depth and formation stress level as same as frac sand.
- Acid solubility: Acid solubility should be checked. Gravel should be greater than 98% pure silica. Feldspar content should be nil since feldspar is completely soluble in HF acid. Glass beads are slowly soluble in HF acid.
- Uniformity: the closer the limits on gravel grain size variation, the greater will be permeability. Schwartz suggests a uniformity coefficient less than 1.50. Materials finer than the lower size limit is particularly bad.

To maximize relative permeability to oil, the gravel must be water wet before it is added to the placement fluid.

2.10.5. Well preparation for gravel pack

Productivity of the gravel pack completion in an open or cased hole also depends on the condition of the reservoir behind the filter cake, quality of the filter cake and stability of the wellbore. Given this, it can be said that the completion begins when the bit enters the pay and therefore the goal of drilling is to maintain wellbore stability while minimizing formation damage.

Well bore stability

Wellbore stability in the form of washouts, hole collapse and fracturing is an effect of high fluid loss, high PV and YP, inadequate overbalance and or reaction between filtrate and formation. Thick cement sheaths in washed-out sections result in poor to no perforation penetration and the lack of cement can make sand placement difficult. Hole collapse can prevent running either casing or screen to bottom and failure in the form of fracturing or collapse can stop an open-hole gravel pack, should failure occur while the pack is in process. Since stability is an effect of the reaction between drill-in fluid and formation, filtrate, filter cake, weight and rheology become key parameters in building a drill-in fluid.

Formation Damage

Formation damage is expressed in the form of skin and is an effect of filtrate and particle damage and filter cake quality in the case of open-hole gravel packs. Skin in turn is reflected in poor productivity. With open-hole completions filtrate requirements seem rather obvious, and if this filtrate is incompatible with reservoir rock and fluid, then there is a damaged ring past which it may not be possible to perforate. For open-hole completions, the quality of filter cake is also as important as the other requirements. Since the cake is to be gravel packed into place, it is necessary that the cake be thin, friable and have a low breakout pressure.

Cleaning the Casing, Open Hole, Work String, and Surface Facilities

Cleanliness may be one of the most important considerations when implementing a completion for gravel packing. Since a gravel pack represents the installation of a downhole filter, any action that promotes plugging the filter (i.e., the gravel pack sand) is detrimental to the success of the completion and well productivity. While cleaning the well and rig equipment can be expensive, it is not as expensive as lost productivity or having to rework the entire completion because proper cleaning was neglected in the beginning

- Reverse circulation is the preferred method of circulation for cleaning the casing and the recommended annular velocity is 130 ft/min for casing shoe deviations less than 60° and 300 ft/min for deviations greater then 60°. Reverse circulation is more effective than circulating the long way as material is moved down hole with gravity; unrecovered material is pushed to the bottom of the hole; work string scale and pipe dope, provided the connection is wiped off, does not enter the casing and, in the case of an open-hole completion, reverse circulation permits cleaning the casing to specification before addressing the open hole.

- As with the casing, reverse circulation is the preferred method of circulation in open hole gravel packing completions. With the casing cleaned as previously discussed, now all attention can be focused on cleaning the open hole. Well bore losses and stability can be easily detected and repaired if necessary, and any unrecovered material will be pushed to bottom out of the way. Recommended annular velocity is 300 ft/min at any deviation to scour the filter cake in preparation for gravel packing and to clean the hole.

- both the inner and outer surfaces of the work string must be clean because completion fluid will be circulated along both surfaces. Scraping the work string is usually not an option as with the casing, but visual inspections of the tubing before it is run into the well are encouraged to ensure that the tubing is in good mechanical condition and clean. As a minimum, a "rabbit" with a diameter equal to the drift diameter of the work string will help to loosen scale and other debris, as well as providing assurance of the internal diameter of the work string.

- Tanks must be thoroughly scraped and jetted to ensure any residual solids from the drilling fluids are removed. When possible, tanks should be dedicated to completion fluids when a drilling program involves drilling numerous wells requiring gravel packs. Casing sweep chemicals and sea water are recommended for removing debris from rig lines.

Completion fluids

In addition to being clean, the fluids used in the well completion must be compatible with the formation and formation fluids. Of particular concern is clay swelling and compatibility with formation water to avoid ion precipitation.Fluid loss control is a common consideration when completing unconsolidated formations with a gravel pack. This is especially true in very high permeability formations. In addition to the potential formation damage caused by fluid loss, there is particular anxiety when high cost fluids are involved or when completion fluid reserves are low.

2.10.6. Gravel Packing Method

Based on the experience gravel packing on various wells by service companies, the following are the absolute requirements for an open hole gravel pack tool system:

- Capability of maintaining over burden pressure at all times
- All operations should be performed without the occurrence of surging and swabbing of the formation
- Must have clearance for positive tool postioning

Three basic tools used in gravel packing operations:

(1) packer / cross over tool assembly

(2) over the top tool assembly

(3) port collar

Completion tools are tools which are left down hole as a part of the assembly once the gravel has been packed while, service tools are removed after placing the gravel pack.

Packing Method for Vertical wells

Reverse circulation method for gravel packing was used before the introduction of the crossover tool. It was frequently used in low depth holes with a small interval requiring no zonal isolation or separation. But it is not widely acknowledged as a method of gravel packing now because of the following reasons:

- Requires very large volumes of fluids
- There is a risk that casing debris might damage the gravel pack during placement
- Damage due to interaction of gravel pack with the filter cake and formation sand

For low pressure, shallow wells, one widely accepted method is 'over-the-top' system. It makes use of a downward cup type pack above the crossover tool. Gravel is placed beneath a cup type service packer. For reversing, clean fluids are pumped past the cup packer and back up through the tubing. The cup packer is then pulled up and an inexpensive O-ring is landed on the top of the screen.

In a vertical open hole well the gravel screen and tool hook up should be as follows:

1) A blank liner should be provided to allow for some sloughing of formation sand for the time lapse between gravel being placed and the screen being on the bottom. 5 ft blank for strong formations and a 10 ft blank for relatively weaker formations would be enough.

2) A lower tell tale screen and a seal bore above it will indicate sand fill, screen plugging and when gravel reaches the bottom.

3) Slotted liner or screen extending from blank liner to less than 10 ft below the top of the under reamed section

4) About 20-30 ft of blank liner up in the casing.

5) Approximately 5 ft of upper tell tale screen, for conventional gravel pack.

6) Crossover tool assembly and packer.

7) Wash pipe hanging from the crossover tool with its bottom in the seal assembly.

8) Bow-spring centralizers spaced out evenly.

Procedure

The tell tale screen is a part of that system which detects the arrival of gravel and filling of the lower portion of the annular space. A sudden pressure increase occurs when gravel completely covers the tell tale screen this indicates that the first stage has been completed.

The crossover permits the fluid to flow from the drill pipe to the annular space and vice versa. The crossover permits the gravel pack operation to be carried out in a single trip without the need to flow downward through the annular space between the casing and the drill string, which is undesirable because of the large volume requirements and effects of contamination of fluid.

When the wash pipe is seated within the O-ring sub, i.e. in the lower circulation position the fluid is forced to flow through the lower tell tale screen. In the upper circulation position, the wash pipe is raised and the fluid can flow through the lower tell tale screen and the production screen.

When the production screen is opposite the perforations, the sump packer is set by rotating the drill string and the production packer is set by application of fluid pressure. At this point, a mixture of gravel and carrier fluid is pumped down the drill string, through the cross over, and into the annular space to be filled with gravel. The wash pipe is positioned such that the fluid mixture containing the gravel through the tell tale screen where the gravel separates and begins to 'dehydrate' thereby forming a compact gravel pack. The fluid stripped of the gravel returns through the cross over and up the annulus.

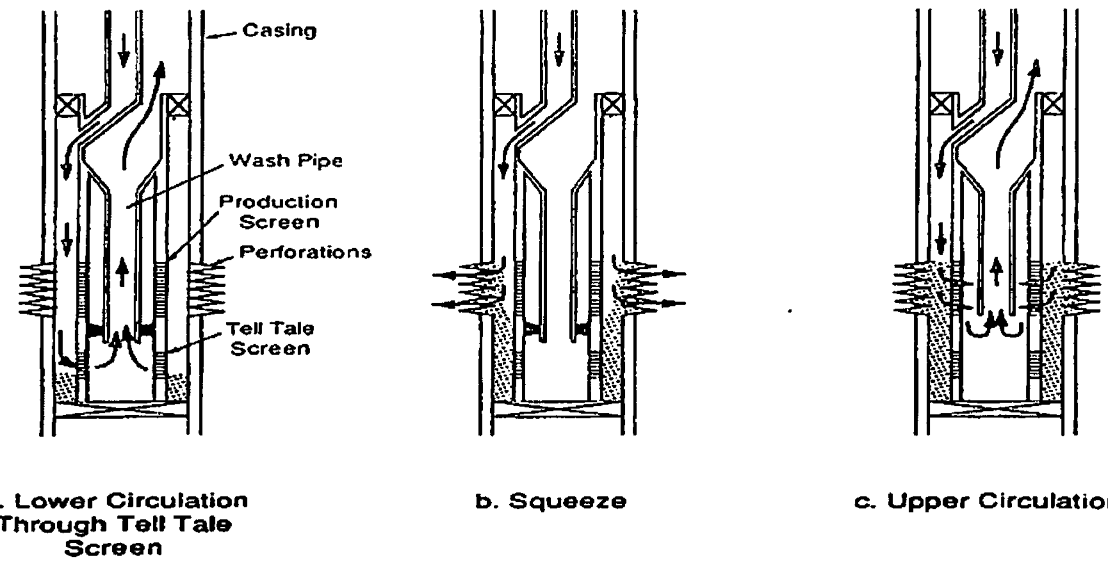

Fig.2.8. Steps in crossover method

Once the pressure drop across the tell tale screen becomes significant, signalling the compaction of the gravel pack around the screen, the tool is placed into the squeeze position. In this configuration, the fluid is not allowed to circulate back to the surface, but is in fact, forced into the producing formations. This is a very important phase of operation because it is important to pack the formation with gravel. Fluid injection in squeeze position should be done until the surface pressures reach their maximum allowable values.

Once the perforations are fully packed, the wash pipe is raised to allow the fluid to flow through the production screen to ensure that it is completely filled with gravel.

At the final stage, the gravel packing tool is set into reverse mode and gravel laden fluid that remains in the drill string is forced upward by the fluid injected into the annulus and flow through the crossover. The flow during reversing stage does not disturb the gravel pack.

The amount of gravel contained in the blank liner above the screen at the time reversing is started, settles to form a gravel reservoir.

Finally, by rotating the drill string, the crossover and wash pipe arrangement is detached from the screen and is removed. The gravel pack is then set into production configuration.

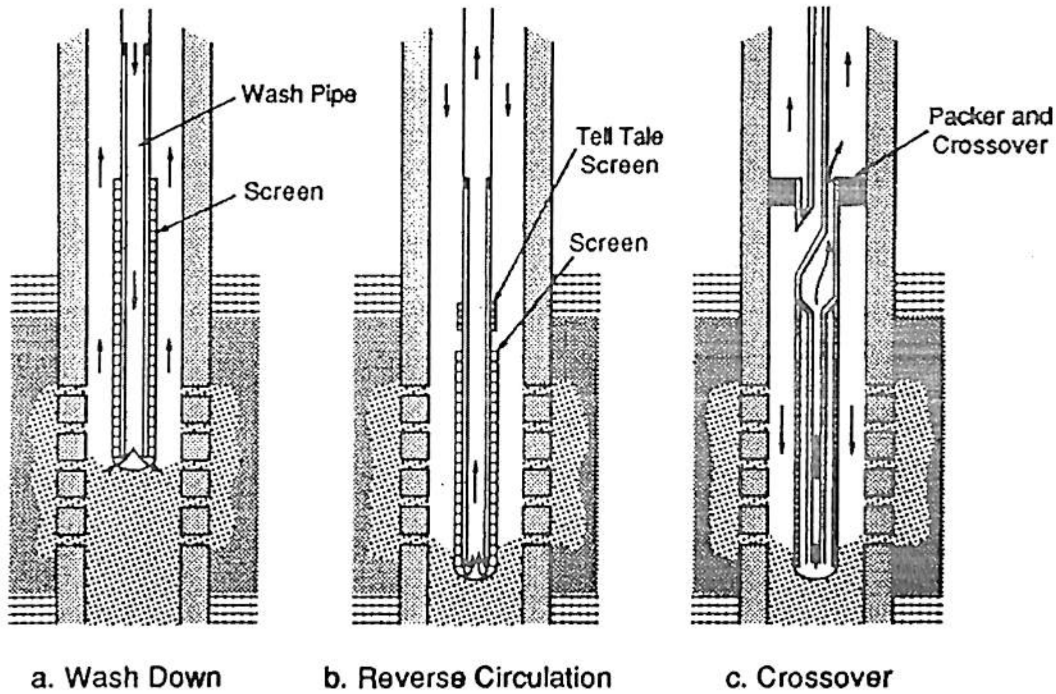

Fig.2.9. Inside casing gravel pack

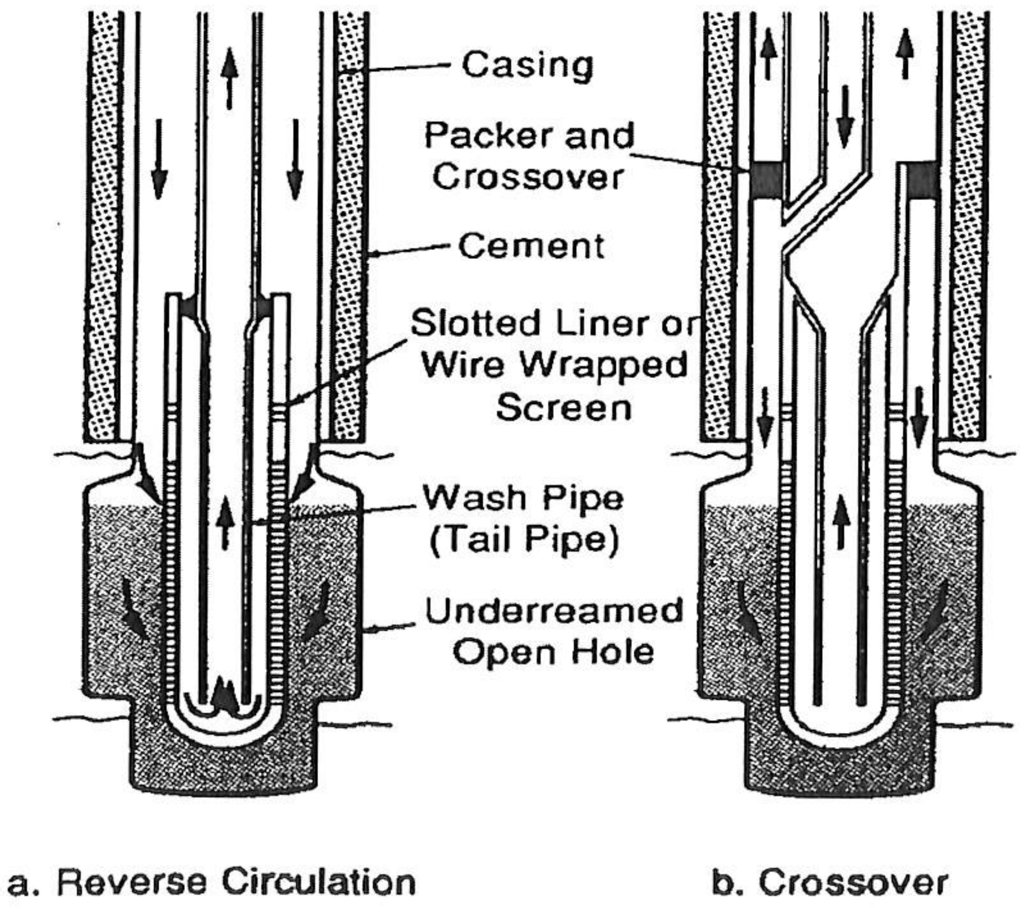

Fig.2.10. Open Hole Under-reamed Completion

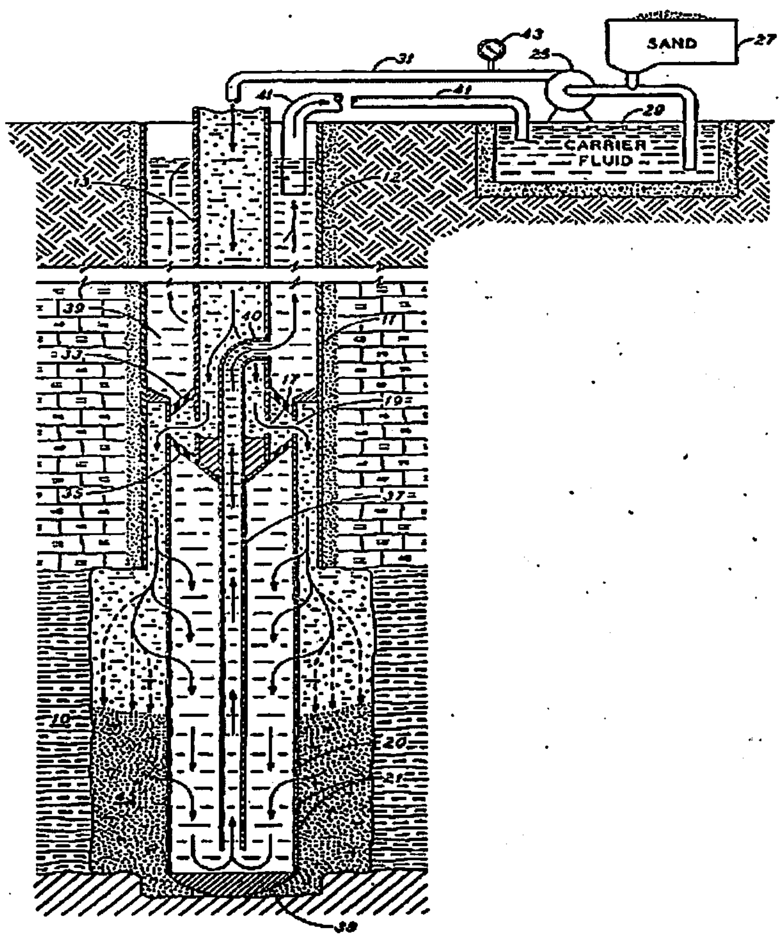

Fig.2.11. Gravel packing using liner

2.11. IMPROVED PRESSURE PACK METHOD

Pressure pack technique avoids the necessity of washing or under-reaming the formation and is therefore ideally suited for slim hole completions. This technique involves the injection of an aggregate suspended in a carrier fluid into the formation at pressures approaching those in fracturing operations. The formation is physically displaced outwardly from the wellbore by the aggregate/fluid slurry so that at the conclusion of the placement step, the aggregate is tightly packed about the wellbore and defines a sand exclusion zone of considerable radial extent.

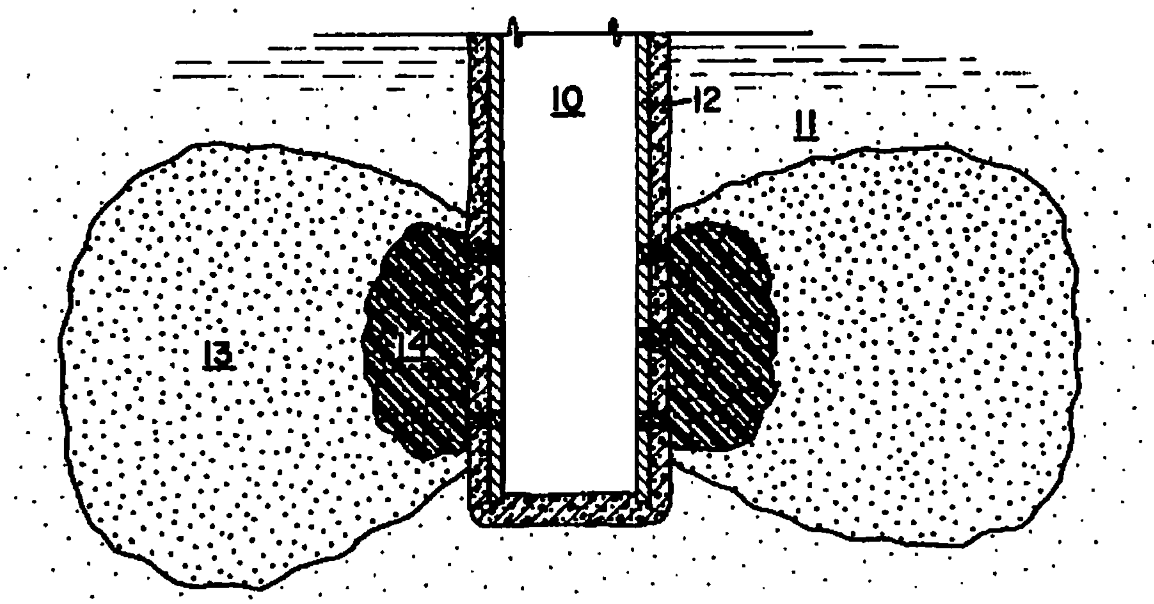

Fig.2.12. Sectional view of a well completed by one embodiment.

It has been observed that the injection of a viscous fluid into an unconsolidated body(rock) at high pressures causes the body to deform in a plastic like manner. Moreover, the injection pressure for plastically deforming an unconsolidated formation is frequently higher than that normally required to fracture a consolidated formation.

Principle of pressure pack method:

We aim at providing two generally concentric packed zones: an inner zone surrounding the wellbore and an outer zone extending radially outwardly from the inner zone. The outer zone constitutes the sand exclusion zone and is packed with particularly sized aggregate for controlling migration of formation sands. The size of the aggregate in the sand exclusion zone can be determined on basis of 10-percentile point on sieve analysis. The inner zone embracing the critical flow area is packed with a highly permeable aggregate. Relatively large size of pore spaces in the inner zone will permit the passage of formation fines which escape the outer sand exclusion zone and thus it prevents the plugging of interstitial flow passages in the critical flow area adjacent to the wellbore.

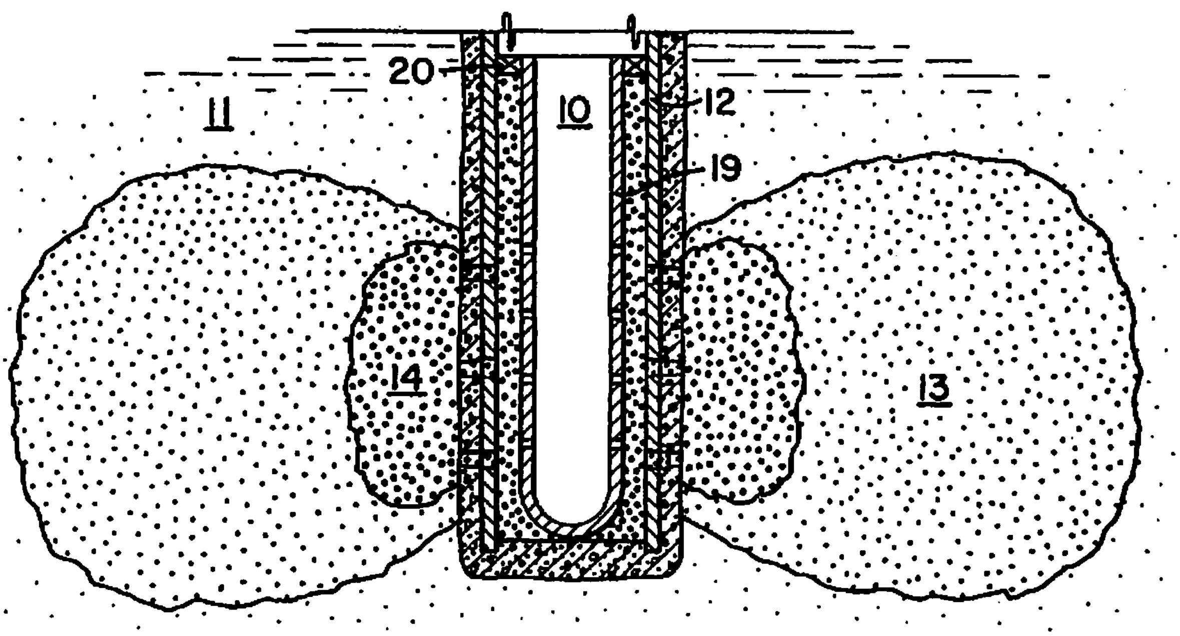

Fig.2.13. Sectional view of a well completed by one embodiment.

Here,

10 → Wellbore

11→ Unconsolidated formation

12→ Casing

13→ Outer sand exclusion zone

14→ Inner high permeability zone

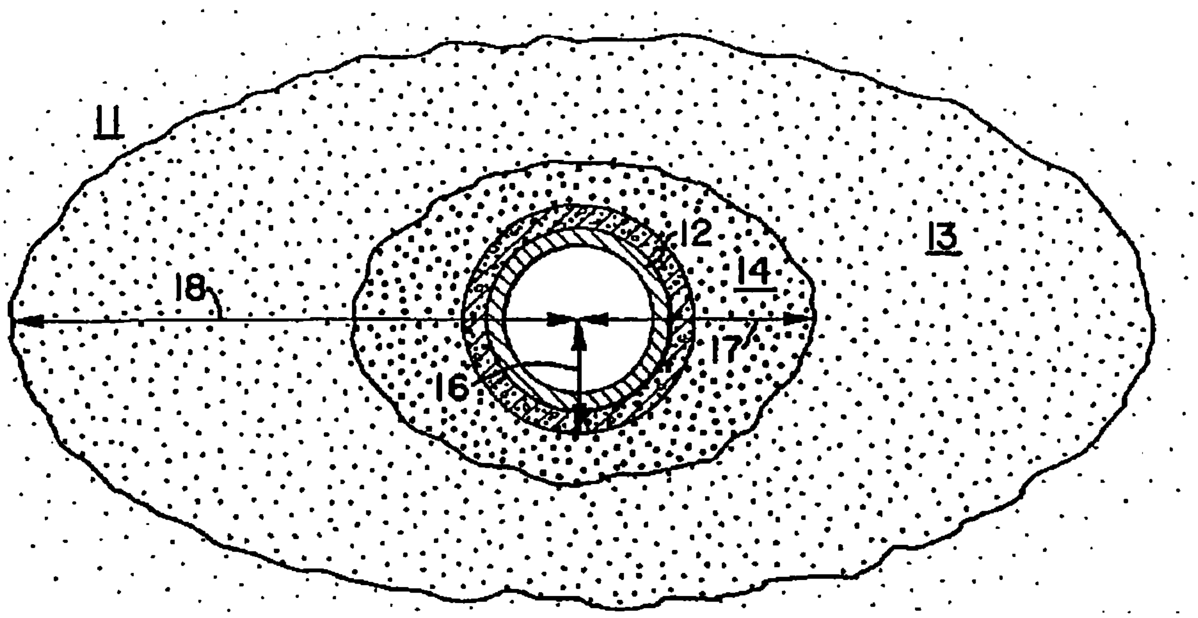

Fig.2.14. Transverse sectional view (cutting plane taken through completed interval)

Sequence of completion method:

1. **Cleaning of well:** Water is injected down the casing and through the perforations. This is done to clean the formation and establish that the formation can be deformed.

2. **Deformation of formation and forming cavities:** The formation is broken down by pumping water into it. Then a pad of carrier fluid such as lease oil or a fracturing fluid is injected at such a pressure and rate to physically displace the formation grains away from immediate vicinity of the wellbore forming a cavity adjacent the wellbore. The viscosity and fluid loss properties of the displacing fluid should be such to prevent excessive penetration or leak-off into the pores of the formation. The carrier fluid can be an oil-water emulsion frac. fluid having a viscosity of about 50,000 cp at atmospheric temperature. At formation temperature it should be viscous

water in oil emulsion with viscosity in excess of about 50 cp. Total volume of carrier fluid injected varies from 2,000 to 3,000 gallons.

3. **Injection of pack sand:** After the formation is broken down that is the formation begins receiving large quantities of fluid at a pressure gradient indicating physical deformation, a carrier fluid containing the pack sand is injected into the formation at about same volumetric rate. The formation is further deformed and displaced radially outwardly as the aggregate screens out on the formation face.

   The particle size of sand pack sand is determined by 10-percentile point on the sieve analysis curve of the formation sand. A particle size falling in 20/60 mesh range will satisfy most well requirements. We can also use 20/30, 20/40 or 40/60 depending on formation condition. This pack sand is blended into the carrier fluid at concentration of from 1 to 4 lbs/gallon. The total amount of pack sand injected usually ranges from 14,000 to 32,000 lbs depending upon the interval being packed. About 3000 lbs of sand is injected for each foot of perforated interval.

4 **Injection of gravel:** After the desired volume of pack has been placed, the gravel is blended in the stream and injection continued. The gravel can be substituted for the pack sand in the carrier fluid or alternatively, the carrier fluid for the gravel can be different than the carrier fluid for the pack sand. It can be a resin diesel oil dispersion. The packed zone continues to grow in a generally radial manner until almost all of the slurry is displaced from the wellbore.

   The particle size of the gravel should be such to bridge the pack sand and provide an inner zone permeability at least 5 times greater than the outer zone permeability. The proper gravel size can be determined by 10-percentile basis. For most of applications, an 8/12 or 10/12 mesh sand will provide the desired permeability and effectively bridge the pack sand. The gravel concentration in the slurry can be between 1 and 4 lbs/gallon. The amount of slurry injected is based upon the volumetric displacement of gravel in forming the inner filter bed .The amount of gravel injected ranges from 1,000 to 4,000 lbs. About 300 lbs of gravel is injected for each foot of perforated interval. The amounts of pack sand and gravel preferably should provide an outer filter bed having an extent of at least 5 wellbore radii and an inner filter bed having a radial extent of at least 2 wellbore radii.

5 **Support to maintain aggregate in place:** With the graded aggregates placed in the two zones, we must provide some means to retain the aggregate in place during production of the well. Basically it is provided in following two ways:

- Use of mechanical device (screen or liner): The slurry containing the gravel is displaced from the tubing or casing by the completion fluid at such a rate and pressure to leave excess gravel in the casing. If necessary additional gravel is spotted to provide a packed interval which completely traverses the perforated interval of the casing. The perforated liner suspended on the tubing is then washed in place by conventional techniques. Optionally the liner can be provided with a packer to seal the upper end of the liner-casing annulus. With the liner located, the well is gradually brought in by swabbing or other techniques whereupon formation fluids flush the carrier fluids from the packed zones. The formation fluids pass first through the sand exclusion zone and then through the high permeability zone. The majority of formation sand entrained in the fluids are filtered out in the sand exclusion zone by screening or bridging. Formation fines which escape the sand exclusion zone upon entering the high permeability zone will be carried to the wellbore owing to the inability of the coarse gravel to establish a sand bridge.

- Plastic consolisation technique: Thermosetting plastics commercially available for sand consolidation treatment include phenol-formaldehyde, furan and epoxy resins. These plastics can be applied to consolidate the inner zone gravel by a precoated treatment or by injecting the plastic after the inner zone gravel has been placed. In the precoated treatment, the carrier fluid for the gravel includes the consolidating agents. Preferably the plastic treatment should be designed to consolidate at least all of the gravel in the inner zone. Plastic consolidation inherently involves some reduction in permeability because of the plastic filling the gravel pores. However, the permeability of the coarse gravel which generally will be in the order of 500 darcies, can readily accommodate permeability reductions with little effect on well productivity.

6. Clean the well to total depth and then if we have used plastic consolidation technique, we apply a resin catalyst compatible with the type of thermoset is injected into the formation. The well is closed for a sufficient period of time to permit the resin to harden.

7. Finally the well is put on production.

2.12. Gravel Pack Evaluation

The evaluation of effectiveness of gravel pack is a key aspect in the evaluation of the completion operation. An early failure of screen or premature sand production may result from a poorly executed treatment requiring costly remedial operations. Determinations of treated formation intervals, annular gravel pack success and pack assembly placement provides the necessary feed back to make important decisions following the completion.

For a long period of time, the tools used for evaluation were wire line conveyed. But with the advent of new technologies, tools can be sent through wire lines, slick lines, tubings and coiled tubings. Memory based tools, conveyed at the end of the wash pipe for logging after the operation is growing in popularity.

A number of logging services and techniques for evaluation are available to assess the placement of material in gravel packs. These include:

- Density log – a full bore detector senses gamma rays from a tool mounted radioactive (RA) source.
- Dual detector neutron log – changes in the count rate of neutrons emitted by a tool mounted RA source indicate changes in the hydrogen index.
- Spectral Gamma ray "tracer log" – in a single logging operation, spectral gamma measurements can help identify multiple RA isotopes tagged to pumped materials.

2.12.1. Density Log

Unfocused y-ray density logs can be used to locate the top of the gravel-packed section and to detect voids in gravel packs by measuring the density of the materials in the region of the well completion. The tools used are gamma-gamma density devices having a gamma-ray source, typically cesium- 137, and a single y -ray detector. In a gravel-packed well, the material through which the y-rays travel should be constant except for the amount of gravel present in the annular space between the liner and the casing or formation. Thus the y -ray intensity measured at the detector should provide at least a qualitative measure of the amount of gravel present-where the annulus is completely filled, the detector response is a minimum while void spaces yield higher count rates.

An unfocused y -ray density log displays regions of high y -ray intensity in the packed zone when the gravel pack contains voids, as illustrated in Fig. 6-8 (Neal and Carroll, 1985). Though a portion of the gravel packed region produces a low count level, through a large region of the completion the y-ray intensity is high, indicating an incomplete pack of gravel minimum while void spaces yield higher count rates.

An unfocused y -ray density log displays regions of high y -ray intensity in the packed zone when the gravel pack contains voids, as illustrated in Fig. 6-8 (Neal and Carroll, 1985). Though a portion of the gravel packed region produces a low count level, through a large region of the completion the y-ray intensity is high, indicating an incomplete pack of gravel.

2.12.2. Dual Detector Neutron Log

This technique uses a dual detector neutron log which comprises a chemical source of neutron and two thermal neutron detectors. The high energy neutrons emitted by the source are slowed down by collisions with other nuclei (mainly hydrogen). Neutron count rates would be high where the pack is good and low where it is not. The reason behind this is the ease of propagation of neutrons through gravel pack than through the fluid.

2.12.3. Spectral gamma ray "tracer" log

The most commonly used method for gravel pack evaluation technique is to tag the gravel with radioactive tracer material. Materials commonly used are Iridium(Ir) and Scandium (Sc). Sc tags the packing of the perforation and Ir for tagging the main annular-pack stage. A detector is then run through the packed interval. If the RA agent is uniformly mixed with the gravel, the count rate indicates the presence or absence of the gravel pack.

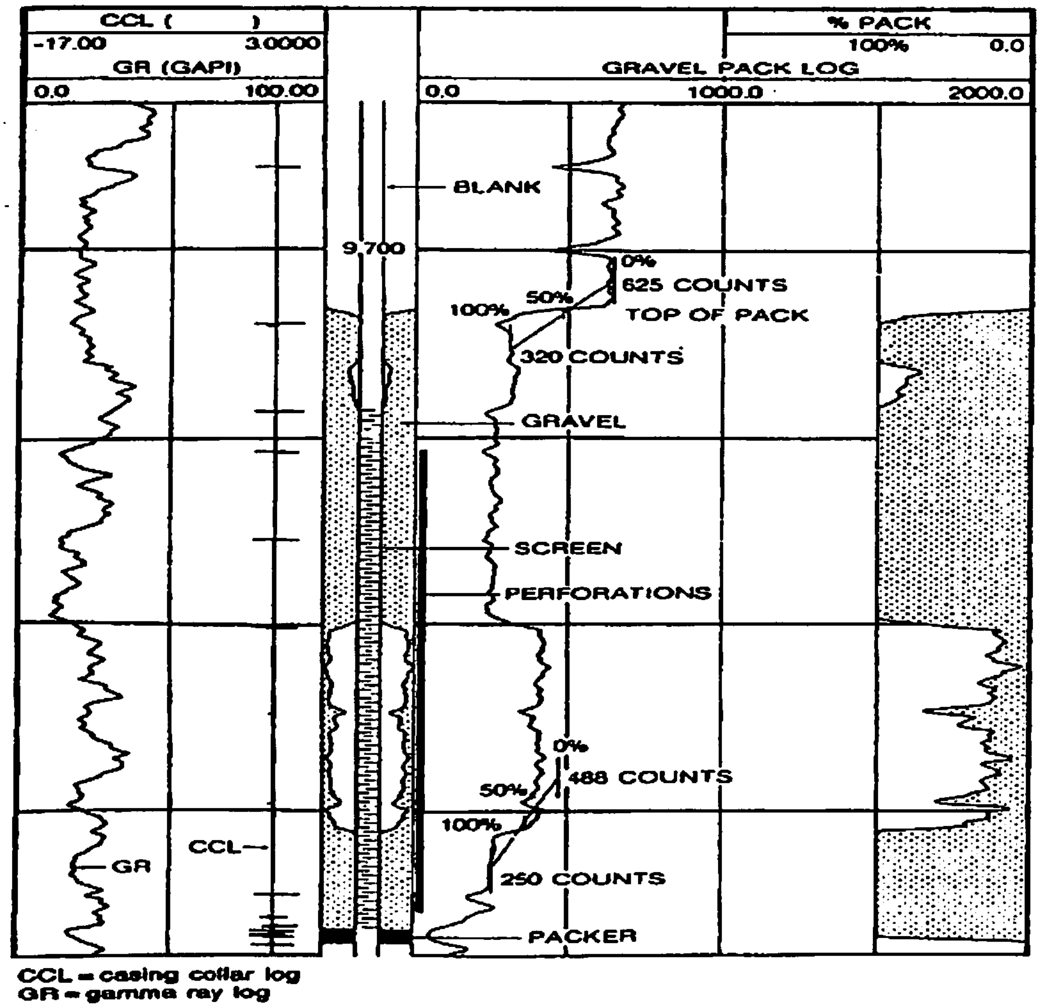

Fig.2.15. casing collar log and gamma ray log

2.13. Analysis of Gravel Packing Using 3-D Numerical Simulation

Introduction

Numerical simulators have proven to be viable tools for studying dynamic systems and providing accurate predictions. When combined with the advanced capability of modem computers, the flexibility of the numerical approach allows a wide array of variables to be investigated that otherwise would be limited by time, safety, or cost.

To determine causes of incomplete packing, physical and numerical models of gravel placement have been used to simulate the gravel packing process downhole by examining formation conditions, fluid properties, wellbore parameters, and operating procedures. However, the currently known numerical gravel pack models can only simulate the gravel placement in a two-dimensional manner, which results in a number of limitations. The development techniques of past numerical models therefore were reviewed to study their merits and distinct features in implementing applicable criteria for an alternate approach of simulating the gravel placement process. Here we have described a three-dimensional, mathematical analysis to simulate the complete process of a gravel pack treatment, and thus facilitates planning and optimizing treatment designs. A simple yet powerful numerical method, equipped to handle complex boundary conditions of the gravel pack transport system is described here.

Previous numerical gravel pack models:

1. Equilibrium bank theory:

Gruesbeck et-al postulated the idea of an equilibrium bank by, closely examining the phenomenon of gravel deposited from the bottom side of a deviated wellbore. They developed a mathematical model to predict the packing profile of the gravel packed in a casing screen annulus for a set of experimental conditions. Gruesbeck et al also examined the packing process in perforations in terms of particle-transport efficiency based on theoretical considerations of potential flow

2. Paden et al model:

Paden et al were among the first to expand the equilibrium bank theory of Gruesbeck et al.,' coupled with theoretical principles of slurry transport, to study the gravel packing phenomenon in deviated wells. By applying dimensional analysis to their experimental data for an 8 ft long by 6 in. inside diameter wellbore, Peden et al. were able to derive correlations, which were used to develop a mathematical model for evaluating the gravel pack efficiency of perforations and casing screen annulus. For a set of predetermined parameters, the model can evaluate the effects of perforation phasing, deviation angle, carrier fluid properties, and perforation parameters on perforation packing efficiency.

Their model can also examine annular packing efficiency based on washpipe size, deviation angle, gravel size, and carrier fluid properties. The coefficients in these correlations were estimated from the experimental analysis, which depended on initial physical properties of gravel and carrier fluid, parameters of the test wellbore, and flow behaviours.

The Paden model has some limitations in simulating the actual gravel packing process of a well in the field because of its empirical nature. For instance, it does not determine the exact location of voids, or when and where the sandout points have occurred during a given gravel pack treatment.

3. Wahlmeier and Andrewsi numerical model

Wahlmeier and Andrewsi developed a numerical model to design and evaluate gravel-packing treatments. They partitioned the wellbore with cross-sectional slices to have a pseudo-3-dimensional structure. These slices were arranged parallel and normal to the axial direction. Conservation of mass and momentum was first expressed in term of a set of partial differential equations to describe the transport process of slurry in the wellbore. They were then converted to ordinary differential equations by finite difference method, prior to combining with an iterative scheme to solve for the materials and forces involved during the transport process for a time increment.

The gravel pack simulation capabilities of the Wahlmeier-Andrews model included:

- Vertical and deviated wells
- Tapered casing and toolstring
- Multiple formation zones
- Multiple perforated intervals
- Multiple fluids
- Squeeze and circulation modes

Their numerical model when compared with the experimental results obtained from an 18 ft long, 6.2 in. diameter wellbore model reportedly gave good results.

The numerical model of Winterfield and Schroeder was designed to simulate gravel placement in the perforations and annulus of a large, full scale, 100 ft long, physical model. The model wellbore was numerically divided into cross-sectional slices in the axial direction. A finite element method was applied to solve the system of non-linear partial differential equations which were derived to describe the mass and momentum balances. The method requires Newton iteration in determining the time dependent quantities. This model has the following reported capabilities:

- Applicable to vertical, horizontal and deviated orientations
- Various wellbore configurations
- Predicts location of voids, point of sandout, of voids, degree of gravel packing in perforations, and in casing screen annulus
- Multiple fluids

The Winterfeld-Schroeder numerical model results were successfully compared with the experimental runs of the physical gravel pack model. Modifications were required in the mathematical derivations to take into account reservoir characteristics when applied to wells in the field.

2.14. Current Three Dimensional Numerical Simulator

The current three-dimensional numerical simulator can monitor the transport process of the slurry in both axial and angular directions for the gravel pack zone in the wellbore.

Capabilities of current simulator:

- Can determine local packing efficiency of gravel at a particular point within the casing screen annulus can be determined during a treatment design.
- The effect of perforation density and the optional range of perforation phasing angles can be evaluated as to the amount of gravel packed in them and their influence in annular sand placement
- Allows inclusion of recent improvements in perforating technology, especially for highly deviated and horizontal wells.
- Situations may be handled where the potential for an incomplete pack may exist (caused by settling) on the top portion of the casing screen annulus, even after slurry has filled all perforations

The current model was designed to simulate all the flow paths performed during a conventional gravel pack treatment, which includes individual or combinations of lower circulation, upper circulation, and squeeze. The process of pumping fluids from the surface to downhole is monitored from the initiation of the treatment to the completion of pumping all the fluids, or by surpassing the maximum pump pressure or fracture pressure.

Mathematical derivations

To simulate the slurry transport process in three-dimensional orientation, the wellbore annulus between the gravel pack packer and the sump packer is numerically segmented into units of control volumes, called sector elements, in both axial and angular directions (Fig. 1). This segmenting scheme provides detailed descriptions of gravel transport and its buildup in the annulus. The screen washpipe annulus, washpipe, and other flow areas above the gravel pack packer need to be segmented only in the axial direction.

The number of sector elements divided in angular directions is provided as an optional variable, while the number of axial segments is determined by the optional segment lengths

Each sector element is represented by (i,j) where the subscripts i and j denote the axial and angular directions, respectively. Each sector element is assumed to possess homogeneous properties within its control volume. For example, sector element (I,j) may have a different gravel concentration (i.e., void volume fraction) in comparison to that of sector (I,j-1).

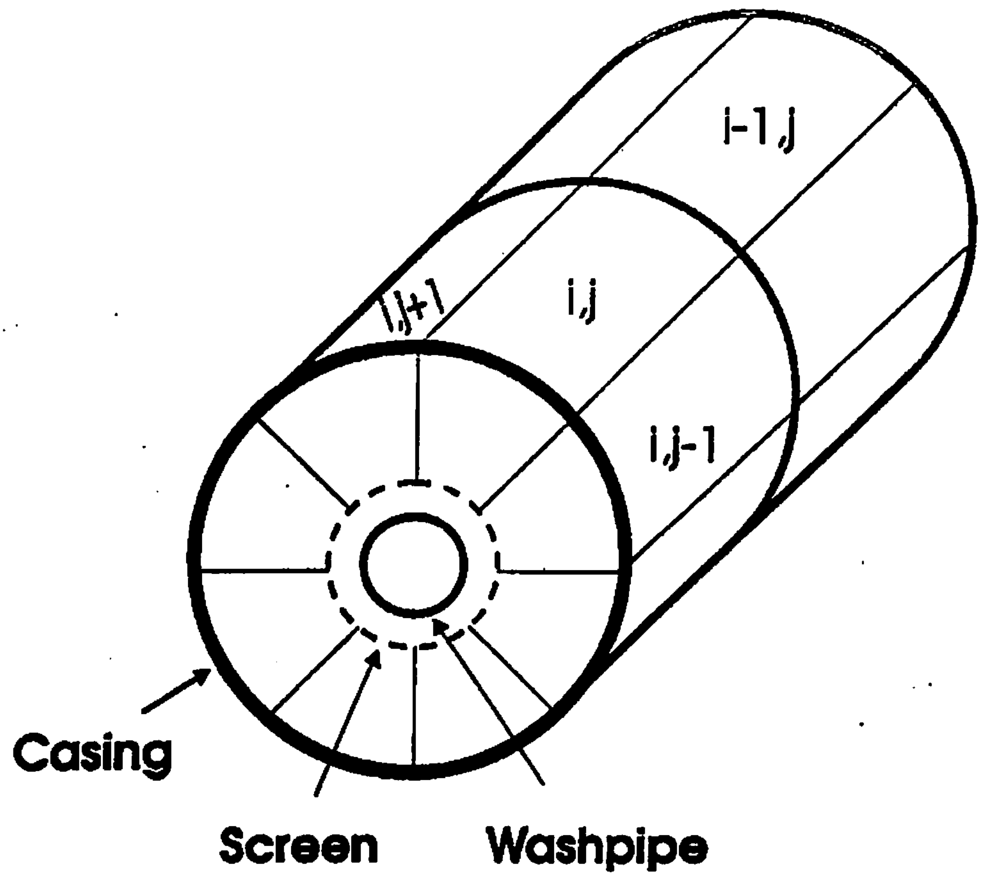

Fig.2.16. Division of borehole in control volumes.

The existing axial sectors, when containing more than one fluid, must be further divided into smaller sectors until each sector contains only a single fluid. This process is repeated for each time increment in which a certain volume of a fluid is being pumped into the sector. As a result, the number of sectors alters dynamically with time. They can be increased or decreased depending on flow rates, fluid volumes, and wellbore parameters.

2.14.1. Transport Processes and Gravel Placement Behaviour

Conservation of mass:

Mass balance is derived in terms of flow rates for sand-free fluid transported through the sector with the assumptions that there is no reaction and accumulation within the controlled volume of the sector element.

Rate in = Rate out

Or,

$$\boxed{(Q\varepsilon)_{i-1,j} + \left(Q_{si_\perp}\right)_{i,j+1} + \left(Q_{si_a}\right)_{i+1,j} = \left(Q_f + Q_s + Q\varepsilon + Q_{si_\perp} + Q_{si_a}\right)_{i,j}}$$

Where,

Q = flow rate of liquid (sand free or sand laden)

ε = volume fraction of sand free fluid

$Q_{si\perp}$ = flow rate of sand free fluid entering or leaving the sector in the angular direction caused by displacement of settling sand.

$Q_{si\,a}$ = flow rate of sand-free fluid entering or leaving the sector in axial direction caused by displacement of settling sand

Q_f = rate of fluid leaking off to the formation

Q_s = rate of fluid filtering through the screen

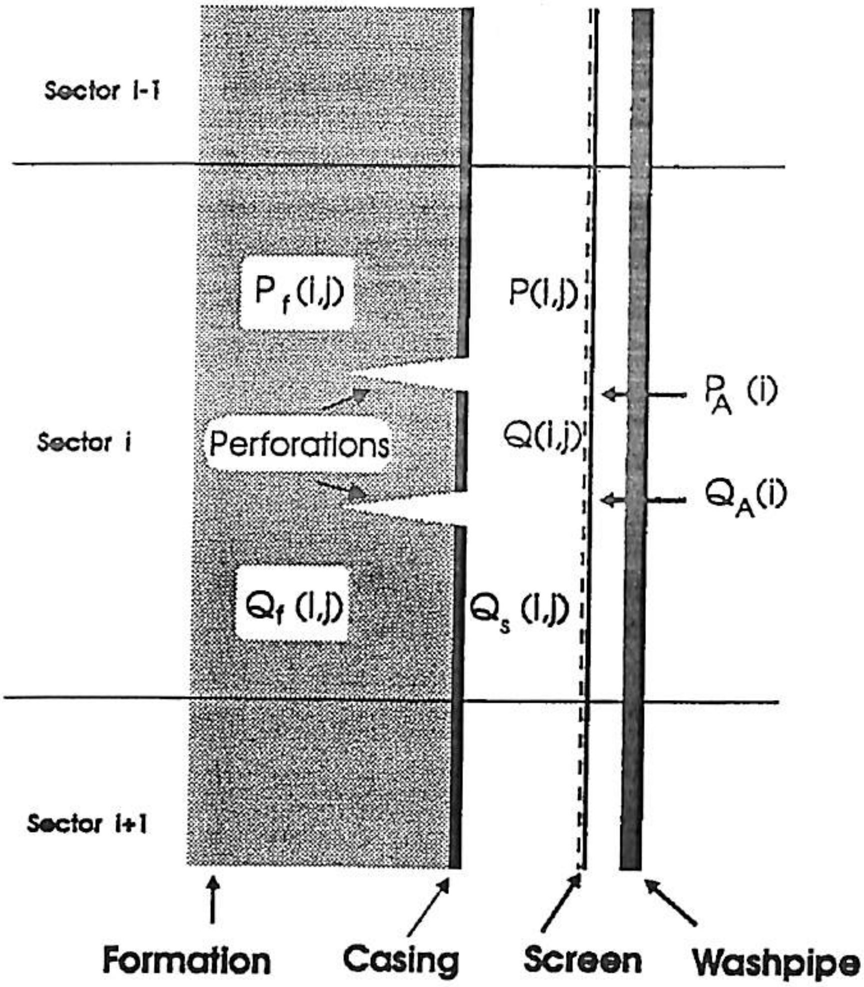

Fig.2.17. Showing wellbore completion geometry

There must be a driving force for the fluid to flow through a given geometry. The fluid flows either through an open cross sectional area or through a filter medium. This driving force is expressed in terms of differential pressure (ΔP), and is directly proportional to the flow rate Q as,

$$\Delta P = C * Q$$

Where,

C = Coefficient relating transport properties of the fluid and the geometry through which the fluid is flowing.

- For fluid leakoff we have,

$$\boxed{\left[\frac{P_{i-1,j} + P_{i,j}}{2}\right] - P_f = (C_f)_{i,j}(Q_f)_{i,j}}$$

Where,

P = local pressure in the casing screen annulus

P_f = formation pressure

C_f = coefficient related to properties of formation and of fluid flow in formation

- For fluid filtration induced by differential pressure,

$$\boxed{\left[\frac{P_{i-1,j} + P_{i,j}}{2}\right] - \left[\frac{(P_{swa})_{i-1} + (P_{swa})_i}{2}\right] = (C_{scr})_{i,j}(Q_{scr})_{i,j}}$$

Where,

P swa = local pressure in screen washpipe annulus

C swa = coefficient related to filtration through gravel packed screen

- Momentum balance for fluid flowing in the casing screen annulus,

$$\boxed{P_{i-1,j} - P_{i,j} + \rho_s h = (C_{csa})_{i,j} \left(\frac{Q_{i-1,j} + Q_{i,j}}{2} \right)}$$

Where,

ρ = fluid density

h = true vertical length of sector element

C_{csa} = coefficient related to flow in casing screen annulus

Mass and momentum balances in screen washpipe annulus

$$\boxed{(Q_A)_{i-1} + \sum (Q_{scr})_{i,j=1,jmax} = Q_{A_i}}$$

and,

$$\boxed{(P_{swa})_{i-1} - (P_{swa})_i + \rho_L h = (C_{swa})_i \left(\frac{(Q_A)_{i-1} + (Q_A)_i}{2} \right)}$$

Where,

Q_A = flow rate of sand free fluid in screen washpipe annulus

P_{swa} = local pressure in screen washpipe annulus

ρ_L = density of sand free fluid

C_{swa} = coefficient related to flow in screen washpipe annulus

These mass and momentum equations are established for each sector element, starting from the downward path in the tubing and casing screen annulus, and returning to the surface through the washpipe and casing tubing annulus. The unknowns are solved at each time step without any iterative approach. The results can be easily obtained by solving the set of linear, simultaneous equations.

Initial known variables:

- pump rate,
- surface pressure,
- wellbore dimensions and
- formation pressure

Results:

- flow rates through annulus of sector elements,
- flow rates through screen and formation,
- local pressures throughout the wellbore,
- flow rate of fluid returning to surface

The amount of sand packed in the perforations is computed from the mass balance of fluid leak off through perforations and the screen respectively, which is potentially dependent on the rheological properties of the slurry, friction pressure and effect of gravel settling rate.

Determination of frictional drop

Frictional pressure drop during transport of gravel pack fluid is evaluated by classifying the fluid into sand-free or sand-laden fluid, and whether the fluid is expecting laminar or turbulent flow.

$$\boxed{\Delta P = \frac{2 \rho f L V^2}{D g_c}}$$

Where,

L = segment length of tubing

f = non dimensional friction factor.

The friction factor f is determined on the basis of flow, whether it is laminar or turbulent.

Fluid leaking off to formation

Each band of fluid leaking off to the formation can be determined as a function of time or volumes pumped. The leak off rate and bandwidth of the individual fluids are controlled by the differential pressure (between formation screen annulus and formation pressures), fluid transport property, and formation permeability.

$$\boxed{Q_{LO} = Q_{LO}\left(\Delta P, \mu_i, k, D_i\right)}$$

Where,

Δ P = differential pressure

μ = fluid viscosity

K = formation permeability

D = distance up to which the fluid penetrates into the formation

The knowledge of fluid lost to formation, based on analysis of the gravel placement design enables the completion engineer, to decide whether or not to minimize the leak off rate by using a high viscosity "prepad" fluid, to act as a control system

Effect of gravel settling:

The degree of sand settling depends on a number of factors, including density and transport properties of carrier fluid, pump rate, gravel concentration, and gravel size. Based on Stokes equation, Steinour derived a correlation for hindered settling velocity of suspensions by taking into account the densities of the gravel and base fluid, the particle size and concentration (e.g., 0), and the viscosity of the slurry:

$$V_H = \frac{d_p^2 * (\rho_p - \rho_f) * g * (1 - \phi)^2}{18 * \mu_s}$$

Where,

V_H = hindered settling velocity

d_p = gravel particle diameter

ρ_p = gravel density

ρ_f = carrier fluid density

g = gravitational constant

ϕ = volume fraction of gravel in slurry

μ = viscosity of slurry

The rate of sand settling, orientation of wellbore, and fluid leakoff rate determine the sand accumulated in each vector. Implementation of sand settling effect into the model enhances its capability in handling various gravel pack execution scenarios. By differentiating the transport properties of slurry carrier fluids, ranging from highly visco-elastic polymers to simple Newtonian brine, the model allows selection of the best gravel pack fluid which is likely to give optimal gravel placement.

This model is meant to serve as a research tool both to evaluate current technology and practices and to investigate alternate, and as yet, untried methods. For field applications, this gravel packing simulator is particularly beneficial when:

- Gravel packing in areas where there is little or no treatment history.
- Estimating the efficiency of a treatment design before performing the actual treatment.
- A treatment design that has been resulting in poor gravel packs needs troubleshooting.
- Anticipating near maximum treating pressure limits (mechanical and/or formation).
- Developing new fluids, equipment, and/or procedures.

2.15. Special Features of Numerical Simulator

- **Reservoir characteristics**: The decision to perform a gravel pack treatment on a well is in part dictated by the conditions of the reservoir formation. These conditions involve formation pressures, permeability, porosity, consolidated, or unconsolidated formation. Based on these factors, the present gravel pack simulator has the capability to predict consequences as a result of applying certain design treatment criteria. It indicates that, for example, formation parting is likely if the pump rate exceeds the upper limit. The penetration depths of leakoff fluid into formation for each fluid pumped downhole is also determined to help evaluate the degree of formation damage caused by fluid interaction.

- **Gravel pack fluid properties**: The effects of transport properties of carrier fluids and gravel-laden fluid can be conveniently evaluated with the numerical gravel placement model. This model is being used intensively as a tool to assist in the chemical formulation of the fluids with desired rheological properties.

- **Perforation parameters**: This model considers the packing process in the perforations and the packing efficiency based on the effects of fluid loss, gravel concentration, carrier fluid viscosity, differential pressure, perforation density, phasing angle, and wellbore deviation angle. These all factors contribute and control the degree of pack completion in perforations. In addition, the current model allows simulation of prepacking of perforations as an alternative for full gravel pack treatment and provides options to handle open hole gravel packing (no perforations involved).

- **Wellbore circulation and tool design:** The simulator also helps in the design of the wellbore equipment and dimensions. Some of these considerations are:

    - Effect of fluid properties on the packing efficiency in casing screen annulus.
    - Effect of perforation phasing, density, size, and length on the packing process of the casing screen annulus.
    - Effect of washpipe size on the packing efficiency of casing screen annulus.
    - Effect of deviated wellbores on the packing efficiency.
    - Flow behaviour of slurry in annulus, sand dune effect (equilibrium bank).
    - Effect of multiple screen sections instead of one main screen, including the upper and lower telltales.
    - Effect of eccentric (off-centre) pipes and liners in wellbore effect of prepacked screen or liners instead of conventional wire-wrapped screen.

3. OVERVIEW OF EQUATIONS AND METHODS USED IN CASE STUDY

For designing a gravel pack completion with a screen, it is important to evaluate formation parameters as well as those of gravel pack sand.

The objective of the case study is the calculation the following parameters

1. Gravel particle diameter for annulus and perforation both.
2. Settling velocity for gravel.
3. Gravel pack permeability K_g.
4. Optimum wire spacing for screen size.
5. Volume of gravel to be pumped in annulus.
6. Volume of gravel to be pumped in perforation

3.1. Gravel Pack Diameter

The samples should be taken at each lithology change or every two to three feet. Sieve analysis provides grain size distribution on percentile basis. Sieve analysis consists of placing a formation sample at the top of a series of screens, which have gradually smaller mesh sizes. The sand grains in the original well sample will fall through the screens until it comes across a screen through which that grains size cannot pass because the openings in the screen are too small. By weighing the screens before and after sieving, the weight of formation sample engaged by each size screen can be determined. The cumulative weight percent of each sample retained can be plotted as a comparison of screen mesh size on semi-log coordinates to obtain a sand size distribution plot. Reading the graph at the 50 percent cumulative weight gives the median formation grain size diameter which was found to be 1.11×10^{-3} in.

There are several methods for the selection of gravel-pack sand size to control the production of formation sand. The technique most widely used today was developed by Saucier. The basic premise of Saucier's work is that optimum sand control is achieved when the median grain size of the gravel pack sand is no more than six times larger than the median grain size of the formation sand.

Optimization of gravel pack sand size can be accomplished using the following guidelines:

When:- $D_{50}/d_{50} < 5$

Then, there is good sand control but restricted flow due to low gravel pack permeability.

When:- $5 < D_{50}/d_{50} < 7$

Then, there is good sand control and maximum pack permeability.

When:- 7 <   /   < 9

Then, there is good sand control but restricted sand flow due to formation sand invasion of gravel-pack sand.

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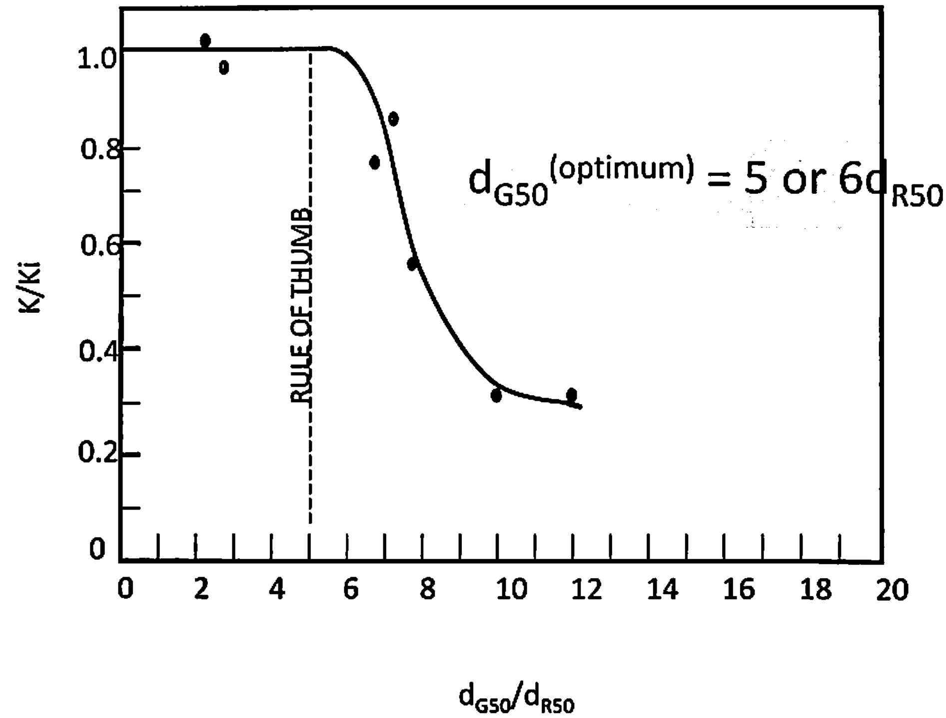

Fig.3.1. Results of Saucier's gravel size experiments

3.2. Settling Velocity

Stokes law, in which the velocity of a single particle falling through a liquid medium is

=(   )   (-   ) /μ

Where,

is the settling rate in ft/s
is the average particle diameter in in.,

μ is the fluid viscosity in cp,
and   are the specific gravity of the particle and the fluid respectively.

3.3. Gravel Permeability

It is determined from the gravel pack grain size effectively,

US Sieve Number	Grain Diameter in.	Median Grain Diameter in.	Median Grain Diameter mm	Perm. darcies	Usual Wire Spacing in.
10 to 20	0.033 to 0.079	0.048	1.219	500	0.024
10 to 30	0.023 to 0.079	0.051	1.295	191	0.018
20 to 40	0.0165 to 0.033	0.023	0.584	121	0.012
30 to 40	0.0165 to 0.023	0.019	0.483	110	0.012
40 to 50	0.0117 to 0.0165	0.014	0.356	66	0.010
40 to 60	0.0098 to 0.0165	0.013	0.330	45	0.008
50 to 60	0.0098 to 0.0117	0.011	0.279	43	0.008
60 to 70	0.0083 to 0.0098	0.009	0.229	31	0.006
50 to 70	0.0083 to 0.0117	0.0101	0.257	20	0.005
40 to 100	0.006 to 0.0165	0.009	0.229	30	0.004

Table 3.1. Mesh size, permeability and wire spacing

Optimum Size for Screens or in other words the wire spacing should be done keeping in mind the smallest size of particles that can be generated down hole. The most common screen opening designs are listed. The selection is based on the size of the gravel and best suited option from the recommended sizes is made.

3.4. Wire spacing

Screen diameters are adjusted to provide at least two inch clearance from the well bore to minimize the chances of gravel bridging and also to provide a tight pack. It is determined from the above table.

4. CASE STUDY ANALYSIS

Problem: -

A client company xyz has drilled a well in KG basin which is 10,500 ft deep. It desires to gravel pack (along with screen) a zone from 9500 to 9600 ft (100 ft) which is the producing zone. This client company contracts a service company ABC (us) for the job. Details are provided below.

Data provided by client company:-

Total Depth 10,500 ft

Completion Interval 9500 ft to 9600 ft

Tubing used

O.D. = 3.5" = 0.291 ft

I.D. = 2.6" = 0.246 ft

Capacity = 0.00677 bbl/ft

Weight = 14.3 lbs/ft

Casing used

O.D. = 7"

I.D. = 6.350"= 0.529 ft

Capacity = 0.03945 bbl/ft

Weight = 23 lbs/ft

Perforation length (L) = 2 ft (8 SPF)

Perforation diameter = 0.01332 in.

Available data with us :-

Particle density (D_p) =22.07 ppg = 165.06 lbs/ft^3

Density of carrier fluid (D_c) =8.6 ppg = 64.31 lbs/ft^3

In order to design a gravel packing completion using a screen, we can break the designing process into the following modules:

1. To determine the gravel particle diameter for annulus and perforation both.
2. Settling velocity for gravel.
3. Gravel pack permeability $K_{g.}$
4. Optimum wire spacing for screen size.
5. Volume of gravel to be pumped in annulus.
6. Volume of gravel to be pumped in perforation.

Now we shall take up these modules one by one to complete the assignment.

1. **Determination of gravel particle diameter for annulus and perforation both.**

Formation sand is of uniform texture.

The samples were taken at each lithology change or every two to three feet. As most pay zones have different permeabilities, average grain sizes, porosities and strengths. Thus, as a result experiments the average diameter of sand was found out to be,

$D_{sand} = 1.11\ x\ 10\text{^}(-3)$ in.

It was deduced that we will be using two different sizes of gravel

Gravel_1- to be used in annulus

Gravel_2- to be used in perforations.

Total height to be gravel packed is 100 ft. We take extra 5 ft above & 5 ft below, so a total of 110 ft is to be gravel packed.

Reason:-

We take these extra heights on top and bottom for better efficiency of the job.

$$D_{gravel1} > P_{erforation} > D_{gravel2} > D_{sand}$$

The designing of Gravel 2 is done first.

Using the Saucier's method, since it is most widely used and loss of fine or coarse particles does not affect result as much as with other method.

$$D_{gravel\ 2} = 6\ X\ D_{sand}$$

(Where D_{sand} is given to us)

$$\text{So, } D_{gravel\ 2} = 6X\ 1.11X10^{-3} = 6.66X10^{-3} \text{ in.}$$

Now sizing of Gravel-1 is done.

According to formula for settling velocity for gravel:-

$$V_s = (D_p - D_c) * p_d^2$$

Where,

D_p = Particle density

D_c = Density of carrier fluid

P_d = particle diameter

Dimensional analysis of above formula:-

$$= (D_p - D_c) p_d^2$$

$$= M/L^3 \times L^2$$

$$= M/L$$

Which indicates that if we find the total mass of gravel to be pumped divided by 110 ft gives us one value of settling velocity (V_{s1}).

Now,

Since we know the values of D_p and D_c, so we can find out the settling velocity (V_{s2}) by varying various values of p_d until we get,

$$V_{s2} = V_{s1}$$

So, we get the size of $D_{gravel-1}$.

BUT,

This adverse permutation and combination to fit this value of p_d such that it is practically feasible is done by software (which we lack), therefore, we at this instance take $D_{gravel-1}$ = 0.08" (which is most widely used).

And, as we know,

$$D_{gravel-1} = 6 \text{ X } D_{perf.}$$

$$D_{gravel-1} = 6 \text{ X } 0.01322 = 0.0799 = 0.08"$$

2. **Settling velocity for gravel.**

Since we have calculated $D_{gravel-1}$, we need to find the settling velocity (mass flow rate)

$$V_s = (D_p - D_c) p_d^2$$

$$= (165.06 - 64.31) \times (6.66X10^{-3})^{\wedge}2$$

$$= 100.75X4.76X10^{-5}$$

$$V_s = 0.00479 \text{ lbs/ft}$$

3. **We need to know for better job efficiency whether our gravel pack is effectively permeable**

US Sieve Number	Grain Diameter in.	Median Grain Diameter in.	Median Grain Diameter mm	Perm. darcies	Usual Wire Spacing in.
10 to 20	0.033 to 0.079	0.048	1.219	500	0.024
10 to 30	0.023 to 0.079	0.051	1.295	191	0.018
20 to 40	0.0165 to 0.033	0.023	0.584	121	0.012
30 to 40	0.0165 to 0.023	0.019	0.483	110	0.012
40 to 50	0.0117 to 0.0165	0.014	0.356	66	0.010
40 to 60	0.0098 to 0.0165	0.013	0.330	45	0.008
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60 to 70	0.0083 to 0.0098	0.009	0.229	31	0.006
50 to 70	0.0083 to 0.0117	0.0101	0.257	20	0.005
40 to 100	0.006 to 0.0165	0.009	0.229	30	0.004

Table 4.1. Mesh size, permeability and wire spacing

As we know our $D_{gravel-1}$ so from this chart we can get our permeability of our gravel pack = 500 Darcies.

4. **Correct wire spacing should be known in order to estimate the sizing of wire mesh and screen.**

US Sieve Number	Grain Diameter in.	Median Grain Diameter in.	Median Grain Diameter mm	Perm. darcies	Usual Wire Spacing in.
10 to 20	0.033 to 0.079	0.048	1.219	500	0.024
10 to 30	0.023 to 0.079	0.051	1.295	191	0.018
20 to 40	0.0165 to 0.033	0.023	0.584	121	0.012
30 to 40	0.0165 to 0.023	0.019	0.483	110	0.012
40 to 50	0.0117 to 0.0165	0.014	0.356	66	0.010
40 to 60	0.0098 to 0.0165	0.013	0.330	45	0.008
50 to 60	0.0098 to 0.0117	0.011	0.279	43	0.008
60 to 70	0.0083 to 0.0098	0.009	0.229	31	0.008
50 to 70	0.0083 to 0.0117	0.0101	0.257	20	0.005
40 to 100	0.006 to 0.0165	0.009	0.229	30	0.004

Table 4.2. Mesh size, permeability and wire spacing

Again, as we know the $D_{gravel-1}$ and permeability, so using above chart we know the used wire spacing as 0.024".

5. Volume of gravel to be pumped in the annulus.

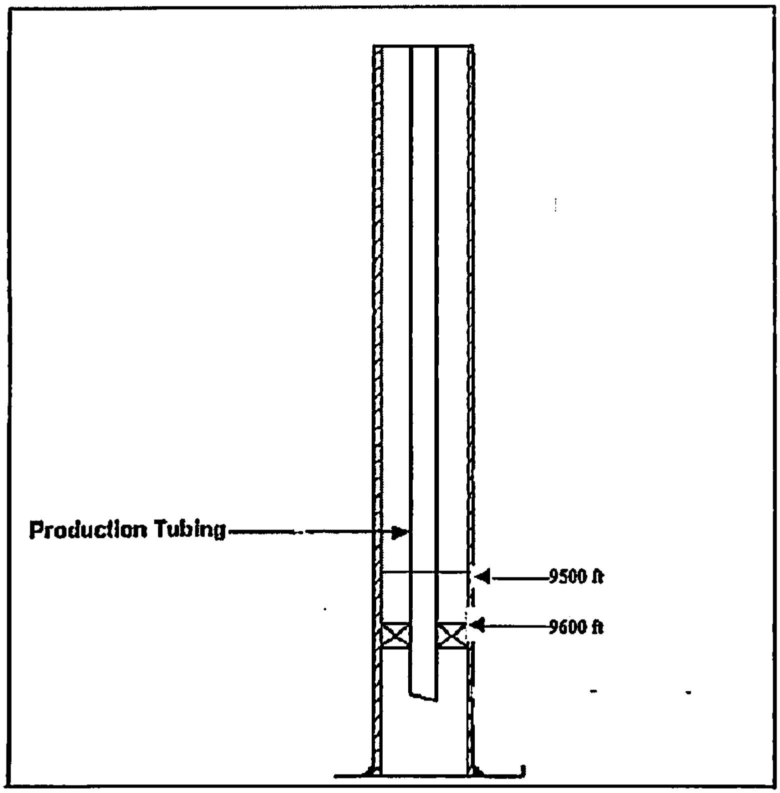

Fig.4.1.well bore

We need to gravel pack the above zone with gravel of 0.08" diameter.

Mechanism:-

The gravel will be pumped first and settle at the packer. Then as $gravel_1$ with carrier fluid is pumped and as they are heavier will replace the lighter $gravel_2$ and these particles will surge into perforations as there are voids present. Also the use of $gravel_2$ will help as if there is any leak in packer at the bottom, it will go and seal it and make our job perfect.

Conversion factors:-

1 ft = 12"

1bbl = 5.615 ft^3

1bbl = 42 gallons

1 ft^3 = 7.479 gallons

The volume of $gravel_1$ req. = annulus volume for (110 ft)

$$= \pi/4[ID_{casing}^2 - OD_{tubing}^2] X110$$

$$= \pi/4[0.5290^2 - 0.291^2] X110$$

$$=16.85 ft^3$$

The volume of $gravel_1$ required or pumped = 3.001 bbl

Now, using the wire spacing data and our availability,

Screen OD = 4.5" = 0.375 ft

Therefore, we can apply the screen with mesh some amount of annular volume initially calculated will be reduced.

That reduction in volume is calculated as follow:-

Volume reduced = $\pi/4[OD_{screen}^2 - OD_{tubing}^2]$ X110

$$= \pi/4[0.375^2 - 0.291^2] X110$$

$$= \pi/4[0.14 - 0.08] X110$$

$$= 4.74 ft^3$$

Now, two methodologies can be applied:-

1. Either we pump a volume of gravel which is equal to (total initial annular volume) – (volume reduction + safety factor ($1 ft^3$))

= $17 ft^3 - 4.74 ft^3 + 1ft^3$

Volume of $gravel_1$ pumped =13.26 ft^3

So, efficiency = {13.26 ft^3/17}X 100 = 78%.

2. The second way is to pump the total volume of $gravel_1$ (17 ft^3) and re circulate back the extra to the volume reduced by the screen

So, job efficiency = {(17 ft^3 – 4.74 ft^3)/17} X100

= 72%.

Now, we also need to know the total volume of gravel-2 to be pumped which in term is equal to the volume of total perforation in 110 ft.

Perforation length (L) = 2 ft (8 SPF)

Perforation diameter = 0.01332 in.

As, volume of one perforation = $1/3\pi r^2 h$

$$= 1/3 x \pi x \{(1.11 x 10^{-3})/2\}^2 x 100$$

$$= 3.22X 10^{-5} ft^3$$

As perforation is 8 shot per foot (given), then

Volume of 8 perforation = $3.22X10^{-5}X8 = 2.5X10^{-4}$ ft^3

Total Volume of perforation in 100 ft = $2.5X10^{-4}X100 = 0.025$ ft^3= $4.452x\ 10^{-3}$ bbls.

5. RESULTS AND DISCUSSIONS

In completing wells in poorly consolidated formations, consideration is given to sand production problems likely to arise during the operation of the well. The erosion and plugging effects of sand entrained in produced fluids are well known and can seriously reduce well productivity.

Since the early application of gravel packing, there have been several new processes introduced with varying results. Results from these new techniques varied widely, so the industry moved rapidly from one process to another, but most often returned to gravel packing. In the 1980's and 1990's made some breakthroughs to improve productivity in gravel pack completions. Therefore, gravel pack remains the most popular and most reliable form of sand control methodologies.

A case study for a well in KG basin was found to be a candidate for sand control completion. A design plan for its completion using gravel pack along with a screen has been formulated and the results from the data are obtained as follows:

- Sizes of Gravel pack sands were found to be 8×10^{-3} inch and 6.66×10^{-3} in diameter respectively for annular and perforation gravel.
- Settling velocity for the given data was found to be 0.00479 lbs/ft.
- The permeability of the gravel pack was 500 darcies.
- Wire spacing for the screen should be 0.024 in.

Gravel packs have a slight initial cost over other types of control mechanisms. These methods of favourable reliability, cost, versatility make gravel packing the preferred method of sand control in most, but not in all cases.

Advantages:

- Easiest gravel packing method because of large availability of annular space between the screen and the formation. It also presents the least difficulty in transportation of gravel since the gravel does not have to be carried into the perforations.
- Highest theoretical productivity because there is no restriction to flow in perforation tunnels.
- Lowest possible velocity for produced fluids flowing through the gravel pack
- Less expensive as the casing and cementing costs are eliminated

Disadvantages:

- It is more difficult to control unwanted water and gas production, or injection into thief zones
- Hole stability poses a problem during placement in case annulus is sand filled the gravel is placed
- Screen is more easily plugged as against a cased hole
- Generally limited to a bottom interval in case of multiple zone completions

6. CONCLUSIONS AND RECOMMENDATIONS

Design of gravel pack depends on various factors. A technique used successfully in one well may be of no use in the other well. We have to consider whether it is an open hole or cased hole completion. The well bore diameter also plays a major role. The success of gravel pack depends on selection of proper gravel size, proper screen slot size and the placement of gravel at the proper location and then holding it in place for the life of the well. A major challenge faced by gravel pack technique is in its application in highly deviated and horizontal wells due to non-uniform packing of grains brought about by gravity and creation of voids.

Gravel packs should include the following design features:

- Sand free operation after development.
- Give lowest possible resistance to permeation.
- Offer low entrance velocities.
- Be resistant to chemical attack and have an efficient service life.

The gravel pack should ensure that the completed well operates free of sand; thus the particle size of the pack depends upon the particle size of the aquifer. Gravel pack design should be guided by standard sieve analysis.

It is evident from the variety of claims made for well screens and gravel packs that further research is necessary. It is suggested that the following points need further investigation:

- Improved design of nonblocking opening
- Design consideration of screen resistance to chemical attack.
- Best type of gravel and optimum thickness of the pack.
- Head loss through the screen and pack.

The potential benefit to the industry of improving predictive measures for sand production. The operator's predictive capability is the key enabling component for this holistic approach and needs to be able to answer three questions:

- When will sand be produced?
- How much sand will be produced?
- What are the characteristics of the sand being produced?

Predicting that a reservoir will produce sand at some point in a well's life is relatively easy with today's tools.

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APPENDIX

O.D., outer diameter
I.D., inner diameter
D_{sand}, Diameter of formation sand
D_p, density of particle
D_c, density of carrier fluid
$D_{gravel\,1}$, diameter of gravel to be used in the annulus
$D_{gravel\,2}$, diameter of gravel to be used inside the perforation
$D_{gravel\,1}$, diameter of gravel to be used in the annulus
V_s, settling velocity
P_d^2, diameter of the particle
Q, flow rate of liquid (sand free or sand laden)

E, volume fraction of sand free fluid

$Q_{si\perp}$, flow rate of sand free fluid entering or leaving the sector in the

$Q_{si\,a}$, flow rate of sand-free fluid entering or leaving the sector in axial direction caused by displacement of settling sand

Q_f, rate of fluid leaking off to the formation

Q_s, rate of fluid filtering through the screen

P, local pressure in the casing screen annulus

P_f, formation pressure

C_f, coefficient related to properties of formation and of fluid flow in formation

P swa, local pressure in screen washpipe annulus

C swa, coefficient related to filtration through gravel packed screen

ΔP, differential pressure

μ, fluid viscosity

K, formation permeability

D, distance up to which the fluid penetrates into the formation