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Abstract

This thesis aims to give a general insight into sand control and various sorts of sand control measures and applications of sand control tools. Special focus will be given to expandable sand screens – a technology which came about in the late 1990's through the use of flexible, expandable tubulars as base pipe in sand screens. More specifically Darcy's Hydraulic Endurance Screens, a compliant sand screen system using hydraulic activation, and the future use of these will be discussed. This technology has been successfully deployed in a test rig environment(System Integration Test)¹⁴ and was planned to be field tested for Statoil on the Statfjord field(Well B-03)¹⁴, an operation which eventually was delayed as the 9 5/8" casing above the reservoir could not be cemented due to heavy losses. Insight will be given into possible future use of the Hydraulic Endurance screens - specifically in water injector wells.

Sand control is one of the key aspects to be considered when planning the completion of a well. Sand control tools may not always be necessary in a well - at least not from the start – and whether or not these are to be installed is one of the first things that need to be decided on. However, in poorly consolidated or unconsolidated sandstone reservoirs sand production is one of the biggest challenges for the completion and production engineers and some sort of sand control tools will almost always have to be installed at some point during the wells lifecycle. These tools or sand control methods may include, but are not limited to, slotted or pre-drilled liners, gravel packs, frac packs, selective perforations, oriented perforations or as mentioned above, different types of sand screens. All of these sand control measures and their use will be discussed. In water injectors, sand production poses certain specific challenges. These challenges usually arise not during the actual water injection, but when for various reasons the injection has to be stopped and the well is shut-in. These "water injector"-specific challenges include reservoir cross-flow between formation layers of different permeability, the "water hammer" phenomenon, well-to-well backflow, thermal fractures and gravel loss into fracture systems. If one or more of these factors come into play, sand production may be initiated and a situation where the injection well is filled with sand may be the case. It is the aim of this thesis to discuss and analyze whether or not the Darcy's Hydraulic Endurance Screens may solve or improve on these challenges in water injectors and how they compare to the Open Hole Gravel Pack and the Stand Alone Screen, specifically with a possible use at the Johan Sverdrup field in mind. A theoretical case of a field installation of Darcy's Hydraulic Endurance Screens in a water injector well at the Johan Sverdrup field will be presented.

It was found that Darcy's Hydraulic Endurance Screen is a fully viable alternative to Open Hole Gravel Packs and Stand Alone Screens in water injector wells. It is particularly well suited for the Johan Sverdrup field as the innovative utilization of a solid base pipe together with a compliant screen design enables among other things injection selectivity with the possibility of future shut-off, integration of Inflow Control Devices and easier filter cake removal - factors that may be vital in the two-zone reservoir encountered at the Johan Sverdrup field. Uncertainties with the Hydraulic Endurance screens mostly relate to the lack of experience running the system.

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Abbreviations

LPSA = Laser Particle Size Analysis

OHGP = Open Hole Gravel Pack

SAS = Stand Alone Screen

WWS = Wire-Wrapped Screen

PPS = Pre-Packed Screen

ESS = Expandable Sand Screens

EZI = Expandable Zonal Isolation

SET = Solid Expandable Tubular

ICD = Inflow Control Device

RIH = Run In Hole

ECP = External Casing Packer

LCM = Lost Circulation Material

DP = Drill Pipe

HWDP = Heavy-Weight Drill Pipe

RT = Running Tool

PBR = Polished Bore Receptacle

POOH = Pull Out Of Hole

TVD = True Vertical Depth

M/U = Make Up

P/U = Pick Up

OBM = Oil Based Mud

DIF = Drill-In Fluid

ID = Inner Diameter

OD = Outer Diameter

Nomenclature

σ_v = Principal vertical stress

σ_H = Principal horizontal stress, maximum

σ_h = Principal horizontal stress, minimum

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Introduction to Sand Control

Sand production causes excessive wear on downhole- and surface equipment – especially in bends and curves in the flowline and on the choke valve. Downhole, sand screens may erode until they are no longer functional.¹ Decrease of well productivity may also result from sand production. This may happen when sand is produced, but not transported to the surface, hence accumulating downhole and in the end blocking off the whole wellbore. It may also happen when sand is transported to the surface, but accumulates in surface equipment like for example the separator, heater treater or flowline. This is two examples of scenarios that may cause lost time as the well needs to be cleaned. If the sand is in the surface equipment the cleaning may be done manually. If the accumulation of sand is downhole - wireline with bailer or coiled tubing operations may be required. Cleaning is costly both in terms of the extra operations needed and also the lost production time. If sand production is large enough the formation may be weakened to a point where the formation will collapse. A sand formation that collapses towards the wellbore may rearrange and result in lower permeability. Generally the permeability will be lower if a poorly sorted sand formation is rearranged, as the finer grains will then fall into the pore space between the coarser grains and result in decreased porosity and permeability. If a uniformly sized sand formation is rearranged the permeability will most likely be more or less the same. Either way a formation collapse is a worst case scenario and highly undesired.¹ In order to fully understand the need for sand control it might be advantageous to have a look at the factors that induce sand production in the first places, and the alternatives there are to install sand control tools downhole.

Rock Mechanics

Bellarby² lists three main factors in predicting sand production;

1. Rock strength
2. Regional stresses
3. Local loads

Rock strength will depend on the diagenesis and lithification of the mineral grains. These geological terms refer to the deposition, burial, compaction and cementation a rock is subjected to - the processes which transform loose grains to solid rock. Generally, it can be said that older rock formations will be harder than younger rock formations, as the older rock normally will have been buried deeper and compacted more. However, if the rock is protected against the compaction and cementation this may not always hold true. The most accurate method of determining rock strength is from core samples. This however is a costly and time-consuming method and an alternative often used is to interpret and estimate the rock strength from MWD- or wireline-logs.²

Regional stresses refer to the in-situ stresses the rock is subjected to. In rock mechanics it is normal to assume three principal stresses; the vertical stress, σ_v , the maximum horizontal stress, σ_H , and the minimum horizontal stress, σ_h . The vertical stress simply refers to the overburden load subjected on the rock, i.e. the weight of the overlying rock (plus hydrostatic column if it is an offshore well). These stresses are influenced by the tectonic activity in the region, and depending on the magnitude of the stresses one can determine whether there is a normal tectonic regime, a strike-slip tectonic regime or a thrust tectonic regime (Fig.1). Thrust regimes, where the two horizontal stresses

are greater than the vertical stress, are particularly well known for drilling and wellbore stability challenges, which may lead to sand production in the production phase.² Estimating σ_h may be done from Leak-Off Tests, Extended Leak-Off Tests or Mini-Frac Tests. The Extended Leak-Off Test and Mini-frac test may also be used to estimate the maximum horizontal stress, σ_H .^{2,21}

Local loads refer to processes the rock is subjected to due to the drilling of the well, i.e. flow, reduced pore pressure and water reacting with the minerals of the rock.²

Sand Management

When the values of rock strength, in-situ-stresses and local loads have been estimated, analytical techniques are utilized to predict sand production rates for the well. These may be empirical techniques developed specifically for the field in question drawing on previous experiences, or it may be analytical or numerical techniques.²

When the sand prediction modelling has been performed, the need for sand control tools has to be evaluated. One can make a distinction between sand management and sand control. A sand management approach may be used in wells where the probability for sand production is predicted to be low (and if there is sand production this will also be at a low and controllable rate), and any sand production can be managed through adjusting the critical flowing bottomhole pressure. Installing sand control tools will almost always result in increased skin, so if it is not necessary then a sand management approach may often be preferable with respect to production rates.^{1,2}

If applying sand management techniques instead of sand control tools then the factors mentioned above - predominantly erosion of pipe and equipment and sand accumulation either downhole or in surface equipment - need to be fully understood and assessed. Erosion of the flowline and the surface equipment need to be assessed and evaluated. The probability for these scenarios to occur and mitigating measures to be taken if, or when, these scenarios occur need to be planned for. Depending on the sand production rate preventive procedures may be taken – for example “straightening out” bends in the flowline, using stronger and more resistant metals or add thicker joints of pipe in bends and areas where the erosion will be strongest. Separators may also be designed with an automatic sand washing function using internal jets to flush out accumulated sand, to save the time used when having to clean them for sand manually (not to mention the HSE risk).² Secondly, methods of sand detection need to be applied in order to monitor the sand production rate and be able to adjust production parameters accordingly. This will typically mean use of sand detectors (intrusive and/or non-intrusive), or estimating sand production rate from clean-outs in desanders and separators.²

Sand Control

With sand control it is referred to all the physical measures that may be taken to prevent sand from being produced. This may be a sand control tool, like for example a screen, or gravel slurry which is being pumped into the reservoir interval to screen out the sand grains - most commonly a gravel pack or a frac-pack. Techniques like oriented perforations or perforating only the strongest and most competent reservoir intervals are also a form of sand control. A distinction can be made between

cased-hole completions and open hole completions, although some of the tools and techniques can be utilized in both types of completions. As a general rule it can be said that a cased-hole completion is the most reliable as the casing/liner will provide support for the borehole wall and protection for the completion tools. At the same time cased-hole completions are usually associated with higher skin, i.e. lower production rates. Open hole completions on the other hand provide no support for the borehole wall or protection for the completion tools, but are usually associated with zero or negative skin factors and are preferable if applicable.²

Particle Size Distribution

Finding the formation grain size distribution of the reservoir sand is paramount to being able to identify the correct sand control tool and the size and design of this. Samples for particle size analysis is taken from core samples and then analyzed. There are several different analysis techniques, with Laser Particle Size Analysis (LPSA) and dry sieve analysis being the most common.

Dry Sieve Analysis

In this method the grains in the sample is separated, washed, dried and weighed. They are then passed through stacked sieves, where the coarsest sieve sits on the top and the finest sieve on the bottom. After the sample is passed through the stack of sieves the amount of sample material contained in each sieve is weighed. From this percentage of sample material from each sieve the Particle Size Distribution is estimated.¹⁸

Laser Particle Size Analysis

The LPSA is an electronic means of analysis, utilizing a laser beam that is sent through the dispersed sample and measuring the intensity of the light scattered as the beam passes through the sample. The size of the particle is inversely proportionate to the angle of light scatter.¹⁸ If two samples of the same sand is run through the LPSA and dry sieve analysis the results are going to vary. The dry sieve analysis measures the second smallest dimension of the particles, because of the way the particles will orient to pass through an opening. The LPSA on the other hand measures an average of the grains dimensions as the grains flow past the laser beam.¹⁸

The percentile distribution resulting from these tests are then used to choose the correct size of the filter media. Various methods to interpret the PSD into suitable sand control tool and filter media sizing design exists. One of the most commonly applied is Saucier's criteria which states that the median grain size of the filter media should be 5 to 6 times greater than the median PSD size¹⁹, however there are also other approaches to choose the size of the filter media.

Sand Retention Tests

For sand screens there are also two types of sand retention tests that may be used to see how much sand is produced through the screen(when the screen openings are based on the PSD). The Slurry Test simulates a gradual sandface failure, with low-concentration slurry being pumped against the

filter media. In this test only the sand grains that exceed the openings in the filter media are retained.¹⁸

The Pre-pack test simulates full hole collapse, where a pack is placed on the filter media and clean fluid is pumped through the sample (and filter media). In this test there are two processes of retaining sand; sand exclusion like with the Slurry Test, i.e. the sand grains too large for the openings are retained, and bridging as the sand particles build up towards the screen.¹⁸

By measuring the pressure build-up during a Slurry Test it is possible to estimate the quality of sand retention. With good sand retention the pressure build-up should be steady. If the sand is not retained properly the pressure curve will be erratic as sand passes the screen.²⁰

Sand Control Methods

The choice of sand control method depends on several factors, including reservoir characteristics, regional preferences and economic considerations. For example, Price et al³ estimated in 1998 that in the Gulf of Mexico over 50% of the sand control installations was frac-packs and around 30% were high-rate water packs(a form of gravel pack), whereas in the UK sector of the North Sea around 70% of the sand control installations are horizontal open hole Stand-Alone Screens. The preferences of sand control method clearly vary from region to region.

A distinction can be made between cased-hole completions and open hole completions, although the tools used in both types of completion will often be the same (i.e. Open Hole Gravel Packs and Cased-Hole Gravel Packs). Dependent on whether an open hole completion or cased hole completion is wanted or needed, various sorts of sand control tools may be applied. These include different types of sand screens, expandable sand screens, non-expandable compliant sand screens, slotted or pre-drilled liners, gravel packs or frac-packs, all of which are explained in more detail below.

Open Hole Completions

Open hole completions are in general less costly and less complex than cased and perforated wells. They do also have a larger inflow area than cased and perforated wells, with the potential that gives for higher production rates. The main disadvantages with open hole completion when compared to cased and perforated wells is the lack of wellbore support that a casing provides. Zonal isolation may also be a little more complex, although it is fully achievable for example through the use of External Casing Packers(ECP) or swellable elastomer packers.² A summary of the various forms of open hole completions with sand control is given below. Sand screens are covered in the section 'Sand Screens'.

Barefoot completion

As the simplest form of completion a barefoot completion has no sand control, only the production tubing and a packer. With no sand control barefoot completion is obviously only suited for the hardest and most competent sand reservoirs with no or minimal sand production expected. This will - as mentioned under 'Introduction' - typically be in older formations where the diagenesis and lithification processes have had more time to solidify the rock.

Pre-Drilled/Pre-Perforated/Slotted Liner

Slotted liners (or pre-drilled or pre-perforated liners, depending on the manner of which the holes/slots are created) are the simplest and cheapest form of sand control (some would argue that it does not qualify as a sand control method). It applies the same bridging theory as sand screens; the coarser particles will bridge against the slot openings and in that way filter out the finer particles while letting the fluid flow through and be produced. Slotted liners will usually plug easier, have a smaller inflow area and experience higher pressure drops through production than the regular sand screens.¹ Like with the apertures of the sand screens the slots can be both straight or keystone shaped, with the keystone shape being the preferred choice due to the lesser chance of plugging.

The slots may be arranged in different patterns. The pattern most in use is the single-slotted, staggered row pattern. This has primarily two advantages to the other patterns¹;

1. As holes are made in the liner it will lose some of its original strength. This pattern preserves more of this strength.
2. This pattern gives a more uniform spread of the slots across the pipe surface.

The slots are usually 6 inches in length and may range in width from 0.012 inches to 0.250 inches, which is substantially larger than what metal mesh or wire-wrapped screens can provide, hence the liner only filters out the coarsest particles.¹

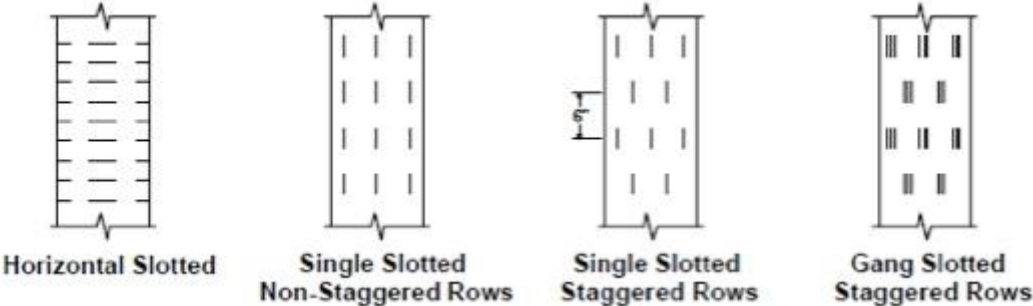


Figure 1: Various slot patterns, from www.i.sereeneenergy.org

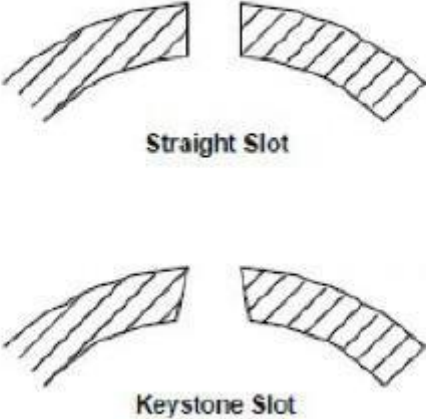


Figure 2: Straight opening and Keystone-shaped opening, from www.packerchina.net

Open Hole Gravel Pack

The concept of a gravel pack is to pump gravel as a slurry mix into the well, packing the annular space around the tubing throughout the reservoir interval. The purpose of this is for the gravel to screen out the reservoir sand, but at the same time allow the reservoir fluids to be produced. Commonly used in combination with a form of sand screen the sand screen will be the innermost element, ensuring that the gravel of the gravel pack is kept in place and is not produced. The gravel pack will pack around the screen and screen out the reservoir sand. A successful gravel pack installation with a fully packed annular space will provide support for the borehole wall, which in itself will also help

minimizing sand production as there will then be less reservoir fines produced in the first place as collapse of the formation is hindered or minimized. Hence, a successful open hole gravel pack provides some of the same qualities as a cased-hole completion when it comes to borehole compliance and support. Compared to for example a Stand Alone Screen(SAS) installation, a gravel pack operation is more complex and costly. The critical time is when pumping the slurry, as losses may lead to a premature “screen-out” and a failed or incomplete installation of the gravel pack. The design of the gravel pack will also depend on the ECD/Fracture margin, which may limit the length of the slurry-packed interval. Underreaming the interval which is to be gravel packed may also be advantageous in some cases, as it leaves a bigger clearance to the wellbore which may reduce the risk of bridging and erosion of the wellbore during pumping and also lower the ECD.⁵

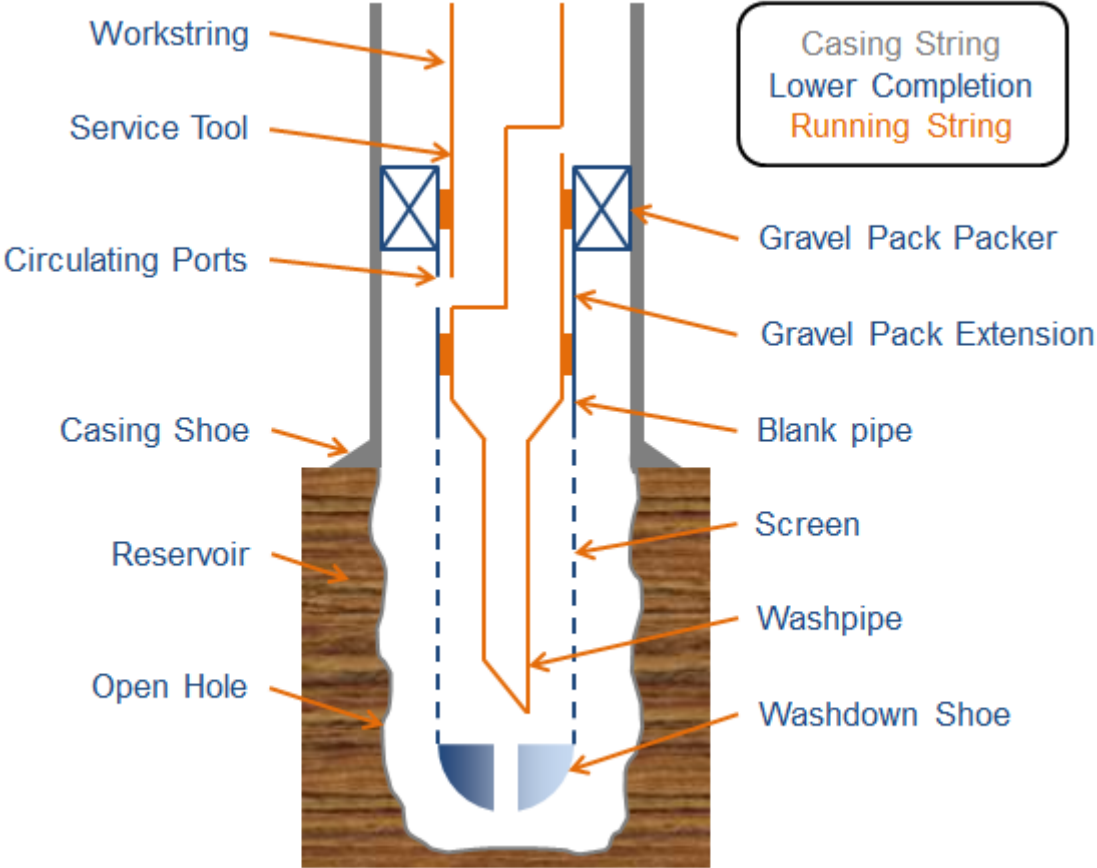


Figure 3: OHGP tool string, from www.dunefront.com

As mentioned under ‘Introduction’ finding the correct size of the gravel is vital and is the first thing to be done in the design of a gravel pack operation. The correct sizing for the gravel pack will depend on the size of the reservoir sand grains. Another consideration is that while the main concern is to prevent sand from entering the production flow there is also a need to avoid plugging of the gravel by formation fines.

In horizontal holes the placing of the gravel will occur in to waves; an alpha wave followed by a beta wave. This process is illustrated in the figure below:

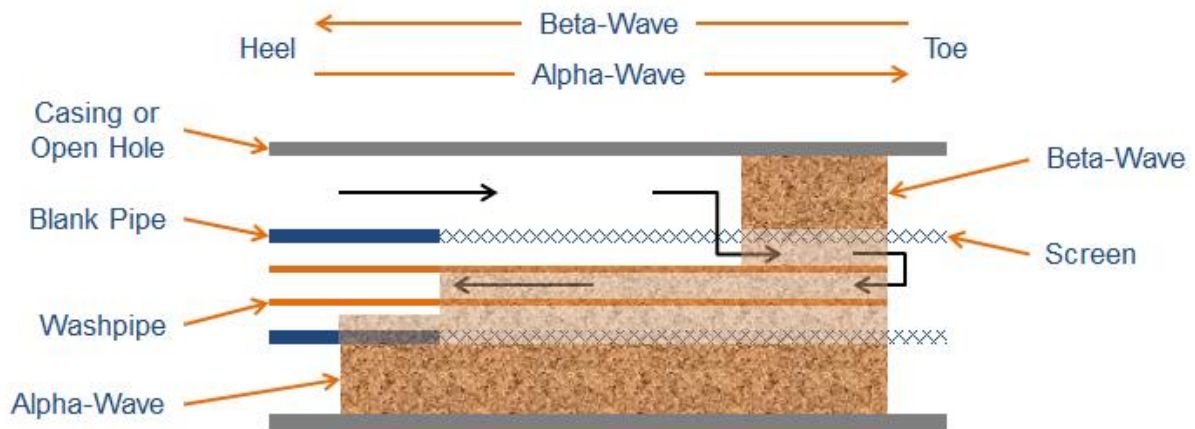


Figure 4: Alpha wave and Beta Wave in horizontal gravel pack, from www.dunefront.com

After the screen, washpipe, crossover tool and gravel pack packers have been set the pumping operations may start. The gravel pack is pumped down the workstring and out into the annulus between the screen and the formation through a circulation port in the crossover tool. As the gravel is deposited the gravel pack fluid returns are taken through the screens and washpipe and back to surface. The alpha wave packs the annulus all the way to the toe of the well. As the alpha wave reaches the toe, the beta wave will start packing backwards from the toe to the heel. As mentioned it is vital not to have excessive losses during pumping, as this may lead to a premature screen-off, i.e. the sand may bridge between the screen and the formation, preventing further packing to the bottom of the well and hence resulting in an incomplete gravel pack operation.² Keeping the ECD between the pore pressure and the fracture pressure is the key, which may be challenging in certain conditions - for example in depleted reservoirs or deepwater wells. Keeping the pump rate low and avoiding high friction pressure is one way of maintaining a reasonably low ECD, however there is a balance as the rate cannot be lowered to below the critical velocity where depositing of the gravel occurs. This may in turn lead to bridging between the screen and the formation and subsequently a premature screen-out.²

Another form of gravel pack is the alternate path gravel pack utilizing shunt tubes to provide an extra flow path in the case of sand bridges during pumping. This makes the alternate path gravel pack slightly more flexible than the conventional gravel pack. There are also differences in the gravel pack fluids and the volumes and duration of the pumping operations.²

Cased-Hole Completions

The main advantage with a cased and perforated well completion is that it gives higher reliability than an open hole completion, as the casing will provide support for the wellbore, reducing likelihood of sand failure. It also gives the operator selectivity with regards to which zones to produce from and for example to shut off water-producing zones. The main disadvantage is the increased cost that comes from the perforating operations.² A summary of the various forms of cased-hole completions with sand control is given below.

Selective Perforations

The concept of selective perforating is to perforate only the strongest intervals of the reservoir. As only the strongest intervals are perforated, the weaker intervals need to be produced through the strongest intervals, hence good communication between them are an absolute necessity. A disadvantage with this technique is that since the weakest rock will usually be the less dense and most permeable - and hence the most productive – there will necessarily be some loss of production if only the strongest rock is to be perforated. Another disadvantage is that due to the lower production rate there will also be an increase in drawdown pressure, which in turn may be a factor that contributes to sand production. In reservoirs with thin layers, applying the selective perforation technique may be risky due to the possibility of thin, weak layers accidentally being perforated. Bellarby² also underlines the inevitable increase in turbulence and rate-dependant skin that occurs when the reservoir fluids are produced through a lower-permeability interval. Selective perforating is best applied in heterogeneous formations with variations in rock strength.²

Oriented Perforations

Oriented perforation refers to the sand control technique of perforating along the axis of the highest in-situ stress of the rock in order to avoid formation collapse. Referring to the rock mechanics mentioned under 'Introduction', there are three directions of the in-situ stresses; one vertical and two horizontal. Depending on the stress regime, the three principal stresses may, and usually will, have different magnitudes. In a normal tectonic regime, also called an extensional stress regime, the vertical stress is the highest. This will not have any effect in a vertical well, but means that in a horizontal well the perforations has to be aligned vertically. In a strike-slip regime or in a thrust regime, the maximum horizontal stress is the highest, which means that the perforations have to be aligned in the direction of the maximum horizontal stress. Oriented perforating is best suited for tectonically active regions with large variations in magnitude of the in-situ stresses.²

Cased-Hole Gravel Pack

Cased-Hole Gravel Pack utilizes mostly the same tools and techniques as the Open Hole Gravel Pack. The main difference being that it is desirable with both circulating and squeezing, in order to ensure proper packing of the perforations. It is also possible to pack the perforations at a pressure higher than the fracture pressure, in which it is called a High Rate Water Pack (HRWP), which may be characterized as a sort of a hybrid between the conventional gravel pack and the frac-pack. The high pressure will ensure proper packing of the perforations, but at the same time the pressure is not high enough to cause any more than minimal fracture growth. The HRWP is not a very complex operation; however it does require high pump rates and volumes of gravel pack fluid due to the high leak-off into the fractures.²

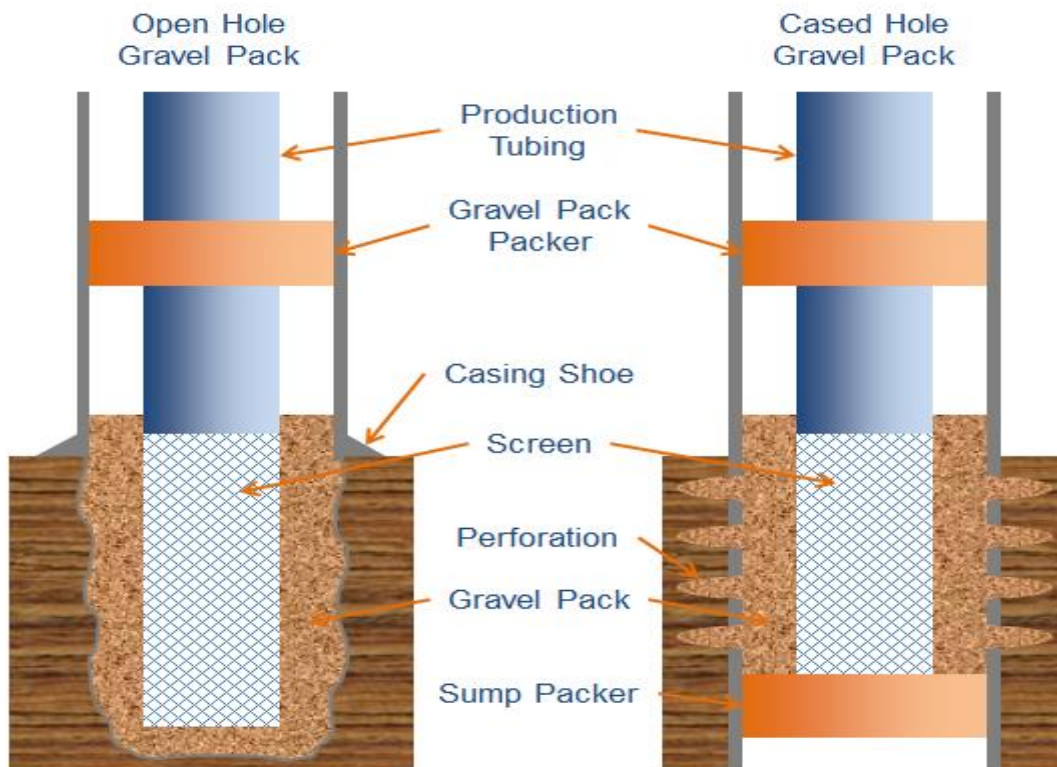


Figure 5: OHGP compared to Cased-Hole Gravel Pack, from www.dunefront.com

Cased-Hole Frac Pack

A frac pack is in essence a form of gravel pack which is pumped at such a rate that it exceeds the fracture pressure and as a result creates fractures in the formation. The gravel which is pumped will follow these fractures and pack them, much like gravel in a perforation in a cased-hole gravel pack. The gravel will also prevent the fractures from closing again after the pumping operations have finished and the pressure again has fallen below the fracture pressure.

As the fractures will help bypass near wellbore formation damage and increase exposure to the reservoir this sort of sand control has been known to increase production and often times provide negative skin values. The frac pack is the most complex of the sand control methods, requiring more complex fluids than the gravel pack, and also larger volumes and higher pump rates. It needs its own dedicated pumping and mixing equipment. In regions like Brazil and the Gulf of Mexico – where frac packs have become the preferred method of sand control in cased and perforated wells – it is common with stimulation vessels dedicated to frac packing.²

Chemical Consolidation

Chemical consolidation may be subdivided into two categories; sand consolidation or in-situ consolidation, and resin coated sand/gravel consolidation. The first method is a method used where the likelihood and magnitude of sand production is considered low, and is a preventive technique pumped before sand production is initiated. The latter is considered as more of a remedial technique in the event of increasing sand production. Chemical consolidation is typically used in short,

perforated intervals. An important factor to be considered with the treatments is that they generally have a negative effect on the productivity of the well.²

Sand Consolidation

This technique utilizes liquid chemicals that are injected into the formation through the perforations. The chemicals will then solidify and help bind the sand grains together. Bellarby² lists three criteria that have to be met in order for the treatment to be considered successful:

1. The treatment has to be performed through all the perforations
2. After the treatment the well still has to be permeable
3. The consolidation should not deteriorate with time

There are mainly two categories or groups of sand consolidation; epoxy resin or furan, phenolic resin and alkoxy silane. Using epoxy resin is a three-stage pumping operation where the first stage is cleaning the wellbore with isopropyl alcohol to reduce water saturation, which can prevent a successful operation. Then the epoxy resin is pumped, followed by viscous oil that is to displace the resin from the pore space in order to restore permeability. There are some limitations to this treatment - mainly that only around 20ft can be treated at the time. Also, it is only functional between 100 and 210° F and there is a requirement of no more than 20% clay content in the interval to be treated.²

The latter group of chemicals reacts with the in-situ water to create silica and to some extent calcium carbonate which helps in the bonding of the sand grains. These chemicals are more robust when it comes to temperature, but creates some challenges in handling and HSE. The quality of the consolidation may also be brittle, leaving it prone to premature collapse.²

Resin-coated sand

This technique can be compared to a gravel pack. Sized gravel or sand is pumped down the well and into the perforations where it stabilizes against the sandface, much like a gravel pack. The sand pack is then bound together as the resin coating hardens. Some excess resin-coated sand may be left in the casing after the treatment, which is then drilled out. The procedure is performed on live wells through the tubing, typically by the use of coiled tubing. As this technique requires open perforations, and as a consequence possibly also clean-out trips and controlled flow rate, it may not be applicable in weak intervals due to possible perforation collapse.²

Sand Screens

Sand screens are a mechanical way of preventing formation solids entering the wellbore. The concept of sand screens is based on the process of bridging, which is that larger particles will be accumulated on the filter medium, causing these larger particles to create a bridge which will then filter out the finer particles, but still allow the fluids to pass. In this thesis sand screens have been subdivided into two categories; conventional screens and expandable screens, conventional screens basically covering all screens that do not utilize expandable tubulars. Darcy's Hydraulic Endurance Screens have been covered in a section of its own. Sand screens can be installed alone as Stand Alone Screens or together with a gravel pack. They are also used in both open hole and cased-hole completions.

SAS completions are a sand control method with low installation complexity. As there are no pumping involved in running a screen they are particularly suitable for wells where the ECD/Fracture margin is low. They do however have a reputation for high failure rate. Bellarby² cites several different case studies and reports from large oil companies, based on experiences with SAS installations in fields throughout the world. Generally, most of the failures seem to develop the same way. Initially low skin factors indicate a successful running and installation of the screen and filter cake removal. Then the productivity would start to go down and the skin factor start to increase, followed by an onset of sand production. A report from Shell²⁵ indicates a 20% failure rate of SAS installations. Another report²⁶ refers to a field where SAS, gravel packs and expandable screens were all installed in similar conditions, with SAS performing worse than the other sand control methods. The sequence was the same as explained above. In this particular field the fines content were 12%.²⁶ Bennett et al. (2000)⁶ recommends that SAS should not be used in areas where the fines content is above 5%. In general, good conditions for the SAS is a homogeneous reservoir with well sorted sand and low fines content (<5%), and few shale sections.²

Conventional Screens

Conventional screens can be split into three types; Wire-Wrapped Screens (WWS), Pre-Packed Screens (PPS) and Premium Screens. They all share the basic principle of a base pipe with holes with one or several layers of filter medium outside the base pipe, but there are also some differences in design and use of the screens.

Wire-Wrapped Screens

WWS have the simplest design of the conventional screens, with a base pipe and a keystone-shaped wire wrapped around the base pipe. In most cases they will also have longitudinal ribs or rods between the base pipe and the wire, which are the point to which the wire is welded and connected to the base pipe. These rods/ribs also help offset the wire openings from the holes in the base pipe to avoid hot spots for erosion. The choice to use a keystone shape on the opening of the wire is to prevent or limit plugging of the screens. This is because the keystone shape will ensure that if the particles are not large enough to be retained by the sand bridge, it will not plug as easily as a straight shaped wire opening as the particles will be allowed to pass through the wire opening easier. The WWS are the thinnest of the three conventional types and commonly used both in combinations

with a gravel pack or as a SAS-assembly. A factor to be considered with WWS is that it has a relatively low inflow area. Failures with WWS will usually occur due to eroding hot spots, corrosion or from chemical treating of the well. Usually these problems will be related to the wire-wrapping. Failures of the base pipe are quite rare, but may occur if the screen has been plugged.²

Pre-Packed Screens

The PPS is built up from inside to outside with a base pipe with holes in, longitudinal ribs/rods, wire-wrapping, resin-coated/consolidated gravel, and longitudinal ribs/rods and lastly a second layer of wire-wrapping. Occasionally a protective shroud is also added for additional protection, but this adds to the thickness of the screen, which is already larger than that of both the WWS and Premium Screens. Like with a gravel pack the screens/wire-wrapping is here dimensioned to keep the gravel in place, while the gravel does the actual filtration of the reservoir fluids. The positive factors with PPS are that they offer the depth filtration and permeability elements of a gravel pack. A negative factor that has to be considered is that they are prone to plugging², it is especially vital that the completion fluid is solids-free or else the screen may be completely plugged up.⁵ The WWS and premium screens have to some extent replaced the PPS, but it may still have its use in some areas. For example as an alternative to gravel pack in wells where this is not applicable, typically in long, horizontal reservoir intervals or in reservoirs with a small ECD/fracture-margin.²

Premium Screens

Premium screens, also referred to as shrouded metal mesh screens, have a pre-drilled base pipe just like WWS and PPS, but instead of wire-wrapping has several woven metal mesh filtration layers outside the base pipe. A shroud outside the filtration layers makes it more robust than the other screen types. The diameter of the screen is less than the PPS, but slightly larger than the WWS. The mesh has non-uniform openings which mean that screen sizes will vary from manufacturer to manufacturer. The robust design of the premium screens makes them suitable for harsh environment installations. Premium screens usually have an inflow area of around 30%.²

Expandable Screens

Expandable Sand Screen technology came about through field trials in the Omani desert in early 1997. The predominant goal in developing this technology was to achieve improved downhole sand control by eliminating the annulus between the sand screen and the reservoir. The idea has developed from combining the functionality of the OHGP and the simplicity of the SAS. OHGP can be a rather complex installation method, and the SAS - albeit quite a simple and straight-forward installation - does have its limitations as covered in the section 'Conventional Sand Screens'. The Expandable Sand Screen may in some situations avoid the negatives from both these methods of completion, and at the same time combine the positives.⁷

By expanding the screen against the reservoir wall the completion skin is reduced and productivity of the well is increased, at the same time as it retains the sand better, hence giving increased well reliability. Field trialing started in 1997, but full commercial use with the first Expandable Sand Screen

coming on the market was not until two years later, in 1999. As of the end of 2012 the Expandable Sand Screen technology had been deployed in 677 wells and more than 418 184 feet of screen around the world. Expandable Sand Screen technology has often been used in cased-hole completions, but is predominantly a technology developed for use in open-hole completion – usually in sandstone reservoirs that are either weak and poorly consolidated or unconsolidated. By doing so the Expandable Sand Screen helps support the rock matrix, hence stabilizing the rock grains and hindering sand production from the start. Also, the larger flow area resulting from an expanded screen will improve the wells productivity and increase the drainage from the reservoir. In addition to this the increased ID and increased filter area, also resulting from an expanding screen, will lower the risk of plugging and erosion of the screen. Another advantage is that when running in with the Expandable Sand Screen there is a lower risk of getting stuck or similar problems, due to the smaller diameter before it is expanded. Getting stuck while running in is a problem that is known to happen for example when completion solutions involving packers are chosen.⁷

The Expandable Sand Screen build up is quite basic and follows the same principles as conventional screen build-up more or less with the obvious exception of the expandable tubulars. There is a base pipe, which is slotted longitudinally. This base pipe is surrounded by the outer, protective shroud, which is also slotted in the same way. The layers of filter media, which is overlapping, is laid across each other to provide the sand retention characteristics.⁷ The slots in the shroud and the base pipe are forced open during the expansion. This accommodates the increasing of the pipes diameter. According to Ismail and Geddes⁷ these slots enable the pipe to be expanded up to 45% more than the original diameter. Slots also provide a larger inflow area than regular, perforated pipes. The expanding of the screen towards the wellbore wall is done by using a hardened cone and driving it through the Expandable Sand Screen joints, as a result expanding them and “cladding” them towards the wellbore wall.⁹

As mentioned above the Expandable Sand Screen technology was originally developed in order to find an alternative to the OHGP technology and the SAS system, with the aim of combining the best features of both sand control methods. However after a couple of years with increased use of - and success with - the Expandable Sand Screen technology, it was also suggested to further develop the Expandable Sand Screens together with multi-zone systems and integrate them into a total completion system for zonal isolation in open hole conditions. Traditionally zonal isolation has been achieved by cased-hole technology. A production casing or liner has been set and cemented and then perforated, before being typically gravel packed or frac packed. Focusing only on the sand control part and the zonal isolation this has been very efficient, but it has however resulted in very high skin. Also, the decreased inner diameter has made the setting of inner-completion applications very troublesome.⁸

Initially trialing were made with elastomer clad Expandable Sand Screen and swell packers, but neither achieved the desired results. As the market for the still quite new technology of single-zone Expandable Sand Screen was growing, the possibilities a multi-zone Expandable Sand Screen system provided was not really paid much attention to until 2003. Weatherford, who also was one of the driving forces behind the original single-zone Expandable Sand Screen then looked more closely at how to develop a multi-zone isolation solution. This happened as the demand from the operating companies for this kind of solution grew. Weatherford worked together with two major operating companies operating in the Caspian Sea and in deep-water fields West Africa, and this process which

led to the development of a 7" multi-zone isolation system is described in a field study by Nicol and Geddes⁸. The demands for functionality of the system from these two operating companies were quite similar, as was the demands from the rest of the oil industry, so Weatherford embarked on developing a system with an overall applicability. Certain system specifications were identified early on, as cited from Nicol and Geddes⁸:

1. Method of sand control would be the compliant Expandable Sand Screen
2. The target of the open-hole size would be 8 ½"
3. There would be a minimum compliant range from 9" to 9 ¼"
4. The selective completion capability would be full with standard size
5. The method of zonal isolation would be the compliant expandable system
6. The system would also have a pressure differential rating of 3000 psi⁸

The best solution for this multi-zone isolation system was found to be Solid Expandable Tubular (SET) annular barrier combined with the Expandable Sand Screen. The 7" Expandable Sand Screen in this system is similar to the original single-zone Expandable Sand Screen developed by Weatherford, however one notable difference is that this one is designed to have solid, non-expandable premium connections, as opposed to the expandable ones in the original design. This is done to ensure the flexibility of the system in terms of interchangeability of components. More importantly it facilitates the use of a rotary compliant expansion method which is the preferred method of setting this multi-zone isolation system in place. As an annular barrier/isolation device between zones Weatherford developed the 7" Expandable Zonal Isolation device, EZI. This is a base pipe with elastomer elements, which are compliantly expanded towards the wellbore providing an elastomer seal. The elastomer elements are ribbed and molded to provide a better seal. Like with the Expandable Sand Screen the connections are solid, non-expandable premium. Between the Expandable Sand Screens and the Expandable Zonal Isolation devices there is regular 7", non-expandable casing. This Unexpanded Space-Out Tubular is important as it allows for the setting of regular size inner-completion equipment. The use of non-expandable joints and connections in the completion string is made possible by the rotary expandable method used. The expansion tooling can be switched on and off and when they are switched off they have a diameter less than that of the non-expandable parts.⁸ The Expandable Sand Screens and Expandable Zonal Isolation joints both require their own designated tool, although the tools are very similar. The ESS tool sits at the bottom of the string and consists of two rows of 3 piston-mounted rollers. The EZI tool sits higher up in the string and consists of 1 row of 3 piston-mounted rollers. In between them sits the Diverter Tool, which simply switches between the two expansion tools. The Diverter Tool is controlled using flow rate and backpressure.¹⁰

From the same study, the use of this completion technology in two fields - all of the wells being water-injectors - in deep-water West Africa gave several conclusions about its functionality. In the first field, which is a field with unconsolidated sandstone, nine wells were completed – one of them with the multi-zone isolation technology. All operations were successful, and among the key findings were:⁸

1. ESS provided good sand control in water injectors
2. Good water injectivity was achieved by the use of ESS
3. Expanding 7" ESS with the rotary method gave good reliability from a drill ship in deep-water
4. ESS is less complex than other multi-zone completion technology

5. EZI provided good zonal isolation in open-hole
6. NPT was lower than 5% during operations

As a result of this it was decided to install this completion technology in two of the producers in the same field. This was done during 2009. The experience from these two wells after a year of production is that there is little to none sand production. One well has a validated skin of 0, which is at the level of the best frac pack wells, and the zonal isolation is 100% effective. Operational efficiency has been upheld and these multi-zone Expandable Sand Screen wells are generally more cost-effective than the frac pack wells. In the second field, which has very similar characteristics to the first field, four more injector wells were installed. All of these used the multi-zone Expandable Sand Screen technology. The experience and the findings from these four wells were more or less the same as in the first field, although there was an issue with one of the wells when installing the EZI above the bottom zone. The problem occurred during the expansion of the EZI and has later been resolved for future installations. The conclusions after finishing the Expandable Sand Screen installations in these fields - both the conventional and the multi-zone isolation installations - were the same as the ones listed above. This technology provides good sand control and good zonal isolation at a relatively low cost compared to other completion technologies like for example frac packing.⁸ In general it can be said that the Expandable Sand Screen technology has managed to obtain the productivity that the gravel pack and the frac pack provides, only at lower costs. Also, it provides some of the simplicity in installation that the SAS has, with regards to getting the screens to bottom, however there is the extra process of actual expansion of the screens, which can be challenging. Introducing the multi-zone isolation system it can challenge the zonal-isolation performances of a cased and cemented hole with perforations.

Water Injector Well-specific Sand Control Challenges

For many years sand control in injector wells was not given much thought as the theory was that the pressure from the injection water would push any sand that would be produced back into the formation. If there was sand control installed little consideration would be given to the specific challenges of an injector well, primarily that sand is not produced to the surface in an injector well, but will accumulate downhole resulting in sand fill. The theory of water injection pressure forcing loose sand back into the formation may be a sensible one, however it does not take into account what happens when the well is shut-in, which induces certain processes which can lead to sand production.

Water Hammer

The water hammer phenomenon occurs during shut-in of the well, especially abrupt shut-ins when the tree valves are used. As water is nearly incompressible an abrupt shut-in will cause a pressure wave to travel down the well at the speed of light. As this pressure wave hits the formation downhole the pressure is more than enough to break up weak intervals of sand and fines. Sadrpanah et al. (2005)⁴ has calculated such a pressure wave to 500psi in a well at the Foinaven field in the UK sector. As the pressure wave reaches the bottom of the well the resulting back and forth surging and swabbing and turbulence will help in unsetting and dragging the particles from the sandface into the well where they will eventually settle. Preventive measures may include limiting shut-ins, and when shut-ins are necessary shut the tree valves in steps in order to limit the resulting pressure pulse.^{2,4}

Thermal Fracturing

In seawater injectors there will be an element of thermal fracturing.² These fractures may be advantageous in that the injectivity of the well is improved. Also, the injection water normally has to be filtered for fines before injection, but with the increased openings created with the fractures the challenges with fines is greatly reduced. A negative factor with thermal fracturing is that it creates an uneven injection profile as flow will “favour” the easiest route, i.e. the intervals where fractures have been created. Also, as the fractures have been known to become up to 0.1 inches in diameter (Sadrpanah, 2005)⁴ gravel loss into the formation may occur. This is especially relevant for gravel pack completions. For SAS completions it may actually be advantageous as sand and fines may go into the fracture systems rather than through the screen, with the challenges that may pose of possible screen plugging and subsequent screen failure. A gradual increase of injection rate as injection is started may help mitigate the occurrence of thermal fracturing. As a remedial measure for when thermal fractures cannot be avoided installing ICD's may help even out injection flow profile.²

Corrosion

The injection water will usually contain dissolved gases and corrosive agents. This puts certain requirements to the metallurgy of screens used in water injector wells.²

Cross-flow

In heterogeneous reservoirs there will be various layers with variable permeability. As the well is shut-in, flow between these layers will be initiated. This cross-flow may induce failed sand and fines, but may also help distribute already failed sand and fines around the well, with the increased potential for erosion this will create. Cross-flow may also occur from one well to another if there is a flow path between them. Installing downhole injection valves may increase control of this.^{2,4}

Darcy Hydraulic Endurance Screen – A Conceptual Study

Darcy's Hydraulic Endurance Screen offers a non-expandable compliant sand control system. Using applied surface pressure the screens are hydraulically activated and extended outwards against the wellbore wall; they offer mechanical support for the wellbore, and in that way reduce the risk of sand failure and subsequent production of sand and reservoir fines.¹¹

The main difference between Darcy's Hydraulic Endurance Screens and expandable sand screens is the method of achieving wellbore support. Expandable sand screens utilize mechanical tools to yield the base pipe and expand the tubular towards the wellbore - Weatherfords ESS-systems for example use a cone or expansion tooling (rotary/axial). The Darcy system is hydraulically activated by pumping fluid into multiple activation chambers (via a valve integral to each screen)¹⁴ placed between the base pipe and the drainage/support layer and sand filter media. A general summary of the installation procedure is listed below:^{11, 14}

- 1) RIH while circulating
- 2) On bottom: Release the service tools and close the circulating port
- 3) Darcy engineer instructs cement unit operator to apply pressure to the drill pipe and inside Darcy's hydraulic screens
- 4) As internal surface applied pressure increases, pins in the screen valve are sheared, allowing the sleeve to travel upwards. After releasing this initial pressure, a return spring moves the sleeve and positions the valve in screen activation mode (communication is now open to the activation port)
- 5) A second pressure cycle, applied by the pump operator, adds fluid volume into the activation chambers; the chambers are now energized and the system/filter media is extended to conform against the borehole geometry.
- 6) With the screen now extended to its operating state, the activation pressure is locked in and will remain there for the life of the completion
- 7) Confirm volumes pumped are as expected and monitor for returns of the displaced volume
- 8) Activation pressure applied from surface is bled off
- 9) As pressure is reduced, return spring will shift the sleeve downwards and lock the sleeve closed against the body lock rings. In this process a secondary barrier is also aligned across the activation ports.
- 10) As the sleeve is moved downwards into its permanent and locked state, the production ports are exposed, allowing for production of reservoir fluids.

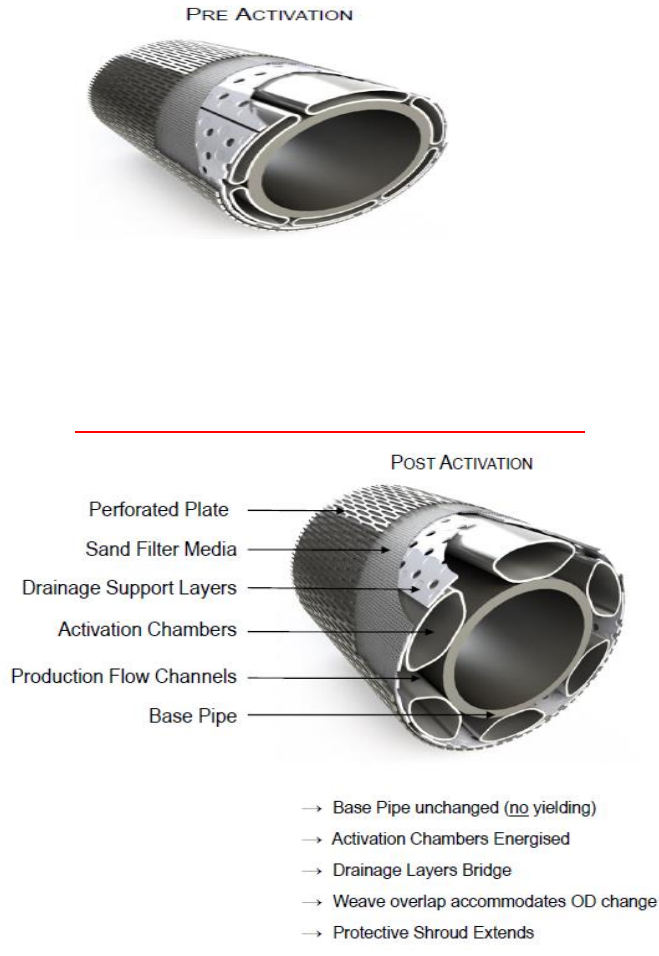


Figure 6: Hydraulic Endurance Screen build-up, courtesy of Keith Oddie/Darcy

There are a couple of advantages with this method of non-expandable compliance compared to the traditional one using expansion with mechanical tools:

1. It is a single-run system. With other expandable screen installations the screens has to be RIH, before doing a second run with the mechanical expansion tool. With the Darcy Sand Control System the screen is RIH, and then expanded by pumping fluid. This means saved rig time with one run compared to two runs, Darcy claims a rig running time savings of up to 40%.¹¹
2. The expansion method is less complex than using a cone or expansion tool and with less risk of failure.

The Darcy screen has a similar build-up as other screen types, with the addition of the activation chambers. Innermost is the basepipe, with the activation chambers outside. Outside the activation chambers is a drainage/support layer, followed by the sand filtration media. Outermost is an outer shroud for extra protection of the screen during RIH. The Darcy screen uses a Petroweave – Dutch Twill Mesh Filter as its sand filtration media.¹¹ Typically, following establishment of the Particle Size Distribution of the reservoir, the screens will be sized to the $D_5 - D_{10}$ value.¹⁴

Darcy currently has one system ready for commercial use and two systems still under development, all of them summarized in the tables below.

Table 4 - Endurance Hydraulic Screen Products





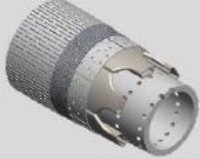

Product Name / Description	Base Pipe		Screen Valve Arrangement	
Endurance 100™ Optional shut off capability	Solid		Combination	
Endurance 200™ Selective production, shut off / isolation	Solid		Dual	
Endurance 300™ Direct sand face access and extreme (HPHT) environments	Pre-drilled		Single	

Figure 7: Status of Darcy's Sand Control Systems, courtesy of Keith Oddie/Darcy

Table 5 – Technology Status

Product Name / Description	Base Pipe OD	Base Pipe	Screen OD	Open Hole Size	Activation Range (Max)	Status
Endurance 100™ Optional shut off capability	6.625"	Solid	7.750"	8.500"	10.000"	Commercial
Endurance 200™ Selective production, shut off / isolation	5.500"	Solid	7.125"	8.500"	9.250"	Under development STATOIL
Endurance 300™ Direct sand face access and extreme (HPHT) environments	5.000" or 5.500"	Pre-drilled	6.500"	7.500"	8.200"	Under development SHELL GoM HPHT

Figure 8: Specifications of Darcy's Sand Control Systems, courtesy of Keith Oddie/Darcy

The Endurance 100™ system is the system planned for installation later this year at the Statfjord field. The design of the lower completion system is shown in the illustration below.

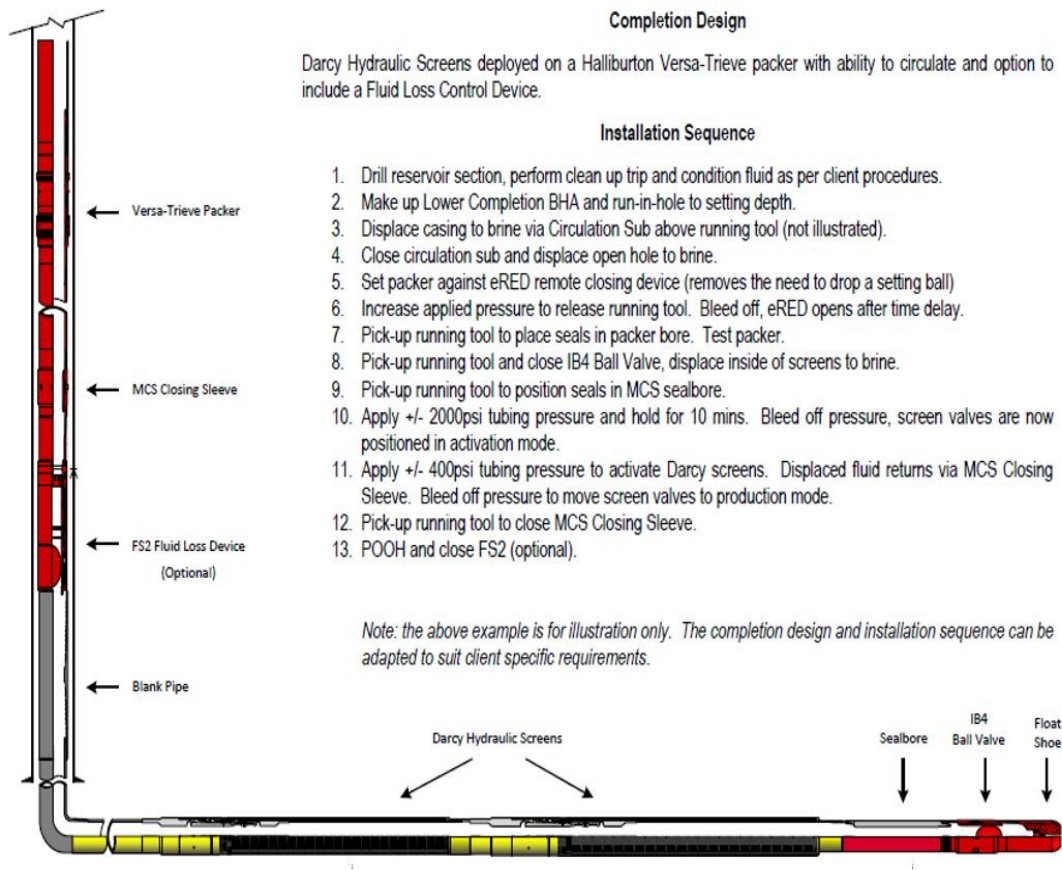
**Darcy**

Figure 9: Hydraulic Endurance Screen system to be installed at the Statfjord field, courtesy of Keith Oddie/Statoil

The screens are to be deployed on a packer. It makes use of an eRED remote closing device when pressuring up the well during setting the packer. The Endurance 200™ is to be installed on the Snorre field. Both systems utilize a solid base pipe, but the Endurance 200™ has a slightly smaller OD than the Endurance 100™ (5 ½" base pipe OD and 7 1/8" screen OD versus the 6 5/8" base pipe OD and 7 ¾" screen OD for the Endurance 100™ system).¹⁴

The 6 5/8" system currently available needs 400 psi applied tubing pressure in order to activate and conform to the wellbore geometry, up to its maximum compliant range of 10". Activation pressure is specific to each system design and depends mostly on chamber geometry and wall thickness. In general it is unlikely that any of the Darcy systems will exceed an activation pressure of 800psi to extend to its maximum compliant range.¹⁴

The hydraulic endurance screen system requires two pressure cycles to activate. After the running service tools and the circulation flow path has been closed, the cement unit operator can start applying pressure down the drill pipe and inside the Darcy's hydraulic screen system. The first pressure cycle will need around 2000psi to shear out the sleeve. After this pressure is bled off the valve will be positioned in screen activation mode.¹⁴

The second pressure cycle adds fluid to the activation chambers which are then energized. As the activation chambers are energized the surrounding filter media is extended to conform to the borehole geometry. Upon reaching the designed activation pressure and having filled the activation chambers with sufficient volumes, a second shear will occur that leaves the activation pressure locked in for the lifetime of the completion. As the screen is now activated, pressure is released

internally to the screen allowing the sleeve to return to its final position, opening ports to injection (or production). The Endurance100™ system may also be delivered with a split sleeve for future injection shut-off.¹⁴

Johan Sverdrup Field Theoretical Water-Injector Darcy Hydraulic Endurance Screen Completion

The Johan Sverdrup Field is currently at the stage of the “Plan for Utbygging og Drift” (= Plan for Development and Operation), PUD, and the operator, Statoil, and its partners, Lundin, have made a conceptual choice. Planned first oil is late 2019 with production estimated to last until 2050.¹² The main drive mechanism for the production will be water injection that will give pressure support for the oil. In addition to this all of the producers will be gas lifted.⁵

The plan as of now is to complete the well open hole. Originally it was planned to install OHGP, but this has for now been changed to SAS. The main driver behind sand production is expected to be that the reservoir sands are unconsolidated. Darcy’s Hydraulic Endurance Screens may be considered as a viable alternative to Stand Alone Screen assemblies in the water injectors.⁵

The reservoir is situated at a depth of 1800-1900m True Vertical Depth (TVD) with a reservoir temperature of around 80-85°C. Reservoir intervals of the wells are planned as horizontals at a length of about 500m. There are two different zones in the reservoir with different permeability, separated by a sand layer with low vertical permeability. A scenario with an installation of Darcy’s Hydraulic Endurance Screen in a water injector well will be presented, with injection testing of both reservoir zones. In this proposed scenario, the use of Darcy’s Endurance 100™ system has been assumed, as this is the system currently ready for commercial use. A generic running procedure is enclosed to outline how the screens may be installed. In addition a risk analysis is added to highlight the main risks as well as some mitigating actions that would contribute to reduce the said risks. An outlined procedure for performing an injection test is enclosed to complete the plans and proposals.

Water injector wells on Johan Sverdrup will be planned with a 8 ½” hole size in the reservoir (with a 6” hole size as a contingency plan) and this is the hole size that is used as a basis for the scenarios that are analyzed in this thesis. The pore pressure is estimated at 1.05sg, and the mud weight used will be around 1.35sg in order to prevent collapse. The mud system used will be a Low-Solids Oil Based Mud (OBM) with CaCO₃ as weight material. For the water injector wells the 9 5/8” production casing is planned to be set inside the reservoir with an unconventional production packer.

An important aspect of the completion design is the choice of Open Hole packer to provide zonal isolation. There are mainly three alternatives; swell packer, External Casing Packer (ECP)/Inflatable packer or Mechanical Open Hole Packer. The principle of a swell packer is relatively simple. The packer consists of elastomer elements that react with either oil or water (depending on which type of elastomer is used – research is also ongoing to find different compositions that will react with different fluids, enabling more field- or well-specific design of the swell packers)¹⁵ and then starts swelling. As the elastomer elements swell towards the wellbore they provide a pressure-holding seal. One advantage with the swell packers is that they can expand more in the future if for example washouts behind the packer occurs.¹⁵ Running and installing the swell packer is very simple, the packers are simply RIH to the predetermined depth and then allowed to swell as it comes into

contact with reservoir fluids (or water, depending on composition). The ECP or inflatable packer is expanded towards the wellbore by the use of an inflatable bladder that is filled with fluid (cement is recommended for providing a long-term seal) that is pumped from surface. As the bladder expands, the packer element is pushed towards the wellbore wall, providing a pressure-holding seal. An advantage with the ECP is that it is capable of large expansion rates.¹⁶ The mechanical non-inflatable open hole packer may use hydrostatic or applied hydraulic pressure to set. A typical set-up is that atmospheric chambers are filled, and the pressure forces two cones towards the elastomeric packer-element, which is then expanded towards the wellbore wall.¹⁷ The choice of correct open hole packer depends on several different factors, Gavioli and Vicario¹⁷ have among other considerations mentioned the formation type the packer is to be set in, the pressure differential rating, the ability to handle variations in hole size/washouts and deployment time as key parameters to be considered. The choice of the correct open hole packer will not be investigated in detail, in the completion strings in the water injection scenarios in Johan Sverdrup a combination of mechanical open hole packers and swell packers have been suggested. However, Darcy's Hydraulic Endurance Screens are compatible with any commonly available hangers and packers and if for example ECP's are preferred these could be changed out without necessitating any other major changes in the completion string.¹¹ In order to pick the correct placement of the packer it might be advantageous to run a caliper log as the reservoir is drilled, to identify any possible washouts. Also, this might be relevant for selecting the correct packer, as mentioned above the inflatable packer has a large expansion ratio which might be considered a deciding factor in the case of washouts. On the other hand, it is also recommended to install ECP/Inflatable packers in competent wellbore sections whenever possible.¹³

Basis of Design

The following is a description of all the elements and their function in a proposed Open Hole completion of a water injector well on the Johan Sverdrup field, utilizing Darcy's Endurance Hydraulic Screen. Most of the components listed are "off the shelf"-items and as such should be cost efficient and well proven technology. Darcy's Endurance Hydraulic Screen use Premium gas-tight connections and are compatible with commonly used tools as hangers and packers¹¹, and therefore the compatibility with items such as swell packers, float valves etc. is assumed. In water injector wells it may be advantageous that the pipe used are of 25% Chrome quality, and accordingly this is the quality recommended in this example. When handling 25% Chrome quality equipment it is recommended to use great care, and possibly try to do it in a good weather window if installed from a floating rig or a drill-ship. For the blank pipe between the 6 5/8" screens it has been suggested to use 7" pipe as this was assumed to be more readily available, however 6 5/8" blank pipe could just as well have been used, the only modification being that the elastomer elements of the swell packer would have to be enlarged accordingly due to the decrease in OD.¹⁴

Liner/Screen open hole completion string as proposed:

1. Float shoe (with valve) – To ensure a guide of the liner/screen and provide well control in preventing Hydrocarbons to enter the string while RIH.
2. Stinger seal "Pack-off" – Will enable circulation through the inner string and out of the shoe while bringing the liner/screen to its predetermined depth in the open hole.

3. Flapper Valve – When activated by the shifting tool in the inner string this flapper valve will allow both circulation and pressure test/appliance of activation pressure above the valve.

Alternatively a ball valve can be utilized (sometimes considered to be a more reliable option)² instead of the flapper valve.

4. Blank pipe, 7" liner (25% Chrome) – Required amount of 7" blank pipe to bring swell packer and Darcy's Hydraulic Endurance Screen to planned depth and space out.
5. Swell Packer, lower isolation – To be spaced out to an adequate position to ensure isolation of the zone of interest above. Swell packers are proposed because they are considered superior to ECP/Inflatable packers for lifetime of well, both in terms of cost and reliability.¹³ Swell packers should be placed in a low-permeable zone to ensure and optimize the seal function.
6. Darcy's Hydraulic Endurance Screen, 6 5/8" (25% Chrome) – Run the required joints of Darcy's Hydraulic Endurance Screens across the zone of interest.
7. Swell Packer, upper isolation – Same as for "swell packer, lower isolation".
8. Blank pipe, 7" liner (25% Chrome) – To extend from the swell packer to inside the 9 5/8" production casing, below the liner hanger assembly.
9. Inner string – The inner string will be a work string to facilitate circulation while RIH through the float shoe up the annulus. The advantages of running an inner string are several; it enables circulation while RIH without exposing the screens to drilling fluid, Lost Circulation Material (LCM) etc. It also allows for displacing the outer annulus with appropriate Low-Solids fluid after reaching setting depth. An inner string also makes displacing the inside of the screen/liner to appropriate fluid possible after the flapper valve has been activated.

Elements in inner string, listed from bottom:

1. Stinger for seal in the pack off above the float shoe
 2. Shifting tool for activation of the flapper valve
 3. Adequate number of 2 7/8" joints
 4. The upper part of the inner string will contain the normal items allowing the standard liner hanger setting operations (swab cups, ported sub, RSM seal, Liner Hanger Running Tool (RT), swivel, packer setting dog sub etc.)
10. Liner hanger assembly with hold down sub and integrated packer, (25% Chrome) – After running the inner string the liner hanger assembly will be run. The bottom of the liner hanger assembly inner string will be connected to the last inner string joint. The liner hanger outer assembly will then be made up to the last joint of the 7" blank pipe

11. Running string above liner hanger – Run the predetermined amount of Heavy-Weight Drill Pipe (HWDP) and Drill Pipe (DP) to ensure sufficient weight to allow for bringing the screen/liner to correct depth and allow for setting the packer.

Flow Sub(Optional): Darcy recommends installing a flow sub below liner hanger(or packer)when running an inner string to maintain hydrostatic balance internal to the screens and avoid trapping a closed volume between inner string OD and screen ID.¹⁴ (The flow sub has not been included in the illustrations of the completion string)

Dual injection zone: If dual zone injection is required an additional section of swell packers and Hydraulic Endurance Screens needs to be included as well as a second flapper valve for isolation between the two zones while running the injection test on each zone separately. In order to ensure extra zonal isolation a pressure activated Mechanical Open Hole packer could be added between the two injection zones. The upper flapper valve needs to be of the ceramic type to be able to remove it mechanically to obtain access to the lower zone.

Metallurgy

As mentioned in the section ‘Water Injector Well-Specific Sand Control Challenges’ the particularly corrosive environment of many water injector wells puts specific requirements to the tubulars and tools that are to be installed. The most commonly used material for water injector wells are duplex corrosion resistant alloys.²³ BP has set 25% chrome content or more as a requirement for material in water injectors below the FIV in their Schiehallon field west of Shetland. They have also listed running less noble quality(13% chrome content) base pipe in between 25% Cr screen joints as a possible reason for the poor injection performance of two of their water injector wells.²⁴ For the Johan Sverdrup example installation in this thesis the use of 25% chrome has been proposed.

In addition to the increased cost and longer delivery times for duplex steels²³, they also pose some extra challenges in handling, from transport to the rig, handling while on the rig and in running the pipe in hole. Great care must be taken to avoid or minimize damage to the pipes before they are installed.

Base pipe

The Darcy Hydraulic Endurance Screens can be installed with both a solid base-pipe and a “traditional” pre-drilled base-pipe which ensures direct contact with the screen/sandface. There is a trade-off in choosing between them; a solid base-pipe provides the opportunity of selective production and zonal isolation through the opening and closing of the actuation/production valves, and it also enables easy installation of an Inflow Control Device to control the flow profile. Also, it eliminates the need for a washpipe/inner string to enable circulation during RIH (which may be vital for well control purposes). When running in with a solid base-pipe, the lack of flow through the screens may help mitigate screen plugging in the installation phase. The filter medium is situated outside the base-pipe, so this will still be exposed to the drill-in fluid in the well during RIH, but the lack of a flow path from outside the screen to the inside of the screen may greatly reduce the likelihood of plugging.^{11,14}

The main advantage with the pre-drilled base-pipe is, as previously mentioned, that it provides a direct contact with the screen/sandface. This simplifies post-installation treatments like for example scale removal.¹¹ It may also be argued that the direct sandface completion of the pre-drilled pipe makes for a slightly less complex installation than the one with a solid base-pipe, where actuation/production valves need to be opened/closed in order to receive flow from (or inject into) the reservoir, with the increased risk that poses of failure or problems during installation. However, the production valves may also be opened mechanically with an activation tool if needed, so this should not be a big factor in the selection process. Also, when utilizing the pre-drilled base-pipe there is the requirement for running an inner string with an activation tool, with the increased complexity that may pose.^{11, 14}

ICD

Inflow/Injection Control Devices are autonomous devices/valves that are installed downhole to help improve flow distribution. They will help limit the negative effects from thermal fractures, thief zones or reservoirs with variable permeability, which will “steal” most of the injected water. A more even injection flow profile will also result in improved sweep efficiency and consequently improved oil recovery from the fields’ producer wells. The risk of water breakthrough into one of the producing wells will also be reduced with the improved injection flow profile.²² If needed ICD’s are integrated in Darcy’s Hydraulic Endurance Screens at the existing ports located in each screen valve.¹⁴ As the reservoir at Johan Sverdrup consists of two different zones separated by a sand layer with low vertical permeability the use of ICD’s might be advantageous.

Fluid Considerations

During all operations where screens are run in drilling fluids there is a risk for screen plugging. As explained in the section ‘Base Pipe’, the risk of this happening is reduced when utilizing a solid base pipe for the screen, however it is not completely eliminated. To further reduce the likelihood of screen plugging thorough planning of the mud system is important. The plugging may be caused by particles from the formation or by LCM/weighting material used in the mud. Especially in wells taking losses the use of LCM need to be carefully considered and acid soluble material should be used if possible. While drilling formations where losses are experienced it is necessary with a careful design of LCM based on the particle size distribution as covered in the section ‘Particle Size Distribution’, and as mentioned the acid-soluble material should be preferred where possible. Also, circulating the hole clean after reaching TD, displacing to fresh mud, and filling the screen with fresh mud while RIH are important factors in avoiding screen plugging. If only acid-soluble material have been used in the mud then acid washing is a possibility if injectivity is poor.

As mentioned above the Drill-In Fluid (DIF) Statoil plans to use is a Low-Solids OBM utilizing CaCO₃ as weight material. This makes acid washing a possibility in the case of high skin, utilizing hydrochloric acid to dissolve the CaCO₃ particles.

Filter Cake Removal

Ensuring excellent removal of the Drill-In Fluid filter cake is paramount in an injector well. When comparing to the Open Hole Gravel Pack, it is clear that Darcy's Hydraulic Endurance Screens have certain advantages when it comes to removal of the filter cake. The OHGP depends on a functioning filter cake during pumping (to avoid losses); hence the filter cake has to be removed after the gravel pack has been placed, with the problems this may pose. With the Hydraulic Endurance Screens it is possible to circulate breakers to enhance filter cake removal prior to activation of the screens. Also, as the screens are activated against the wellbore, they will mechanically disperse the filter cake and in that way help in filter cake removal.^{11, 14}

Generic Installation Procedure

The proposal for running the open hole completion includes an inner string which is optional when utilizing a solid base-pipe, however this is considered to be beneficial for several reasons as described below. A liner hanger with an integrated packer is also included since this way of suspending a liner/open hole completion is considered to be a safe and well proven method for decades. The choice of including a liner hanger is optional, as a conventional packer will most likely suffice for installing the screens.¹⁴ In this proposed scenario swell packers are used in combination with mechanical open hole packers to provide zonal isolation between the two reservoir layers of different permeability. The procedure should be considered as an outline only and some parts need to be considered in more details if this method is decided to be the chosen one:¹⁴

1. After drilled to TD, eventual OH logging is completed, perform a wiper trip and displace the well to 1.35sg "fresh" Low-Solids OBM
2. Hold SJA and rig up for running screen liner. Focus on well control procedures and actions while running screen liner and inner string (manual work)
3. Run float shoe joint, stinger pack off and a spaced out flapper valve
4. Run required amount of 7" blank joints
 - a. Install centralizers (if applicable) according to predetermined program
 - b. Fill joints while RIH with Low-Solids OBM
 - c. Note closed end displacement
5. Run one swell packer
6. Run required amount of Darcy's Hydraulic Endurance Screens, 6 5/8" solid base-pipe with ICD's and 7 3/4" screen OD
7. Run second swell packer, same as above
8. Run required amount of 7" blank pipe across the low permeability reservoir section (consider to include 1 or 2 Open Hole Mechanical Packers, in this section)
9. Run second flapper valve below upper injection zone, ceramic type for later removal.
10. Run second section consisting of swell packer/ Darcy's Hydraulic Endurance Screen/swell packer for the upper injection interval
11. Run required amount of 7" blank pipe to bring liner hanger up to approximately 50 degree inclination(wireline workable inclination for main completion)
12. Rig up false rotary table/bowl and slips with handling equipment for 2 7/8" inner string
13. Perform SJA, focus on manual handling and well control actions

14. Run the inner string with stinger, flapper valve shifting tool and required amount of joints to surface
15. Pick up liner hanger with Running Tool and connect inner string to bottom of liner hanger running string
16. Make up liner hanger with integrated packer outer connection to last blank joint in rotary table
17. Circulate the liner volume to check for any restrictions and record pressures and weights
18. RIH with the screen liner on HWDP/DP as required (calculations to be prepared)
19. Limit running speed to predetermined level from surge/swab calculations
20. Fill pipe every stand, top up every 5 joints
21. Circulate at the shoe and record up/down weights before going in open hole
22. Run screen liner in open hole
 - a. Plot up/down weights
 - b. Circulate and work liner up/down if any restrictions
 - c. Avoid rotation to reduce risk of damage to the 25% chrome screens
23. When on TD, circulate the liner x Open Hole annulus to new and clean Low-Solids OBM(optionally containing breaker for enhancing filter cake removal)
24. Drop the liner hanger setting ball
25. Set liner hanger and release the Running Tool as per procedure
26. Blow the ball seat
27. Pick Up required length to activate lower flapper valve
 - a. This upwards motion will un-sting the inner string at the bottom(stinger pack off) and shift lower flapper valve to closed position
 - b. Seals between liner hanger Running Tool and liner will still be maintained if proper space out.
 - c. Do not set the liner hanger packer at this stage. Preferable to have an open liner/OH annulus to avoid any hydraulic lock preventing the screens to activate during setting action
28. Pressure up down the string and test the lower flapper valve to approximately 500 psi (somewhat lower than Hydraulic Endurance Screen/OH packer activating pressures). Record volumes pumped.
29. Pressure up the well down the drill pipe to activate each Hydraulic Endurance Screen valve(both zones) and engage the Open Hole Mechanical Packer
 - a. Use the cement unit, observe pressures
 - b. Darcy's design normally requires 2000psi/10min¹⁴
 - c. Open Hole packer requirements depending on vendor specifications
 - d. Bleed off the pressure
30. Activate the screens by pressuring up down the drill pipe a second time
 - a. Apply 400psi/10min (Darcy's procedure¹⁴)
 - b. Observe for any return in the Trip Tank while screens activate
31. Pull up to activate the "dog sub" on the liner hanger RT
32. Lower the running string and set the liner hanger integrated packer by applying set down weight on top of the PBR (with dog sub)
 - a. Test liner hanger packer to 2000psi on the annulus (swab cups seals still engaged inside the liner hanger assembly)

33. Pull up to disengage the seals in the liner hanger and displace the inside of the screen liner to new LS-OBM down the inner string (at this stage any mud weight balancing the reservoir pressure would be acceptable, e.g. 1.08sg to keep the well overbalanced (pore pressure assumed to be 1.05sg as mentioned above))
34. POOH with liner hanger Running Tool and inner string
 - a. Activate upper flapper valve while pulling shifting tool through the valve
 - b. Observe overpull
 - c. The upper flapper valve should be of a full bore ceramic type for later removal before testing the lower zone

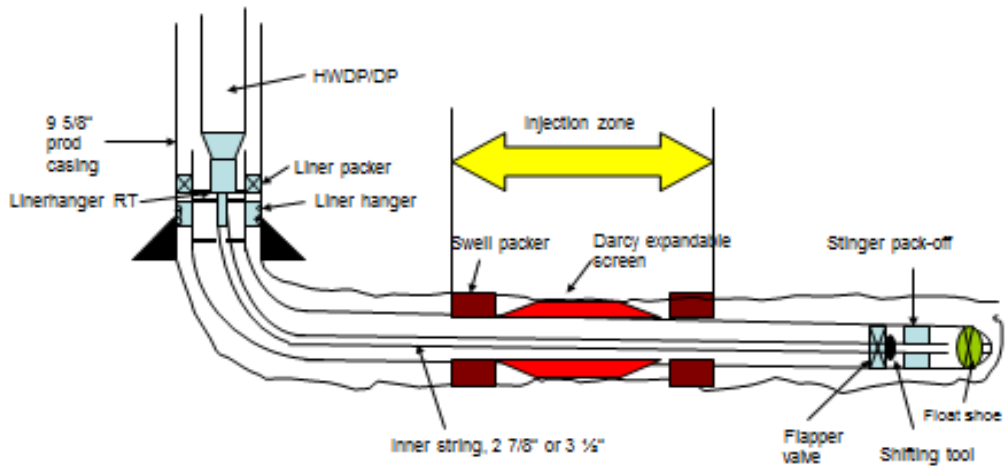


Figure 10: Screen liner installed at TD, single-zone Open Hole completion

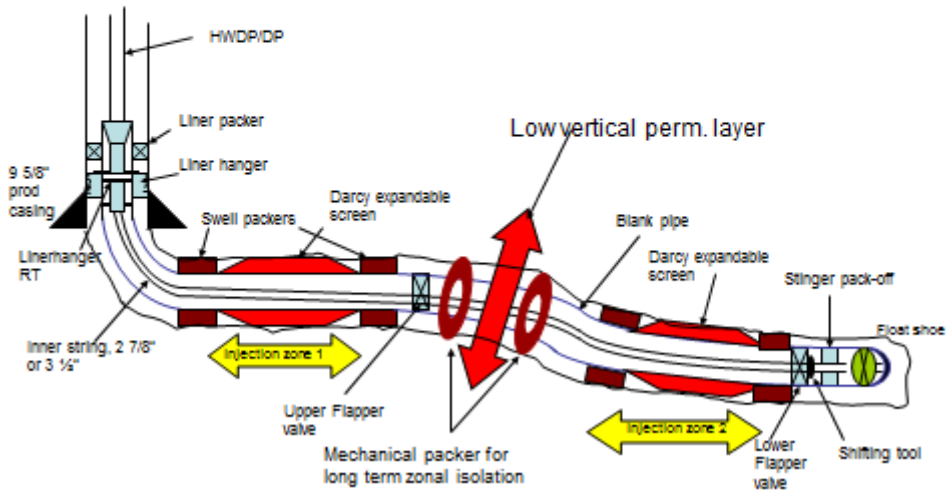


Figure 11: Screen liner installed at TD, dual-zone Open Hole completion

Risk analysis and mitigating actions

Operation: RIH and install Darcy's Hydraulic Endurance Screen.

	Risk	Consequence	Mitigating Measures
1	Kick while running Screen	Unable to shut in well	<ol style="list-style-type: none"> 1. SJA & Review procedures. Verify BOP cutting capabilities 2. Ensure that well is stable before RIH 3. Have X-over and kick stand ready 4. Consider possibility of dropping string if well is flowing 5. Use float valve in shoe to prevent
2	Damage to joints(screen/blank) while running 25% Chrome pipe	Corrosion of pipe, reduced lifetime of completion	<ol style="list-style-type: none"> 1. Ensure good handling procedures 2. Lay down any pipe joint with damage. Ensure visual inspection before Make Up (M/U) 3. Avoid severe

			weather conditions(on floating rig or drill-ship)
3	Kick while running inner string	Unable to shut in well/cut pipe	<ol style="list-style-type: none"> 1. SJA & Review procedures. Verify BOP cutting capabilities 2. Have X-over and kick stand ready to bring solid pipe through BOP 3. Consider possibility of dropping inner string if well is flowing
4	Severe losses while running screen liner on running string	Potential kick. Necessary to pump LCM with risk of plugging screens	<ol style="list-style-type: none"> 1. Ensure all losses are cured before RIH 2. Use acid-soluble LCM material for easier clean-up 3. Perform surge/swab calculations before RIH, adjust running speed accordingly
5	Problems to run screen liner in Open Hole	Unable to reach predetermined depth. Packers not reaching predetermined depth.	<ol style="list-style-type: none"> 1. Wiper trip and condition hole before running screens 2. Work liner within acceptable and predetermined parameters 3. Avoid rotation to damage 25% Chrome pipe. Also, rotation while RIH not recommended by Darcy.¹⁴ 4. Carefully monitor pressures to avoid premature setting of liner hanger 5. Consider to POOH and run wiper trip 6. Ensure hookload

			calculations are done before RIH
6	Excessive pressure while circulating	Unable to RIH due to premature expansion of Darcy's Hydraulic Endurance Screens	<ol style="list-style-type: none"> 1. Running inner string in screen/liner will prevent screen from accidental expansion. However, the inner string will cause higher pressure on liner hanger and hold down sub (if used). Careful consideration to be given to the setting of pressures/ pinning of the liner hanger. 2. Set the screen activation valve pressure as high as deemed feasible 3. Be prepared for pack off in annulus and abrupt pressure changes. 4. Carefully monitor the pressures while pumping 5. Possibly add safety factor to parameters to allow for sudden pressure increase.
7	Stuck with Darcy's Hydraulic Endurance Screens due to premature setting	Loss of hole section	<ol style="list-style-type: none"> 1. Fishing plan to be established in advance 2. Consider to abandon section and sidetrack 3. Cementing plan to be prepared
8	Leak in string/screens/pipe while on setting depth	Unable to reach valve activation pressure to expand	<ol style="list-style-type: none"> 1. Prepare backup plan for running activation tool to expand each joint separately

		screens	according to Darcy's procedures.
9	Unable to reach setting depth due to excessive swell packers/ECP's etc.	Difficult to diagnose the cause of the problem	<ol style="list-style-type: none"> 1. Ensure required amount of swell packers/ECP's are carefully considered 2. Plan for extra weight in the running string (HWDP)
10	Premature setting of Darcy Hydraulic Endurance Screen due to closed volume between inner string and screen	Stuck in hole with screens	<ol style="list-style-type: none"> 1. Install flow sub in inner string 2. Avoid complete filling of the space between inner string and Darcy's Hydraulic Endurance Screens with fluid 3. Circulate frequently while RIH to cool down fluid in closed space

Injection testing of the upper reservoir interval

In this section a generic proposal for a procedure for doing an injection test in the upper part of the Johan Sverdrup reservoir is presented. In this scenario the zonal isolation from the lower reservoir is achieved by the use of the upper flapper valve and a retrievable packer. This installation scenario incorporates two runs; one run for scraping the area where the packer is to be set, and one run for setting the packer, injection testing and POOH with the packer. A contingency plan if the retrievable packer did not provide the proper seal would be to RIH with Darcy's activation tool and use this to mechanically close the activation/production valves across the lower reservoir interval so as to provide zonal isolation to this part of the reservoir. Procedure below: ¹⁴

1. Run a 7" casing scraper/drift to the upper blank pipe section in the 7" screen liner.
2. Scrape setting area for the 7" retrievable packer, circulate B/U and POOH.
3. Run 7" retrievable packer to setting depth in the upper blank pipe section with stinger below extended down to the upper screen zone.
4. Displace the work string to injection fluid and set the packer.
5. Perform injection test in upper zone with the cement unit according to predetermined programme.
 - a) Step up in 200l/min. steps. Allow sufficient time to stabilize conditions on every step.
 - b) Record stable pressures and rates.
 - c) Increase the flow rate to maximum achievable from the cement unit or as dictated by limiting pressures (should normally be the fracture pressure with some safety margin).

6. Upon completion of the test, displace the string to 1.08sg Low-Solids OBM down to the screens.
7. Release the retrievable packer and let elements retract.
8. Circulate Bottoms Up.
9. Flow check well.
10. POOH and Lay Down packer and stinger.

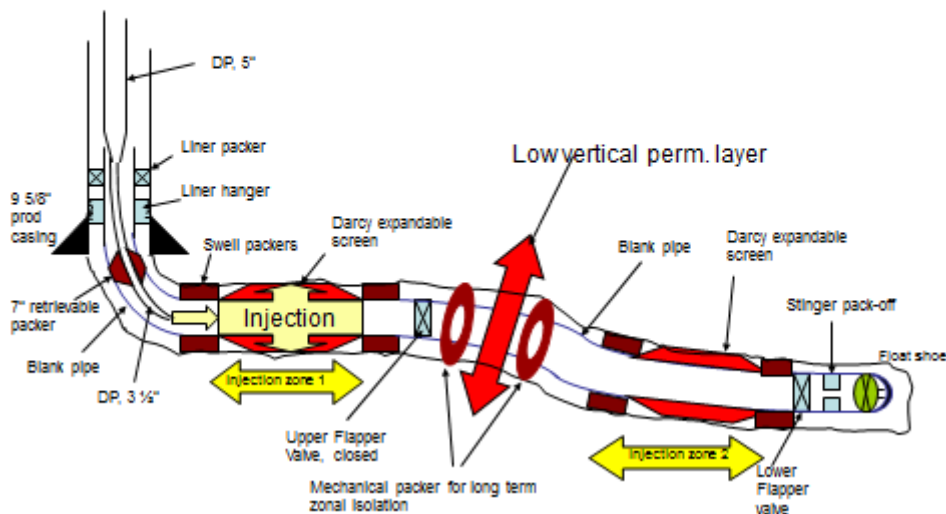


Figure 1: Injection with retrievable packer in the upper injection zone

Injection testing of lower reservoir interval

Below is a generic proposal for a procedure for doing an injection test in the lower part of the Johan Sverdrup reservoir:¹⁴

1. RIH with 7" casing scraper with stinger and bull-nose below to break the upper ceramic flapper valve.
2. Scrape setting area for 7" retrievable packer in blank pipe between the upper and lower screen zone.
 - a) Ensure packer and scraper can pass the 6 5/8" base pipe in upper screen zone.
3. Break the upper flapper valve.
4. Circulate Bottoms Up, flow check and POOH.
5. Make Up 7" retrievable packer and RIH to setting depth in 7" blank pipe above lower screen zone.
6. Displace string to injection fluid and set the packer.
7. Perform injection test in lower zone with the cement unit according to predetermined programme.

- a) Step up in 200l/min. steps. Allow sufficient time to stabilize conditions on every step.
- b) Record stable pressures and rates.
- c) Increase the flow rate to maximum achievable from the cement unit or as dictated by limiting pressures.
- d) When maximum rate/pressures are achieved at stable conditions, shut in the pump and record fall off data (pressure drop over time).
8. Upon completion of the test, displace string to 1.08sg Low-Solids OBM down to the screens.
9. Release the retrievable packer and let elements retract.
10. Circulate Bottoms Up.
11. Flow check well.
12. POOH and Lay Down packer and stinger.

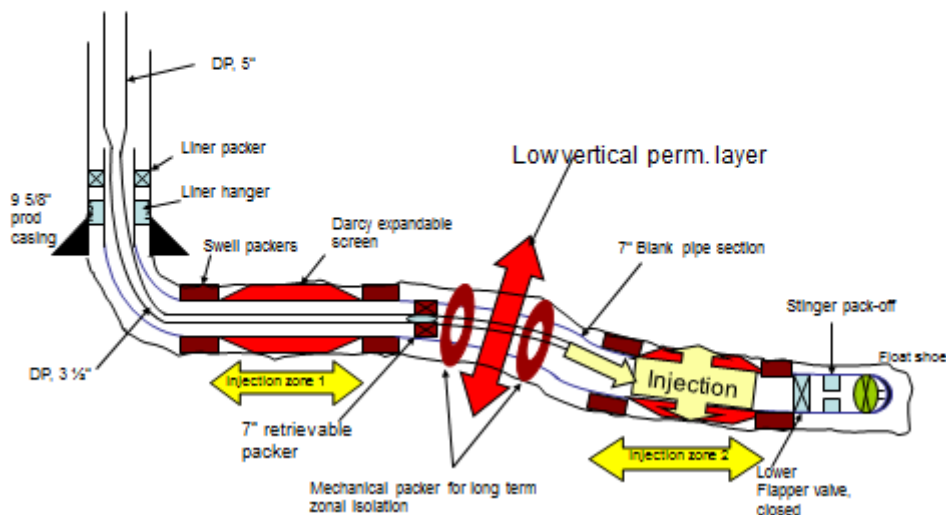


Figure 2: Injection testing of the lower zone

Injection testing after installation of the main completion

If it is preferred to do the injection test after the main completion is installed the intervention in the well would be somewhat more cumbersome. The alternatives for working in the horizontal section would be via tractor operations on wireline/slickline or by the utilization of Coiled Tubing. Both methods have a high risk involved and CT with all the heavy lifts and weather limiting factors should be avoided. Even running a work string through the completion is feasible. This would however be considered a more complex and risky operation than the retrievable packer solution before the upper completion is run. In addition, if the testing results were below expectations (and even unacceptable for the well purposes) it would be a “shorter” way to repair or rectify any issues before the main completion were installed.

A possible scenario for utilizing tractor for the zonal testing after the upper completion is run and the X-mas tree installed could be as follows: ¹⁴

Assumption: The upper flapper valve is in place and tested:

1. Line up the cement unit to the kill side of the x-mas tree.
2. Test all surface lines
3. Start injecting down the completion string into the upper zone at desired rate
 - a. E.g. at a rate of 200 l/min. increments, with stable condition on every step
 - b. Increase flow rate in steps to maximum allowable flow rate limited by either pressures and/or cement pump capacity (pressure limitation would normally be fracture pressure)
 - c. Stop injection and record fall off data (pressure/time)
4. Rig up wireline BOP and lubricator on the X-mas tree and pressure test the PCE (Pressure Control Equipment).
5. Open up the well (X-mas tree valves) and RIH with the Darcy shifting tool on tractor through the completion and into the upper screen section. Be careful when going through the TRSSSV, packer and nipples.
6. Close all Hydraulic Endurance screens with Darcy's activation tool according to Darcy's recommended procedure.
7. Break the upper ceramic flapper.
8. POOH with the tractor and the Darcy activation tool.
9. Rig down the wireline tool string and PCE.
10. Line up the cement unit through to the kill wing and test rig-up.
11. Start injection with the cement unit down the completion string into the lower injection zone.
12. Upon conclusion of the injection tests, inject in upper or lower zone or eventually commingled as deemed beneficial for the reservoir development.

Discussion

To run a prototype of a sand screen on a new field development like Johan Sverdrup is not recommended. In addition to the field test for Mærsk Oil in 2012, Darcy will install two Hydraulic Endurance Screens for Statoil in the near future (on Statfjord and Snorre fields) and also a field installation for Shell in the Gulf of Mexico planned for 2015.¹⁴ Results and findings from these, and other future installations of Darcy's Hydraulic Endurance Screens, should be closely investigated by Statoil when evaluating Darcy's Hydraulic Endurance Screens for Johan Sverdrup.

Areas of Improvement

There are some areas of the Hydraulic Endurance system that there are still some uncertainties to, i.e. they have not been sufficiently field tested to date and should be the subject of further assessment in the upcoming field installations.

The Hydraulic Endurance Screens has only had one field installation to date (for Mærsk). While RIH with the lower completion the screens were accidentally activated and the screen was set in the casing. Even after utilizing heavy duty fishing tools the screens were not possible to retrieve, eventually necessitating a sidetrack of the well. While this certainly proves the compliant qualities of the screens it also highlights a possible major risk with the screens, in that there is no return if the screens are in fact inadvertently activated. In an after-action report¹⁴ the contributing factors in the premature setting of the screens were successfully identified as a combination of rig-specific factors and certain issues with the completion design as a whole (the screens actually activated as per design). Darcy has taken steps to remedy these factors and has also more recently modified the valve arrangements on their screens to reduce the risk of premature risk.¹⁴ Statoil should carefully monitor the upcoming installations and make sure that all pressures are as per Darcy's design during RIH and activation of the screens.

The current Darcy Endurance 100™ system has a screen OD of 7 ¾", which does not leave a lot of open space in an 8 ½" hole. In the installations to come on Snorre and Statfjord hookload, ECD and other relevant parameters should be monitored during RIH in order to identify any problems with running in. The development of the Endurance 200™ system, which is to be tested on the Statfjord field should be followed closely, as this has an OD of 7 ¼" which leaves more space between screen and open hole when RIH.

Comparison between Darcy's Hydraulic Endurance Screens and OHGP/SAS

Open Hole Gravel Pack is perhaps the most natural sand control method to compare Darcy's Hydraulic Endurance Screen with as they both offer some of the same qualities – first and foremost the compliance towards the wellbore geometry. The OHGP was also Statoil's initial choice for sand control in the water injector wells at Johan Sverdrup. This has now been changed to Stand Alone Screen, as mentioned earlier, which also makes a comparison with SAS natural.

Referring to the chapter "risk analysis and mitigating actions" and the potential risks when running in with and installing the Hydraulic Endurance Screens it is clear that some of the risks also apply to both SAS and OHGP. For example, if utilizing 25% chrome steel quality SAS and OHGP have the same

challenges with not damaging the pipe while running in and assuming the requirement for zonal isolation is the same then the challenges with ECP/Swell packers will be the same.

The main difference is the risks related to accidental setting of the screen, as the Hydraulic Endurance Screen is a hydraulically activated system. This did occur when installing the Hydraulic Endurance Screen for Mærsk in December 2012 and led to the well having to be sidetracked.¹⁴ Because there are no expansion/activation to be done with SAS or OHGP excessive pressures when RIH is not a problem in the same way. One risk specific to the SAS is screen plugging while RIH. If utilizing a solid base pipe for the Hydraulic Endurance Screens there is no flow path from the annulus through the screens to the inside of the string, greatly reducing the chance of particles plugging the screens. Risks associated with gravel packs are mostly present during the pumping operations - after the screen or liner has been run to TD with wash pipe, crossover tool and gravel pack packers. The primary risk is not successfully packing the well due to a premature screen-out. This premature screen-out will most likely occur due to losses. As the gravel pack fluid is lost to the formation, its ability to transport the gravel is lost. As this is lost the gravel will create sand bridges across the wellbore that blocks off the toe of the well from packing. Insufficient packing like this may be critical for the gravel pack performance and may in a longer perspective lead to losing well injectivity if excessive sand production and subsequent sand fill in the well occurs.

After installation and when the injector well has been put into use the various sand control methods pose different risks. Stand Alone Screens have a quite high failure rate and are known to be prone to screen plugging, as discussed in the section 'Sand Screens'. A plugged sand screen has to be pulled and replaced with the extra cost that leads to. A common problem in water injectors is thermal fracturing, as covered in the section 'Water Injector Well-Specific Sand Control Challenges'. There is a risk that the gravel of a gravel pack may be lost into these fracture systems, which may cause insufficient sand control and ultimately complete loss of injectivity due to sand fill. A common long-term risk for all completions in water injector wells is the risk of corrosion leading to non-functioning sand control, with the result that the completion has to be pulled and replaced. Other long-term risks for Darcy's Hydraulic Endurance Screens are difficult to identify as there are no data available. The only installation of the Hydraulic Endurance Screens is the one for Mærsk in 2012.¹⁴ In theory the critical time for the Hydraulic Endurance Screens is when RIH and during installation. Once it has been successfully installed there should be less risks associated with it than with the OHGP or the SAS. There is no gravel that can be lost to thermal fractures or thief fractures like with the OHGP. The risk of erosion and screen plugging should be lower than with the SAS, due to the compliance towards the wellbore geometry which lowers the probability of sand production in the first place, and also eliminates the annular gap. The higher inflow area from an activated Hydraulic Endurance Screen (compared to SAS) also results in a lower flow velocity and ultimately reduces the risk of screen erosion.¹⁴

The main risks of failure for each sand control method, for each phase of the wells lifecycle has been summarized in the table below.

Operation	<i>Hydraulic Endurance Screens</i>	<i>Stand Alone Screens</i>	<i>Open Hole Gravel Pack</i>
<i>RIH</i>	Low probability of failure (<i>accidental activation of screens</i>), very high consequence of failure (<i>most likely sidetrack</i>)	Medium probability of failure (<i>predominantly screen plugging</i>), low consequence of failure (<i>POOH and run in with new screen</i>)	Same as SAS, higher risk of plugging if running slotted liner instead of screen
<i>Installation</i>	Low probability of failure (<i>activation valves not opened</i>), low consequence of failure (<i>running in with activation tool and opening each valve mechanically</i>)	Very low probability of failure, low consequence of failure (<i>POOH and run in with new screen</i>)	Medium to high probability of failure during gravel pumping (<i>losses of gravel pack fluid resulting in premature screen-out</i>), medium to high consequence of failure (<i>potentially total loss of injectivity if incomplete packing leads to sand filling well</i>)
<i>Long Term/Injection</i>	Low to medium probability of failure (<i>screen plugging or erosion</i>), medium to high consequence of failure (<i>screen not possible to pull – need to install new, smaller OD screen inside old screen</i>)	Medium to high probability of failure (<i>screen plugging or erosion</i>), medium consequence of failure (<i>pull screen and install new screen</i>)	Low to medium probability of failure (<i>gravel lost to thermal fractures and/or thief fractures</i>), Medium to high consequence of failure (<i>loss of sand control, potentially total loss of injectivity due to sand filling well</i>)

Conclusion

A big factor in the cost of completion is the time needed for the installation.² The fact that Darcy's Sand Control System is a one-trip-system will contribute to considerable cost-savings compared to other open hole completions like for example Expandable Sand Screens or cased-hole completions needing perforating. Compared to gravel pack, the Hydraulic Endurance screens do not need the extra pumping equipment and personnel, which also contributes to cost-savings.

In water injectors where there is a possibility for thermal fractures occurring, a gravel pack may not be applicable due to the risk of the gravel escaping into the formation through these fractures. In such a situation the Darcy Sand Control System is a good alternative as it provides the same wellbore support as the open hole gravel pack, however without the risk of gravel-loss. Also, filter cake removal is vital for injector wells as the filter cake is not produced to the surface in the same way as it is in a producer well. Filter cake removal is a challenge in an open hole gravel pack as the filter cake has to be intact while pumping the gravel to prevent losses, meaning that the filter cake has to be removed through the gravel pack after it has been placed, with the risk that poses of plugging the gravel pack. With a Hydraulic Endurance Screen the screen may be RIH and then breakers for filter cake removal may be placed. As the screens are extended towards the wellbore geometry they will also mechanically disperse the filter cake and in that way further support filter cake removal.

For water injectors the Hydraulic Endurance Screen seems to be a viable alternative to the Open Hole Gravel Pack as it provides a more reliable sand control method (no risk of gravel loss to fracture systems) and potentially better injectivity as excellent filter cake removal is easier to achieve. When comparing with Stand Alone Screens it has the obvious advantage of being a compliant system providing wellbore support. The installation process is slightly less complex for a SAS completion, but the risk of failure during hydraulic activation of the Hydraulic Endurance Screens is somewhat compensated for through the backup solution of running in with an activation tool and opening each screen/valve mechanically. Also, the higher inflow area means lower risk of screen erosion, which is a common problem with the Stand Alone Screen. The opportunity for selectivity and shutting of zones is also very relevant for a Johan Sverdrup field installation due to the two-zone reservoirs, as is the possibility to integrate ICD's with the screens in order to ensure an even injection flow profile.

Areas for further assessment with regards to the Hydraulic Endurance Screens are the risk of accidental premature setting/activation of the screens, as seen on the installation for Mærsk in December 2012. It is not possible to "de-activate" the screens, as the system design is for the fluid to be locked inside the activation chambers for the lifetime of the well. That means that the consequence of a premature setting of the screens most likely will be a sidetrack of the well. Another point to be aware of is the OD of the Endurance 100™ system, which is the system planned for installation at the Statfjord field later this year and the system that has been used in the installation scenario in this thesis. In an 8 ½" hole a screen OD of 7 ¾" does not leave much space and could be a challenge to get to TD. Monitoring the relevant parameters during RIH on the Statfjord installation should be a priority for Statoil, in order to identify any problems getting the screen to bottom. If this were to be problematic then the Endurance 200™ system currently under development and planned for installation on the Snorre field later this year should remedy the problem as this has a smaller screen OD of 7 1/8".

In general Darcy's Hydraulic Endurance Screens seem very suitable for use in the planned water injectors at the Johan Sverdrup field, more so than the Open Hole Gravel Pack and the Stand Alone Screen. The main question marks relate to the lack of a backup solution if the screens were to inadvertently activate prematurely, and as with all new technology the lack of field installation experience leaves an uncertainty regarding the long term performance of the screens. Two field installations are planned for Statoil later this year at the Statfjord and Snorre fields and one HPHT installation is planned for Shell in the Gulf of Mexico in 2015. Gathering experience from these installations and other possible installations up to 2019 when the first wells are planned at the Johan Sverdrup field should aid in making the decision of whether to utilize Darcy's Hydraulic Endurance Screens or not.

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