Production enhancement from sand management philosophy.
A Case Study from Statfjord and Gullfaks
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Abstract
Statfjord and Gullfaks are "Brown" fields operated by Statoil in the Tampen area of the North Sea. The production from these fields is characterized by large volumes of water and increasing sanding tendencies. The operator has for many years followed a strategy whereby sand produced with the wellstreams has been handled topsides prior to on-site disposal. The adoption of a sand management strategy has been crucial for prolonging economic reservoir development during tail production. By choosing to deal with sand topsides the operator has been able to pursue low cost slot replacement drilling where wells are completed without sand control equipment. The cased-hole functionality has facilitated multi-target drilling and is suited to selective production of each sand member through cheap plug/perf interventions.

Significant gains in production (acceleration) and reserves (IOR) have resulted from the pursuance of sand management in these fields. Examples of wells showing productivity improvements as a direct result of allowing intervals to produce sand are presented. In addition, production gains achieved from replacing choked back "sand free" production with "maximum acceptable sand rate" production are presented. Increased sand tolerance has also led to reserve increases in some wells as unproductive intervals that were previously sanded up have cleaned up and started to flow. It will be argued that this strategy negates many concerns with formation damage during well work because such damage is produced out with the sand and the wells clean up naturally.

The transient nature of sand production is discussed and the production gains observed in each field is presented. Such a strategy requires that the sand production is managed in a safe and controlled manner where the negative consequences of sand production are manageable and predictable. This paper will also discuss the improvements made in sand detection and on-line erosion mapping required to improve the sand tolerance of these facilities.

Introduction
Sand management is not a new concept. It has been used successfully in heavy oil developments for several years. Cold production of oils with viscosities as high as 11000 cp has found to be economic provided large sand influx is maintained in these wells. Erosion concerns in such low velocity cases are generally not limiting. In more traditional environments, sand production has been considered unacceptable. Operators have typically implemented a conservative approach where production rate (and revenue) has been restricted to reduce sand production and decrease the risk of erosion leading to a loss of containment. However, recent sand management practices have shown good results in both technical and economic terms through controlled sand production to surface rather than classical sand control through total sand exclusion.

On Statoil’s Statfjord and Gullfaks fields a sand management strategy has been in place for more than a decade. By choosing to permit sand production to surface the operator has reaped production benefits and avoided costly sand control completions during infill drilling operations. This strategy has moved the production bottleneck away from well potential and over to sanding levels on these fields. Typically, wells are choked back to a maximum sand free rate (MSFR) or to a Maximum Acceptable Sand Rate (MASR). Production of sand creates disposal issues and several integrity challenges:

- Sand is erosive and may affect the functionality of valves and regularity equipment.
- Uncontrolled erosion can lead to loss of integrity and hazardous situations.
- Sand fill in separators or storage tanks /transportation vessel may cause process problems and ultimately lead to costly shut downs and removal operations.

In order to further optimize production without compromising safety or environment, Statoil initiated a project in 2000 to further improve the sand tolerance of its offshore platforms. The project resulted in Statoil developing and further refining its sand management strategy and championing improvements in online sand detection and
erosion monitoring. The first implementation was as a pilot project on the Gullfaks A platform but the strategy has now been implemented in full scale on all installations in Gullfaks and Statfjord.

**Sanding Tendencies and Historical Sand Control**

Gullfaks and Statfjord are two large oil fields operated by Statoil in the Tampen area on the Norwegian continental shelf (see Figure 1). At year end 2004, oil production on Statfjord, excluding 3 parties, was ca 22,000 Sm³/d with an average water cut of 85% and GOR of 720 Sm³/Sm³. On Gullfaks, oil production (excluding 3 parties) was ca 30,000 Sm³/d with an average water cut of 75% and GOR of 200 Sm³/Sm³. Three Condeep platforms stand over each field. Yearly sand production on each platform is estimated to be 50 to 100 tonnes. Sand production in individual wells can be up to 5 tonnes/yr. On each field, two thirds of the ±90 active production wells are currently limited by sand production. The d₅₀ grain size for the different formations ranges from 100 to 700 microns. The mean size is 200 microns.

Sanding tendencies on both fields are well documented. The conclusion is that all productive zones have the possibility of sand production with the current drainage strategy. This is confirmed by both theory and experience.

Rock mechanical studies confirm that Gullfaks reservoir material is unconsolidated and that perforated completions will produce sand irrespective of well inclination and perforation design. The extremely weak nature of the sands excludes the application of orientated perforating as a sand control measure (see Figure 2). During the first years of development, wells were naturally completed and selectively perforated in the relatively strong Rannoch formation. Subsequent development of weaker overlying formations and water breakthrough in existing wells led to an increasing number of wells being constrained by sand production. As a result, a cased-hole gravel packing (IGP) completion strategy was adopted two years after production start-up³. Poor trends observed in well productivity due to scaling and fines mobilisation following water breakthrough and diminishing infill reserves has resulted in a return to natural completions on Gullfaks. Hydraulic fracturing from competent sands into weaker formations has also been used successfully for sand control on Gullfaks in the past³.

The sand reservoirs in the Statfjord field are poorly to moderately consolidated. Some sand production has been observed throughout its production history. From startup in 1979 and until the early 1990’s there was sufficient well capacity to fill the process on all platforms. As such, problematic wells were choked back (or worked over) without incurring production losses and perforation designs selectively targeted the stronger sands. However, sand production became more of an issue when production came off plateau. Higher productive, but weaker, zones were targeted and this coupled with the increased transport ability of wells cutting water lead to increased levels of sand production. As a result, internal gravel packing was chosen for infill well design. In the period from 1990 to 1995, eight wells were completed with cased-hole gravel packs⁹. These completions were successful at excluding sand and they had good initial production results. However, well productivity dropped significantly following water breakthrough. In the modest scaling environment in Statfjord where sea water injection is used for secondary recovery, IGP were not found to be acceptable during tail end production. It is now accepted by the operator and by many in the industry, that gravel filled perforations are more likely to suffer from reduced productivity than other completions. Open-hole gravel packing (OGHP) techniques were becoming available at that time but these were not deemed suitable for long horizontal wells where zonal isolation was a critical issue. As such, perforated liners again became the standard well design from 1996 onwards. A passive sand management concept was adopted where sand levels were actively monitored and optimized by selective testing and choking of wells. Rock mechanical studies confirm that most wells completed without orientated perforations will produce sand at the current level of field depletion (see Figure 3).

**Sand Management Operating Concept**

In fields that are operated according to a sand management concept, well designs incorporating downhole sand control are unnecessary. Instead, sand production is managed through the monitoring and control of well rates, sand influx and erosion. Sand is produced in a safe and controlled manner where the negative consequences of sand production are manageable and predictable. This is a risk management approach.

Sand production in the industry has been handled by routines and procedures that have often been based on “gut feelings” and emotions instead of sound engineering principles and operating practices. In recent years Statoil has worked towards improving the sand tolerance of its production facilities through the application of:

- **Topside hardware (sand detection, separator flushing equipment & sand disposal options)**
- **Online mapping of erosion potential**
- **Erosion resistant design and materials in critical elements**
- **Condition based Preventative Maintenance (PM) and Non Destructive Testing (NDT) inspection program**
- **Optimised procedures and operational controls**
- **Information Management. E-field operations**

This has resulted in the implementation of improved sand management strategies on both the Gullfaks and Statfjord fields. The same approach is being considered on other Statoil operated fields. In all cases an individual technical evaluation is required to determine whether sand management is applicable. Several factors such as levels of expected sand production, fluid phases, geometry and dimensions of existing pipework, well potential, jetting and sand cleaning possibilities, geographical location, access restrictions to facilities, corrosion and pigging aspects in subsea flowlines may all dictate that a more traditional approach with active sand control is the optimal solution. In the case of gas and
condensate fields, the high velocities typical in the piping will often mean that a sand management concept is not suitable. However, the improved safety and monitoring inherent in the sand management approach may be desirable for such cases even if sand production is not designed for. Even in cases where active sand control is chosen, solids production can not be completely prevented or ruled out. Production of mobile fines may always occur without creating significant erosion problems. Failure of sand screens and uncontrolled solids production can have severe consequences for production installations.

The assimilation of a sand management concept on these two brown fields resulted from a desire to (a) improve safety, (b) optimize production and (c) reduce well costs and so increase IOR through infill drilling during tail production. Reserves from infill drilling projects were dwindling and associated with relatively high uncertainty. Managing sand topsides was commensurate with prolonging economic reservoir development since it permitted cheap and simple natural completions that:

- Avoided downhole sand control that would otherwise be prohibitive on cost, complex, and prone to scaling problems.
- Combined several small targets in same drilling project in area characterised by stacked multiple pays, “small” volumes, and large uncertainty.

The cased-hole functionality permits selective production of each sand by standard plug/perf interventions from toe to heel. This approach can be important in tail production where the efficient flooding of each sand member may be critical in accessing bypassed reserves and processing them through an efficient flooding of each sand by standard plug/perf interventions from toe to heel. This approach can be important in tail production where active sand control is chosen, solids production can not be completely prevented or ruled out. Production of mobile fines may always occur without creating significant erosion problems. Failure of sand screens and uncontrolled solids production can have severe consequences for production installations.

The operator’s experience with these new generation sensors on Gullfaks and Statfjord is satisfactory. They have been found to give good detection of sanding events even at low fluid flow velocities (0.6 m/s). This is an advantage over inline erosion probes that may not be sufficiently sensitive to sanding events in the lower velocity (low erosivity) range. This may be important for fields where the process may constrain the total sand production allowed. However, unlike erosion probes, acoustic devices do not directly measure erosion. As discussed later, Statoil’s solution has been to tie these sand measurements into trends predicted from the on-line erosion program and findings from the PM inspection.

Sand Detection. Sand production is monitored by acoustic methods and by well samples collected from a sand trap during well testing. Each well flowline is equipped with a dual acoustic sensor system. The two sensors are mounted on separate pipe bends and are separated by 10 meters or more. The employment of two independent detectors per well enhances the reliability of the measurements, adds redundancy to the system in case of errors and also offers the possibility of self correlation. Assuming that back ground noise is random and does not correlate between the two sensors, a cross correlation of the two signals can improve the signal to noise ratio and will also provide a direct determination of sand flow velocity between these two points.

The raw data from the acoustic sensors is useful when looking at sanding events. When this information is correlated to well behaviour (rates, pressures, choke movements etc) in a real time system, a good picture of the wells sanding tendency can be obtained. This real-time system is available both offshore and in town. Quantitative measurement of sand production in a multiphase environment is inherently difficult and such sensors will not provide an exact measurement of sand quantity. However, a continuous review of the relationship between ultrasonic noise level and well behaviour and/or sand trap contents enables the background noise curve to be regularly updated. Furthermore, annual calibration of probe sensitivity (sand signal in nV to g/s) through flow calibration and sand injection also improves the accuracy of the processed sand signal. The sand detection system automatically updates its well performance curves from the production and allocation databases on a daily basis. Real time well data (either choke position or WHP) from the “Process Control and Data Acquisition” (PCDA) system is then coupled with these performance curves in order to ascertain flow velocities in the piping.

The task of managing the sand detection system has been placed onshore. The production engineers responsible for well optimisation and monitoring are now responsible for the daily maintenance of the sand detection system. The operator believes that this placement of responsibility is crucial for the degree of reliability and accuracy that can be obtained the sand detection system. Changes in the raw sand signal caused by changes in well performance such as increasing gas or water rates or slugging can be correctly identified without such
changes causing false sand alarms. Transient well sanding behaviour caused by producing out sand beds in horizontal sections can also be correctly prognosed and the resulting action taken without unnecessary well choking (discussed later). The operator estimates that sand volumes can be estimated with an accuracy of ±50% if the system is continually maintained and calibrated by the production engineers responsible for well monitoring and optimisation.

The sand detection system with built in alarms is naturally integrated with the PCDA. Figure 4 presents a screen dump from the sand detection system. This shows the real-time sand signal as a pie-percentage of the sand alarm for the given wells. All signals can be trended. These signals are also available in a real time system (data stored every second) that can be accessed both onshore and offshore. In this way sand signals can be trended with other well data such as pressures and choke movements in order to improve well diagnosis.

The test separator is equipped with a sand trap mounted upstream of the test separator and, in the case of Statfjord, an acoustic sand detector. The efficiency of the sand trap has been measured on several occasions by injecting known amounts of green “Olivin” sand into the flowline of wells during testing. This method has also been used to calibrate the acoustic sand detectors.

The efficiency of the sandtrap has been determined to be between 1 and 3% on these installations. The main factors influencing variations in sand trap efficiency from well to well on a given installation are flowrates and sand grain size. The operator believes that a well functioning sand trap is an important tool for sand detection. Advantages of a sand trap include:

- Physical proof of sand production and enables samples collection for inspection of sand/scale
- Cross check of sand-free production with acoustic background noise
- Measure of sand during bean-ups where calibration of sand detectors can not be trusted

It is important to realize that it may be undesirable to operate a sand trap with high efficiency on fields operating a sand management philosophy. Volumes of sand can be large in such cases and this can create problems during sample collection and may also lead to problems in attaining representative sand volumes (if sand trap fills and all subsequent sand bypasses trap) and with operating valves on the sand trap drainage arrangement.

During MASR and MSFR testing, the sand trap is emptied once every one or two hours. This measurement together with the raw sand signals provides good control over the wells sanding tendencies. Bean up rates in the MASR and MSFR procedures are governed by trends in the acoustic sand signals and by quantities of sand collected in the sand trap. For example, the final MASR criterion on Statfjord is 0.3 dl sand during the last two hours of stable well production. This corresponds to ca 60 kg of dry sand a day with a sand trap efficiency of 1%. During MASR testing several tonnes of sand may be produced before the well settles down to this final MASR level.

### Online Erosion Mapping

A sand management concept requires a tool that accurately predicts erosion rates in a given geometry exposed to a given set of operating conditions. Production rates of individual wells can then be optimized with respect to sanding levels whilst still maintaining permissible erosion rates.

The API RP 14E practice has often been used by operators to determine maximum flowstream velocities. However, it has been documented elsewhere that this guideline is not actually applicable to wellstreams containing sand. The API RP14E relation does not actually include any of the physical parameters that influence material degradation (such as CO₂, H₂S and sand particle content). It does state however, that fluid velocities should be significantly reduced in fluids containing particles.

Extensive studies have shown that the particle erosion rate is highly dependent on the particle impact velocity. It is generally accepted that the erosion rate is proportional to the particle impact velocity raised to a power of 2 to 3 in steels. As such, high velocity and not large quantities of sand is the primary threat for erosion. A doubling of velocity implies at least a six fold increase in erosion rates whereas a doubling of sand volume gives a doubling in erosion. Note that in cases where erosion is an issue the particle impact velocity will be close to the mixture velocity of the well fluid.

Erosive wear in sanding environments is predictable in that it requires both large velocities and changes in direction. Erosion in smooth, straight pipes is generally small. This means that erosion is typically a topsides problem and not limiting wrt well tubulars downhole (erosion of downhole equipment such as pumps and choking devices can be an issue). When the flow direction is changed in a bend, the particles do not all follow the fluid but will hit the bend wall and result in metal loss. In general, the wear scar is located on the outside of the elbow. Denser well fluids and finer particles will give less erosion as the particles then tend to be carried around the obstruction by the flow rather than impacting on them. In many cases it is the pipe bends that are downstream production chokes that are most prone to erosion due to the lower pressure and higher flow velocities here.

An independent comparison of the various correlations available for predicting erosion rates has been performed for the UK HSE. This concludes that the methods given by DNV RP0501 are sufficiently accurate in predicting particulate erosion rates in piping. Statoil has elected to use these guidelines in its sand management work.

Erosion mapping of all flowlines, manifolds and headers on both fields predicted that these can be classified as having low erosion potential (< 0.01 mm/yr). The required inspection frequency for this piping can be optimised based on these conclusions. For example, on Statfjord B it was determined
that more than 30 tonne of sand is required to give 0.1mm erosion in flowlines whereas over several thousand tonnes was required to give 0.1mm erosion in production headers. Note that pipework on the Statfjord installations is mostly low alloy grade with high corrosion potential. Accordingly, flow rates are limited to 8 m/s in flowlines and manifolds out of regard for the application limits for the corrosion inhibitor. Erosion potential in piping is thus insignificant and, from an inspection point of view, PM in piping should be based on corrosion and not erosion aspects for Statfjord. Piping in Gullfaks is 6MO grade and high fluid velocities will not in general induce or accelerate corrosion degradation. Of course, such corrosion resistant alloys may be sensitive to other degradation mechanisms not related to flow including pitting/crevice corrosion and sulphide stress cracking. Flow velocities are typically in the range of 1 – 8 m/s for the majority of wells on these installations, although velocities of 15 m/s and higher are normal for wells producing large amounts of gas (see Figure 5).

Multi Orifice Valve (MOV) chokes with a wide range of trim sizes (2 x 1/2" - 2x2") are used on Gullfaks and Statfjord. Production experience has shown that these chokes are prone to erosion in the disks and in the outlet sleeve. Erosion has also been observed in the blinded tee immediately downstream the choke. In later years Tungsten Carbide (TC) outlet sleeves have been installed in these chokes owing to its superior erosion resistance to steel (often orders of magnitude better).

The main parameters determining erosion potential in the MOV chokes is the fluid velocity and the resulting angle of sand through the choke discs. The angle through the choke is determined by the trim size and the choke opening. For gas-dominated well streams where critical choke flow occurs (ratio of the pressure before and after the choke is two or more), the velocity through the choke is determined by the acoustic velocity for the given upstream pressure. For subcritical flow the choke velocity is approximately proportional to the square root of the pressure drop over the choke.

Erosion mapping was performed for all the MOV chokes in operation on these two fields. The choke models were based on detailed Computational Fluid Dynamic (CFD) simulations that mapped the 3D flow pattern of several different cases. The particle tracks were determined and sand particle impacts were applied at the choke internals in order to calculate the erosion rates on the walls. Erosion rates were determined in terms of millimetre wall thickness reduction in the TC sleeve downstream the choke. This work concluded that erosion in the choke outlet sleeve and piping immediately downstream can be a primary safety concern. In particular, incorrect choke operation at low %-opening can initiate internal jet formation that sets up a swirling pattern in the outlet. This will result in a concentration of particles into spiralling “ropes” and thus greater risk of loss of containment. Figure 6 shows the results of such calculations for two MO chokes which have the same area open to flow but which have differing degrees of chocking for the different size choke inserts. This erosion pattern has been observed in the field. Figure 7 shows the outlet section of a choke that was used to bean back a high gas rate well on Gullfaks A (5% opening). The erosion in the Inconel 625 material downstream of the TC sleeve is obvious. Such swirling patterns resulting from incorrectly operated chokes have also resulted in erosion in blinded tee bends immediately downstream the choke. Under certain circumstances, sand concentrates in the blind leg and the swirling pattern causes the sand to rotate and recirculate. Once a groove is established the process is self accelerating. In such cases significant erosion can occur in the absence of large sand volumes or high velocity since the same sand may be “used” many times. Note that blind tees are generally regarded to be less prone to erosion than standard elbows. Statoil’s experience however, is that blind-tees should not be used immediately downstream of chokes.

Statoil has, together with a third party, incorporated the DNV correlations for piping and chokes into a web-based computer program that will automatically monitor erosion potential in piping and chokes. This system provides the operator with on-line monitoring of the erosion potential at critical parts in the process facility (90° bends, chokes, headers and production manifolds) for all platform wells on the Gullfaks and Statfjord platforms. Production data (allocated well rates, pressures, choke positions and uptime) is collected daily from the relevant production database. The erosion potential at the various locations is then calculated assuming a base sand load. In this way, wells with high or negligible sand erosion potential can be distinguished. These erosion calculations can be easily related to sand measurements (e.g. acoustic sand signals, sand trap contents during testing) for a given well in the program. Future improvements may include the possibility of combining measured sand rates with these erosion calculations.

This numerical approach where the erosion potential is determined for each well on a day to day basis, has shown that “field wide” criteria for sand levels is often unnecessarily cautious in many wells and may also lead to unacceptable risk in the most erosion prone wells. A well by well approach to permissible sand levels can boost production from several wells whilst simultaneously improving overall safety.

**Procedures and Mitigating Strategies.** Operational procedures must be adapted to the sand management concept. When testing wells, old practices relating to zero sand tolerances must be updated to reflect the change in philosophy. Acceptable sand rates determined by safety (erosion) and sand volume (sand handling capacity of the installation) are now the norm. Control of erosion and sand production means that the operator can determine how much sand a given well can handle and so produce it at the optimum acceptable sand rate.

During normal operation the control room relies on the processed sand signals from the acoustic sand detection system. Continued sand levels over a given limit will initiate an alarm. The operator will then determine the next course of action depending upon trends in the well (sand signals, pressures, temperatures etc) and the availability of the test separator. If the test separator is available the well will be
routed here for re-establishment of MSFR or MASR rates. As well rates have previously been determined based on each wells erosivity potential and, to some degree, the platforms total sand handling capacity, it is not critical that wells are immediately routed to the test separator or that wells should be choked back prior to any further action. Indeed, choking back of wells that exhibit transient sanding behaviour may lead to an escalation in choke erosion. In addition, unnecessary choking may lead to situations where there is insufficient transport of sand out of the well. This may result in a well sanding up and ultimately dying. Expensive remedial interventions may then be required to return the well to production. The intrinsic control over erosion potential on these platforms gives the control room operators more “breathing space” when presented with sand alarms than would otherwise be the case. On the Statfjord installations the alarm for MASR wells is set to 1.5 g/s (ca 130 kg/day) whereas on Gullfaks it is 1.5 g/s. “Sand conditioning” has now become a primary function of test separator in addition to production testing for allocation purposes.

Correct choke operation is crucial for minimizing erosion in both the choke outlet and the bend immediately downstream of the choke. The on-line erosion program gives the operator guidelines as to choke operation as dictated by erosion rates. Previous “critical choke openings” that had been acquired from the choke supplier, have now been replaced by recommendations based on the actual erosion potential calculated in real time. A good rule of thumb is that these chokes should be operated at 50% or more of the maximum CV. If this is not possible, then the choke trim should be replaced with smaller discs such that equivalent well choking (CV) can be achieved with higher percentage openings. The fact that the most critical element for erosion is the choke trim on Gullfaks and Statfjord is actually positive from a monitoring perspective. Erosion will occur here prior to other places in the piping. Such erosion is manageable by correct choke operation and can be simply monitored. More importantly, worn choke discs (and thus signs of unacceptable sand erosion in the choke outlet) can be detected early by a comparison of the trends in effective choke CV (as determined by measured pressure drops and allocated production rates) and notional CV (as determined by CV curves and measured choke opening). The online erosion program performs such a comparison. An example of this is shown in Figure 8 where the CV deviation of a choke is plotted versus time. The choke was inspected and the worn discs were replaced. The CV deviation dropped back to zero immediately following this. As can be seen, the new choke is gradually eroding after this but there is some time left before required to change.

Jetting frequency and procedures have also been upgraded on several of the platforms. Jetting of the separators with seawater is performed routinely without any production constraints. The jet water from the first and second stage separators and the test separator is routed to the produced water flash drum. Figure 9 shows a plot of the sand concentration sampled from the produced water separator on Gullfaks C following jetting operations. This shows nicely that the improved sand management philosophy has greatly improved the sand tolerance of this platform. As discussed later, these increases in sand volumes are accompanied by large gains in production.

The jetting frequency in the different separators is based on experience. Jetting operations are labour intensive as they typically involve several manually operated valves. This operation has been automated on some of the platforms and sand detectors have been placed on the jet water outlet. This has enabled the operator to reduce the period of jetting and process disturbances to an absolute minimum. Some failures of the water jetting chokes were experienced prior to switching to improved choke design.

Partial sand exclusion approaches will also benefit production and operation of the fields. For example, perforation strategies that incorporate selective perforation and orientated perforations can reduce sanding tendencies on some fields. This approach has been used to good effect on the Statfjord field and on many other fields operated by Statoil. Simply drilling extra Rathole may also help reduce problems associated with sand production in some wells. Cheap bullheading treatments for chemical sand consolidation may also be effective in some wells with short perforation intervals.

Detection of erosion as it progresses can be difficult to measure directly in the field. However, the erosion mapping performed on these fields has given the operator a better understanding of where erosion is most likely to occur. By coupling this knowledge with the online erosion and sand production monitoring, the operator is better equipped to direct resources when planning PM and visual inspections. This enables the operator to carry out condition based maintenance which is favorable from both a financial and safety point of view.

Field production Improvements

The increased oil production obtained through adoption of an improved sand management philosophy has been very satisfying. On Statfjord, it is estimated that this gave a total of 0.3 MSm³ (1.9 Mill bbl) of additional oil during 2004. The introduction of MASR criteria for wells with low erosion potential on Gullfaks has played its own part in helping to halt production decline during the last few years. In 2004 it is estimated that an additional 0.6 MSm³ of oil was produced as a direct consequence of this operation philosophy on Gullfaks.

Each platform is estimated to produce an average of 150 to 300 kg of sand a day. However, sand volumes are much lower than this on days without any “sand conditioning” tests. For example, on Statfjord B this “background” sand production has been estimated to 50 +/- 20 kg. This should be compared to the several tonnes of sand produced on days when MASR testing or initial bean-ups following perforation are performed. Figure 10 shows the spread of sand production during a “normal” day on Statfjord B. The cumulative probability plot has been determined from a statistical analysis of the double detectors on each flowline.
The next section will present individual well sanding tests that exemplify the production improvements that can result from allowing intervals to produce sand. Sand tolerant criteria has also led to reserve increases in some wells as unproductive intervals that were previously sanded up are mobilized.

**Sanding Wells; Production Characteristics**

Production experience from many sand producing wells suggests that perforation cavities demonstrate significant post failure stability. Sand production is found to occur in sand bursts and has not been found to occur at catastrophic levels in any of the wells operated on these installations. Sand production is not continuous but characterised by random episodic events that may be accentuated by changing well conditions. Once a plastified zone has been formed around the perforation, the sand volumes that are produced from this can be effectively controlled by controlling well rates and by “sand conditioning” tests. Experience shows that sand production is not coincident with the onset of water breakthrough, but that water production can increase sand transport to surface and result in more “noticeable” sand production.

A schematic model of the operators sand production experience from these two fields is given in Figure 11. This shows that no sand production is expected prior to the point where shear failure occurs around the first perforations. Sand production is then expected to increase with increasing depletion as more perforations plastify. However, once all perforations have plastified sand production is then primarily determined by production rate and not depletion. Sand particles in the plastified region sprinkle down and are carried away with the flow. Sand cavities may then form behind the casing. Increasing rates will increase the transport capacity of this material and may also increase the rate of particle sprinkling. The functional relationship is not well documented. For convenience, the relative sand production levels are represented as continuous lines in the schematic. In practice sand production is found to be composed of episodic events and is not a continuous phenomenon. Note that perforation clean-up associated with water breakthrough and loss of capillary cohesion may lead to some transient sand production irrespective of this model.

Sand conditioning wells typically involve larger levels of sand production. In many cases several tones of sand have been produced during MSFR and MASR tests but this sanding tendency has been found to decay rapidly back to the baseline, punctuated, as always, by random sand bursts. In many cases this “heavy” sand production is the result of sand previously accumulated in the wellbore at lower flow rates. In other cases it may result from sand cavity collapse events caused by destabilization from changing well conditions or from sand accumulated behind the casing in cavities. Conditioning a well at a “high” rate ensures that most of the sand grains that can be eroded at this rate are produced out. When the rate is beamed back to achieve MSFR then all (most of) the grains erodable at this lower rate have been removed from the near wellbore area. The well can then be put back on production manifold and produced safely at this new rate. In many cases, sand conditioning may be related to the transport of sand that has accumulated in cavities behind the casing. This is illustrated in Figure 12. Sand accumulates in these cavities up to a level where the flow velocity is then sufficient to transport any new sand out of the perforations. Sand production during this stage is conceptualized to be low level and consist primarily of sand “sprinkling” down from the sandface. However, when the well is beamed-up, the transport capacity is increased and the sand bed is eroded down until a new equilibrium is achieved. This will be observed as a transient increase in sand production on the surface. Following this, sand production will again be low level. If the well is choked back following such a test, there will be a period of time where any new sand can accumulate in the cavity before sand transport out into the wellbore is again established.

The operator has indirect evidence of such cavities from pressure spikes seen on downhole pressure gauges during well beam-ups on Gullfaks that have been interpreted as a cavity avalanche. In addition, volumes of gravel much larger than the perforation volume have been pumped in old wells during perforation prepacking in the past. This indirect evidence of cavities in the unconsolidated Gullfaks material suggests that such cavities are also likely in other, stronger formations. The negative skins often observed with sanding wells may also an indirect evidence of the formation of large flow conduits.

**Example 1: B-15A on SFB.** This well provides a good example of the self cleaning effect that may derive from sand production. This well was drilled and completed in 2002. Following initial perforation, the well performance was very poor. This was attributed to formation damage caused by mud losses during drilling and inadequate perforation penetration obtained from a 3 ¼” gun shot in 7½” casing lying eccentrically in a 9 ⅝” horizontal hole. The initial liquid PI following clean-up was 2.5 Sm³/d/bar. A skin factor of 35 was determined in a subsequent pressure build-up test. The well was left producing at a back pressure of 5 bar against the test separator in order to maximum flow and pressure drawdown across the sand face. Two days later the well started making sand and the productivity increased as a result. Figure 13 shows the test data as captured in the production allocation database during this event. In the course of 4 days the well produced an estimated 800 to 1200 kg of sand. The well PI was found to have increased to 12 Sm³/d/bar and the oil rate increased by almost 500 Sm³/d.

**Example 2: B-24A on SFB.** Two MASR tests on this well provide typical examples of the episodic nature of sand production and the post failure stabilization seen in many wells. The first MASR test was performed in October 2003. A total of 400 to 750 kg of sand was produced during this test and the oil rate was increased from 303 to 442 Sm³/d. The liquid production increased from 930 to 1300 Sm³/d. The liquid PI before and after this test was 60 Sm³/d/bar. As figure 14 shows, sand production increased during bean-up but settled down again afterwards. The raw sand data show some sand bursts afterwards but these are not long lasting or
of a “normal” sanding behavior following bean-up.

The increased sand observed during bean-up is in many cases associated with the improved transport capacity in the well at the higher flow rates and not necessarily the result of increased sand production from the sand face. During normal production sand will sprinkle into the well and all or part of this may then be lifted to the surface. The flow velocity required to entrain sand in the horizontal well section is typically higher than that required to lift sand in vertical sections. This leads to a situation where sand dunes may develop in the near horizontal well sections. These dunes will grow to a height until the increased flow velocity over them is sufficient at carrying any new sand out of the section. The increased flow rates that follow a bean-up will increase transport rates downhole. The heights of any sand dunes that may have developed prior to this will then be eroded until a new equilibrium is established. This will be observed as a temporary increase in sanding rates topsides. It is important that MASR and MSFR procedures take account of this phenomenon. For the 7th lower completions typical on Gullfaks and Statfjord, sand duning is expected to occur in the horizontal sections at liquid rates under ca 1300 Sm³/d. For liquid rates exceeding this, produced sand will be transported directly out of the well (except for a stationary sand bed in the lower part of the production interval where the flow rate gradually decreases to zero). Another good example of this is afforded by the MASR test performed in well B-33 in October 2003. The well liquid rate was increased from 1090 to 1270 Sm³/d with a concomitant increase in oil rate of 80 Sm³/d. A total of 990 to 1900 kg of sand was produced out of the long horizontal section during the MASR bean-up. Sand production returned to “normal” following the MASR test, where only short lived, low level sand bursts were observed.

Example 3: B-35A on SFB. This is typical example that shows how bean-up procedures that tolerate high sand production can lead to improved flow and increased reserves in wells. Figure 16 shows the real time data captured from this well during the MASR testing. A total of 400 to 600 kg of sand was produced out during this test. The liquid rate was increased from 735 to 1920 Sm³/d with an improvement in the oil rate of 372 Sm³/d. The liquid PI before and immediately after the MASR was calculated to be 65 Sm³/d/bar. However, a few days later the well started to improve and the flowing well head pressure increased from 137 to 170 bar in the course of 12 hours. During this period the sand detectors showed relatively high sanding activity which gradually returned to a more “normal” pattern. A well test that was performed following this event showed that the oil rate had increased by an additional 825 Sm³/d and the calculated liquid PI was now 350 Sm³/d/bar. The sand produced out of the wellbore and the increased drawdown following the original MASR test are believed to have aided clean up of a perforation interval in the Etive formation. This interval was shot in 2001 together with a second interval and was obviously no longer producing in this multi-zone well prior to the MASR. The increase observed in the liquid PI is in keeping with log derived PI estimates.

Example 4: B-06B on SFB. This is a good example of changes in sanding tendencies in wells that do not have any sand beds in the wellbore. A MASR test was performed in February 2004 (see fig 17). This shows that sanding levels were increased during the actual bean-up period but that no long lasting sand production results. In this case, the liquid rate was sufficiently high (1670 Sm³/d) that sand duning in the horizontal section can not explain the increased sand levels observed during bean-up. Changes in rate and drawdown result in a temporary destabilization of sand cavities and thus increased sand levels. These cavities stabilize again once production has stabilized. Improved transport of sand out of the cavities may also partially explain this behaviour. As can be seen from the figure, this post failure stabilization may take a few days and involves several sand bursts. The liquid PI in this well increased from 18 to 22 Sm³/d/bar as a result of this MASR. This increase in PI may be explained in terms of improved clean-up of the various perforation intervals in the well or may simple be the result of increasing drawdown in a multizone well which is perforated in sands of differing reservoir pressure.

Conclusions

1. Techniques are now available that enable sand detection and measurement of metal loss attributable to sand erosion. These monitoring techniques, in conjunction with erosion models and related risk assessment methods enable safer and more efficient operation of sand producing wells.
2. Sand management strategies can allow production to be increased significantly in certain sanding wells without reducing the installation integrity.
3. Sand prone wells exhibit favourable well skins because of self-cleanup associated with the episodic sand bursts that take place. The production decline due to scaling that was observed in earlier wells where sand control was installed is avoided.
4. By choosing to deal with sand topsides the operator has been able to pursue low cost slot replacement drilling where wells are completed without sand control equipment. The cased-hole functionality provides reservoir management flexibility critical for the continued economic reservoir development of these fields.
5. The advantages of reduced well CAPEX and the enhanced production rates outweigh the economic costs associated with the additional risk management associated with sand ingress.
6. Sand management strategies require a multidisciplinary approach to the following aspects: prediction of sand production, sand monitoring, sand transport modelling, erosion control, and sand...
treatment and disposal. A sand management strategy may not be desirable in all cases. However, the improved erosion control will always improve safety of operations. Even in cases where active sand control is chosen, solids production can not be completely prevented or ruled out.

7. Experience from both fields shows that wells produce sand prior to the onset of water breakthrough but that free water does increase sand transported to surface and can therefore result in further choking of wells. Wells have produced sand in random episodic bursts for several years without any well integrity problems.

8. Sand prediction criteria based on predicting shear failure in sandstones is likely too conservative when used to determine whether active sand control is required, especially for installations that have some degree of sand tolerance. Production experience from many sanding wells suggests that perforation cavities demonstrate significant post failure stability. Sand production is found to occur in sand bursts and has not been found to occur at catastrophic levels in any of the wells operated on these installations. Sanding production is not continuous but characterised by episodic events that can be acerbated by changing conditions.

9. Sanding patterns during well bean-up or increased water cut are in many cases related to transport of sand accumulated in the wellbore or in cavities behind casing rather than to formation failure.

10. Sand monitoring reliability is improved by using two detectors on each flowline, separated a minimum distance apart.

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References

SI Metric Conversion Factors

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</tr>
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* Conversion factor is exact.
Fig. 1. Infrastructure and tie-ins in the Tampen Area

Fig. 2. Plot of TCS2 and strength requirements for Gullfaks. Red line is TCS2 strength required to avoid sand production irrespective of perforation design.

Fig. 3. Triaxial compressive strength with 2MPa confining stress from cores in Statfjord well 33/9-A37B. According to a rock mechanical study, sands to left of first vertical line will produce sand irrespective of perforation design. Sands to right of second vertical line are not expected to produce sand with today’s pressure depletion. Sands between the two lines will not produce sand if orientated perforating is employed.

Fig. 4. Screen dump from sand detection system showing overview of all detectors. Current sand volumes are presented as a pie-percentage of the permissible sand alarm.

Fig. 5. Flow velocities downstream choke as determined from allocated production rates.

Fig. 6. Swirling effects in outlet sleeve caused by low % opening in choke with large disc inserts. Flow geometry is better behaved in 100% choke with same area open to flow.
Fig. 7. Erosion patterns in choke outlet on a high rate gas well that was choked back to 5% opening.

Fig. 8. Choke erosion as judged by the deviation between measured CV (red curve) and theoretical CV (blue curve.) The choke trim was changed in Nov 2002. Picture shows actual erosion on discs. Also see that the new choke is gradually eroding, but there is some time left before required to change.

Fig. 9. Sand concentration sampled from Produced Water Separator, GFC following jetting operation. Sand volume measured in 2003 corresponds to ca 7 days production. Sand volume in 2004 corresponds to ca 5 days production.

Fig. 10. Spread in total sand production during “normal” day on Statfjord. Spread has been determined from statistical analysis of the double detectors on each flowline.

Fig. 11. Schematic sand production model. Sand production starts at a given depletion. Sand levels increase with depletion as more perforations experience shear failure but are primarily dependent on production rate once all perforations have plastified.

Fig. 12. Cross section of perforated liner lying on low side of horizontal well. This cavity model may explain why sand conditioning results in transient increases in sand production followed by periods of almost sand free (sprinkle) production. This is related to sand transport in cavity behind casing.
Fig. 13. Production data from testing of B-15A. Red curve shows WHP, blue is oil rate and yellow is water rate. Grey curve is sand detector output.

Fig. 14. Real time data from well B-24A prior to, during and after MASR test. Green curve is WHP, blue is choke opening, red and black curves are raw sand signals (nV) from double detectors.

Fig. 15. Real time data from well B-24A during next MASR test. Same colour scheme as in Fig. 13.

Fig. 16. Real time data from well B-35A during and subsequent to MASR test in January 2004. Same colour scheme as in Fig. 13.

Fig. 17. Real time data from well B-06B during and subsequent to MASR test in February 2004. Same colour scheme as in Fig. 13.