Preventing Scale Deposition Downhole Using High Frequency Electromagnetic AC Signals from Surface to Enhance Production Offshore Denmark

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Abstract

Mineral scale deposition is a significant impediment to efficient operation of oil and gas facilities. Deposition control strategies include brine demineralisation, chemical inhibition and mechanical intervention. Mitigation costs are highest at offshore locations requiring well intervention and include significant production deferment. Hydrocarbon production in the Danish sector of the North Sea has a number of specific regional challenges as reservoirs are often carbonate with high produced water calcium concentration resulting in a high potential for carbonate scaling. Secondary production techniques such as water injection flooding to maintain pressure are used and sea water is pumped directly into the reservoir introducing sulphate leading to downhole mineral scale deposition of barium sulphate, strontium sulphate etc. The offshore location of production facilities dictates that interventions are expensive and put pressure on valuable offshore bed spaces.

This paper reports results of field application of a recently introduced scale control technology based on high frequency electromagnetic AC signals generated and impressed onto a well head or associated piping conduit. Field trial data is provided from a production well with a history of scaling where production pressure was held back to reduce scaling severity. Field trial data describes the impact of the technology in preventing scale in a high value well. Analysis of the results showed that physical treatment using this alternative approach effectively controlled scale deposition such that the production systems was protected and the production benefits included increased reliability of gas lift valves, cessation of any tubing acid washes and enhancing production. The economic value added and reduction in risk to personnel and emissions are described.

An extended (9 month) pilot test has allowed production to be increased and no mineral scaling has been detected. The results achieved are promising. Stable and no lost production added a value to the producing asset and avoided significant revenue loss to the operator.

Introduction

Syd Arne field is located in the Danish sector of the North Sea. Production is via a fixed platform in 60m of water depth. Production commenced in 1999 with water injection started in 2000. The primary reservoir is the chalk Tor formation located between 2,700m and 3,200m below surface. The general reservoir properties can be found in Table 1 below. The well on which the electromagnetic signal generating unit was tested is drilled to the south of the field, completed to a depth of 5,926 mMDRT at 2,923 mTVDRT.

Production well SA-07 is gas lifted and produces from 14 zones that have been hydraulically fractured with proppant. Prior to the installation of the signal generating unit SA-07 produced some 490 BOPD at a water cut of 87% with the water composition as shown in Table 2.

SA-07 began production in December 2000 – the water chemistries indicated that calcium carbonate scaling was likely and the first deposits of scale identified in October 2003 during a Gas Lift Valve (GLV) change-out. In January 2011 a well intervention the 3" gauge cutter tagged a restriction at 2,535 mMDRT which is just below SPM#2 in the 4.5" tubing. The restriction was confirmed to be $CaCO_3$ and milled clean. To prevent formation of mineral scale the well is operated within a scale free 'envelope' derived from an analysis of the pressure, temperature, water composition and well architecture. The effectiveness of the envelope can be monitored with regular VLP analysis modelling to identify increases in the calculated friction coefficient to ensure any scale build up is identified before it results in a loss of production.

Table 1 - Reservoir Properties	
Oil density (°API)	36.70
Gas:Oil ratio (scf/stb)	1,200
Bubble Point (psi)	4,800
Reservoir Pressure (psi)	6,300
Oil Formation volume factor (rb/stb)	1.70
Oil Viscosity (centipoise)	0.30
Oil Gradient (psi/ft)	0.27
Reservoir Temperature (°C)	115
Porosity (%)	20-45
Permeability (mD)	0.1 - 0.8

It should be noted that changes in the pressure, temperature and chemistry can lead to scale build up and render the derived scale free envelopes void as circumstances have changed. Scale was detected in the well again in October 2011 and the scale free envelopes were re-calculated and the well beaned back to bring it into the scale free envelope.
During 2012 the derived friction coefficient had increased from 1.72 to 2.24 and the modelled gas lift orifice size in GLM#1 was reduced from 32/64" to some 23/64" for the model to match. All of these observations pointed to a scale build up in the upper completion. An acid wash was carried out in December 2012 and the friction coefficient was reduced to ca. 1.55.

Table 2. Produced & Seawater Properties

($mg.l^{-1}$ unless stated)	**Produced Water**	**Seawater**		**Produced Water**	**Seawater**
Total Dissolved Salts	66,734				
Density ($kg.m^{-3}$, 15°C)	1050		**Cl^-**	40,993	18,842

Resistivity ($\Omega.m^{-1}$, 15°C)	0.12		**SO_4^{2-}**	21	2,604
Na^+	21,840	10,357	**HCO_3^-**	656	169
K^+	752	500	**CO_3^{2-}**	-	-
Ca^{++}	1,550	494	**OH^-**	-	-
Mg^{++}	202	1,753	**B^{3+}**	68	<0.02
Ba^{++}	364	-	**Al^{3+}**	<1	<1
Sr^{++}	254	9	**Si^{4+}**	25	<0.02
$Fe_{(total)}$	3	0	**P^{3+}**	<0.3	<0.02
$Fe_{(aq)}$	2	1	**Li^+**	8	<0.02

Restricting production to prevent scale deposition is an expensive mode of mitigation with the estimated production loss being ca. 200 bopd. As an operator committed to maximising the value of their assets Hess Denmark investigated alternate means of mitigating scale deposition.

An ability to control scale without intervention and deferment offers significant value to operators. This newly applied method is non-intrusive and non-invasive. The electromagnetic signal generating technology described here offered an opportunity to control mineral scaling and reduce chemical emissions in a sensitive marine environment. Reduction in environmental impact is in addition to reduction in total cost of well operation and, in this case, production enhancement.

The signal generating unit was deployed and production rates and friction factors monitored to determine if scale was being deposited. Production was ‘beaned up’ and closely monitored. Finally, after conclusion of the extended 5 month test period the GLVs from the well were pulled and torn down to inspect for scale deposition.

Theory & Definitions

1 – Vertical Lift Performance (VLP) analysis software modelling to detect scale deposition

The VLP analysis software used is a proprietary software package designed to allow building of reliable and consistent well models such that detailed flow assurance can be studied at well and surface pipeline level. The programmes matching features were used to determine the effect of mineral scale deposition in increasing the friction factors within the matched model for the well. Initial modelling (prior to the electromagnetic signal generating trial) indicated that an increase in friction factor 1.72 to 2.24 was required to match actual production and that the modelled gas lift valve orifice had to be reduced to from 32/64” to 23/64” to match actual production rates indicating deposition of mineral scale inhibiting production. Multi-rate production tests were run on the well used for the test prior to electromagnetic signal generating installation and prior to beaning up to establish baseline values. The same friction factors and simulated orifices were then calculated during the trial.

2 – Electromagnetic Inhibition of Mineral Scale Formation

Water produced with hydrocarbons may come from the following sources:

1. Formation water trapped in source rocks since they were laid down – the chemical composition is determined by the historical geochemical environment
2. Injection water pumped into or adjacent to the oil producing formation to enhance recovery – chemical composition often incompatible with (1)
3. Water introduced to the wellbore during intervention operations such as GLV change-outs or stimulation treatment – lower volumes

These waters may contain dissolved chemical species that become less soluble due to environmental changes caused by the oil production process and can then precipitate as solids from solution – these solids may then deposit on the internal surfaces of oilfield equipment. It is the deposition of the material that causes the risk to production efficiency. This implies that an alternate deposit control strategy would be to recognise that although the material which precipitates causes the deposit problem, precipitation itself is not the problem. Solid mineral scale forms from solution when physical conditions in the produced fluid change. When the change in condition is such that the dissolved ions within the brine become present at a concentration above that which the water phase can support the fluid has become supersaturated. When supersaturation occurs it is energetically favourable for the excess material present to precipitate out as a new, solid phase returning the fluid to a stable, saturated condition. This precipitate is the mineral scale. The thermodynamics of solubility state that (i) when a new phase forms we begin from a supersaturated condition and (ii) when the new phase is forming, energy is released from the system. However the creation of a new phase from solution (solid or gas) requires formation of a boundary surface, requiring energy. Creating fewer surfaces is energetically more efficient. Precipitation onto a pre-existing solid surface or in a crevice reduces the surface area the new phase must create and is thus more efficient. A simple analogy is that the bubbles in a carbonated drink are initially seen present at the glass wall until they grow large enough to float into bulk solution. A gas sphere forming at the glass wall requires 50% of the surface of a bubble forming spontaneously in solution. Thus if that new phase begins to grow at an existing surface less energy is required for the new phase to form. The new phase then forms on the existing surface as fast as material can be transported to that site. In the case of the bubble in the drink it grows until it detaches from the wall, the rate of growth limited by the diffusion of gas to the bubble. In the case of solid precipitation this also implies that the new phase will be strongly adherent to the site from which it grows because intimate contact minimizes the quantity of new surface to be created thus creating a persistent, growing mineral deposit.

The deposits which form on the surface of the oilfield equipment pipes and valves from the ions originally dissolved in produced water form because of deposition. Formation of the solid phase requires nucleation which requires energy. The formation of the new phase occurs most rapidly at existing surfaces as this is energetically more efficient and is the predominant thermodynamic path of normal supersaturated process system. Control can be exerted by use of chemicals to kinetically interfere with nucleation process. An alternate control strategy would be to induce homogenous crystallisation at multiple nucleation sites suspended in bulk solution so that solid phase growth would occur in suspension and not at the tubular surface. Induction of a material phase change in bulk fluid generates a suspension as opposed to a precipitate – the problems associated with adherent deposits no longer occur but, as described above, is energetically disfavoured. The technology applied here overcomes the drive to heterogeneous crystallisation at surface by use of a pulsed electromagnetic signal to provide the energy required to produce the surfaces needed for homogenous crystal formation in bulk solution. The electronic device makes energy available to the charged ions that are crystallite precursors through subjecting them to a fast moving and varying electromagnetic field - this induces homogeneous nucleation in the bulk liquid phase. As multiple nucleation sites are produced the crystals do not grow to a large size as the ionic species that cause oilfield scaling are, in general, sparingly soluble. Diffusion limitation implies that there is then insufficient dissolved material available to allow the crystals to grow to problematic dimensions whilst in the bulk phase as they rapidly pass through the process system. The particles formed are in the 5-8 μm diameter range and remain suspended in the produced fluids – to date there have been no problems reported in resolving emulsions or produced water re-injection in ca. 500 installations of the electromagnetic units.

In the system described the energy required for the homogenous nucleation is provided by an alternating current electromagnetic pulse. The pulse is generated at surface and transmitted down the oilfield tubulars – impedance matching of the signal generator and the system to be treated maximises signal propagation in the well with the well acting as an inverted antenna. As per figure 1 the signal induces a fluctuating field perpendicular to its plane of propagation – the fluids in the wellbore are moving through this field. Any charged particle moving through an electromagnetic field generates energy - the charged, dissolved ions that are the crystallite pre-cursors gain energy. The base frequency of the decaying signal transmitted is in the range of 120-160 kHz and is pulsed at a rate of 5-40 kHz.

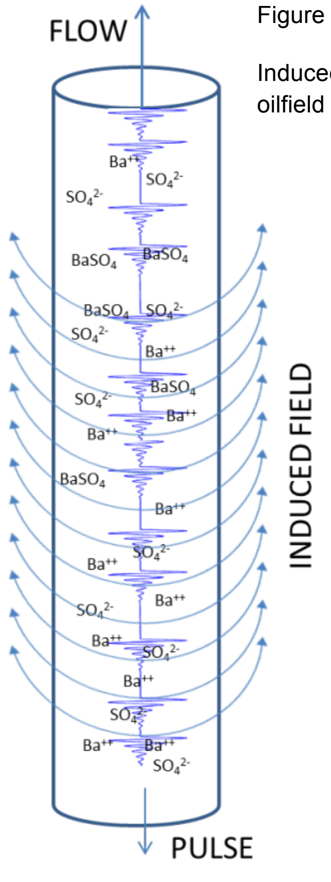
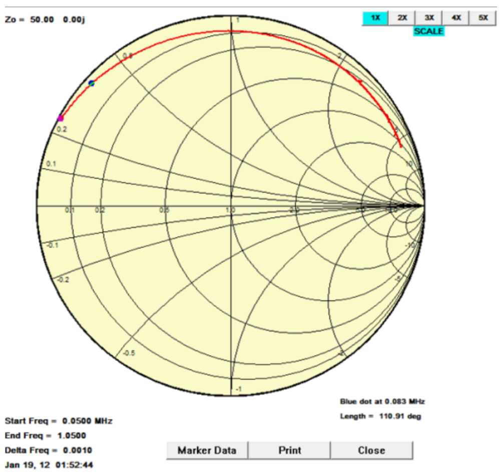


Figure 1.

Induced field in oilfield tubular

The energy provided by the interaction of scaling ions and the pulsed field is sufficient to induce homogenous nucleation in the bulk phase of the fluid where the produced fluid is in a metastable state, i.e. the scaling ions are present above saturation concentration but there is insufficient energy to initiate the production of new surfaces to initiate nucleation without interaction with a surface. In this case the energy is provided by an electrical signal – a number of industrial processes use ultra-sound for the same purpose. With the signal generator unit correctly connected the well completion acts as an inverted antenna and signal propagation distance is equivalent to the transition from "Near Field to Far Field" Transmission. The use of electromagnetic signal allows propagation of the signal to the foot of the well – as the antenna length exceeds 50% of the wavelength signal propagation is limited by Fraunhofer distances. This dictates that, for example, a 120 kHz signal will propagate to 12,800m in a 400m deep well. Efficient signal propagation is verified by use of simple Smith impedance as in Figure 2.

Figure 2. Smith Impedance Chart from Well with optimised ClearWELL™ signal



Application of Equipment and Processes

A nine month trial of the technology was devised and planned. The following subjects were noted as critical to a successful trial that measured actual unit performance:

- Key Performance Indicators
- Effective Installation & Operation of unit
- Well operation
- Data acquisition
- Documentation

The preferred and most clear-cut determination of scale build up in the upper completion was identified as running a 40 arm caliper before the trial and again after the trial with a comparison of the two. Due to a restriction in the number of available offshore bed spaces it was not possible to run a caliper before or after the trial and therefore this method of determination was not used.

As an alternative a series of modelling approaches using well test data and VLP analysis would be performed and monitored during the trial. Multi-rate production tests were performed on Well SA-07 before the electromagnetic signal generating unit was installed to establish a baseline. It was then planned to carry out a further multi rate well test a minimum of once per calendar month. Historical data was used to determine what VLP model variable values had changed to when scale had been confirmed. This approach also removes the need for a physical intervention in the well and this use of a modelling system reduces risk to well integrity and deferment of production.

The production history of the well was examined and modelled. For SA-07 the calculated friction coefficient required to give a match in the VLP analysis software would increase from ca. 1.49 to 2.13 during a 4 month period during which mineral scale was confirmed to have built up and restrict production requiring subsequent remedial treatment.

For the test of the electromagnetic device it was determined that an increase of 0.5 in modelled tubing friction coefficient over a 6 month time frame would be considered as a failure of the unit to prevent scale build up. Success was defined as no increase, or a reduction in modelled friction coefficient over the 3 or 6 month trial periods. Should the friction coefficient have increased by up to 0.2 within the first 3 months then the trial would be extended to 9 months. A 0.2 increase over 9 months would be deemed as a partial success. A 0.1 increase over 9 months will be deemed as a success.

Friction Coefficient Increase (less than or equal to)	**3 months**	**6 months**	**9 months**
0		Success	
0.1			Success
0.2			Partial Success
0.3		Failure	
0.5	Failure		

Table 3: VLP Friction Coefficient Increase Limits to Define Success of Trial.

Another measure of efficiency was to monitor the Flowing Bottom Hole Pressure (FBHP) and the Flowing Tubing Head Pressure (FTHP). If the FBHP remained the same during the trial period then it could be concluded that there was not significant scale build up in the tubing between the downhole gauge and the surface facilities.

An alternate method to determine the build-up of scale in the completion is to model the gas lift orifice size required to make the well test match using a VLP analysis tool. A reduction in orifice size is indicative of scale build up in the upper completion.

The actual signal to prevent mineral scale deposition is generated via the standalone electromagnetic signal generating unit. This is an intrinsically safe enclosure containing proprietary electronics to generate the 120 kHz carrier signal pulsed at 5-40 kHz signal. The unit operates on standard AC (110v or 220v) or DC supply and can be powered via solar panel as it consumes < 20watts continuous power. The unit contains a generator and ferrite ring, generator controller and an electrical series resistance capacitance pack as well as memory and diagnostic circuitry. The signal is impressed to the process pipework and the signal propagation optimised using Smith plots to the selected reverse antenna.

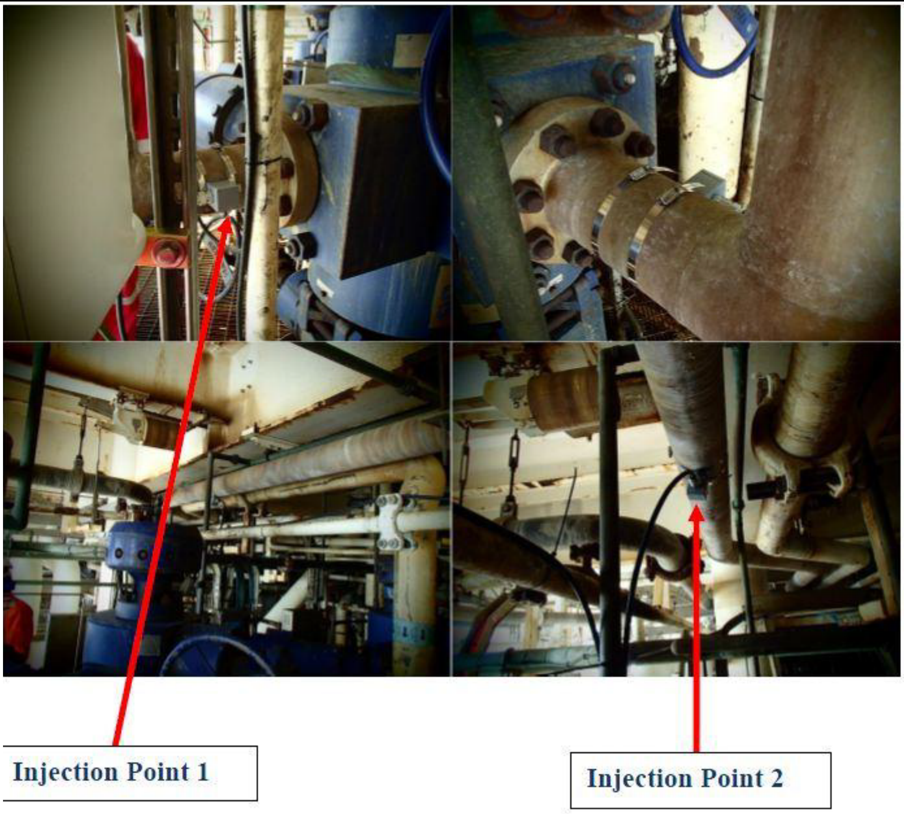


Figure 3 – injection points to pipework

The unit was installed 23rd April 2013. The unit was switched on and the well was operated at normal conditions i.e. within scaling envelope limit until a baseline multi-rate test was carried out. Following the test the well was beaned up over a period of 4 days. The Tubing Head Pressure (THP) was drawn down an additional 6 bar and the bottom-hole pressure (BHP) by 9 bar. This increased production but moved production into pressure-temperature zone where mineral scaling is expected and deposition of mineral scale was a risk.

The vendor's operational engineer visited the offshore location once per month for the first 3 months and then every other month thereafter to ensure that the signal was propagated effectively and that the unit was functioning correctly and, once the setup had been optimised, to collect data from the unit.

Date	Event	Comment
23 April 2013	ClearWELL unit installed	S/N:05160/3
03 May 2013	THP-34 bar / BHP-144 bar	
05 May 2013	THP-29 bar / BHP-139 bar	
07 May 2013	THP-28 bar / BHP135	
16 December 2013	THP-27 bar / BHP130	

Table 4. Listing of changes to production parameters during trial period

In the event of a planned shutdown during the trial period the well was beaned back and closed in and the unit kept switched on. Only in the event of power loss or maintenance work on the power grid were the unit switched off and this only in short periods. Following the shutdown the offshore operations team ensured that the unit was switched on prior to the well's being returned to production and beaned up.

A daily inspection of the unit to ensure the unit was switched on was also undertaken and the switch padlocked in the on position to ensure that it was not mistakenly turned off.

Data & Results

Multi-rate tests were carried out prior to the trial and a baseline for VLP modelling established.

This allowed accurate determination of production rate before bean up and define the VLP friction coefficient. Each multi-rate test consisted of a series of 3 well tests, one at maximum gross rate and two at intervals less than the maximum gross rate. Testing the maximum gross rate and reducing the gross production rate by small increments prior to testing minimises any effect from the well remaining in a transient flow regime and maximises the possibility for all other parameters are stable. It can be assumed that all variables for all three tests are constant. The most important variables to be held constant are the water cut and gas lift rate as these will impact the fluid density which will in turn alter the calculated friction coefficient. The multi-rate test data was then used to model the vertical lift performance using a propriety VLP analysis software. The program input variables were set to give a VLP model match and to ensure that the friction term was the same for each test. Unfortunately the test separator was unusable for almost 7 months during the trial period. The first set of well test data generated in June after ca. 10 weeks indicated a 0.02 increase in the VLP friction term well within the range defined as successful, i.e. friction in the system has not increased to indicate deposition of mineral scale. As this was a single data point it was determined that additional well tests should be conducted to confirm the performance of the unit is preventing scale deposition.

The next test was carried out in October and a VLP analysis showed that the friction term had not changed significantly. The 0.02 changes are within the modelling uncertainty and therefore it can was concluded that the VLP friction term has remained unchanged for 8 months. This would indicate that the electromagnetic signal generating unit is successful in militating against the build-up of mineral scale.

Date	Friction Term
11 December 2012	1.55
08 February 2013	1.79
26 March 2013	1.84
04 June 2013	1.86
28 October 2013	1.84

Table 5: Summary of SA-07 VLP Friction Coefficients.

To support this conclusion it can be seen that following the bean up the FTHP was at a line pressure of some 28 barg and a FBHP at 135 barg. These two pressures remained at their respective levels for the entire 9 month trial period. This confirmed that there was no scale build up between the downhole gauge at 3,335 mMDRT (measured depth from rotary table) and the tubing head pressure gauge at surface.

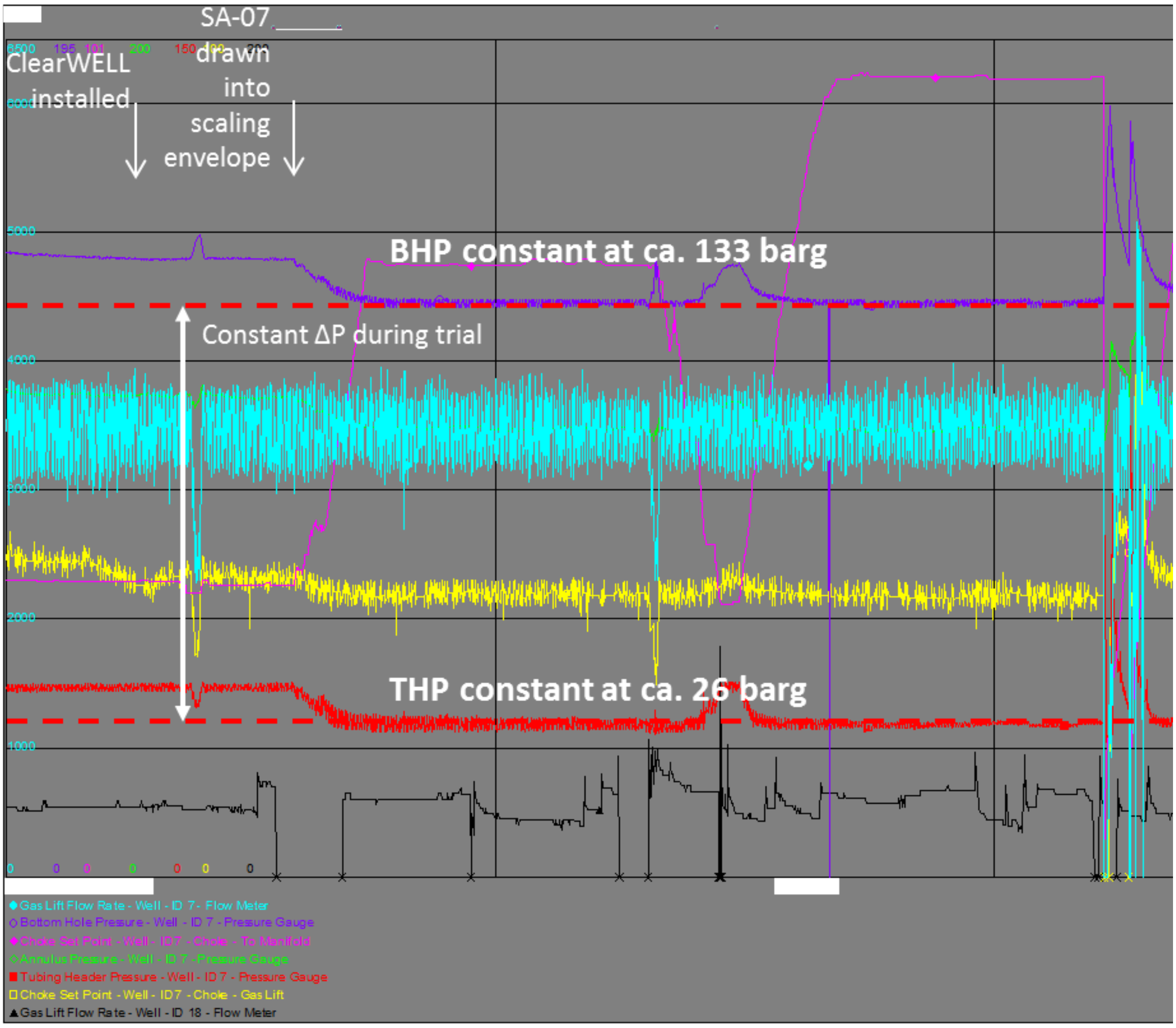


Figure 4. Production data indicating constant ΔP

VLP modelling of the simulated orifice size of the upper gas lift valve did not vary between the different well tests. A constant simulated orifice size indicates no restriction of production due to scale deposition reducing actual orifice diameter, a further confirmation that there is no scale build up in the upper completion.

However in February 2014 it was noted that the upper gas lift valve was unable to open and pass gas – one failure mode would be blockage by mineral scale indicating that the unit had not been effective in preventing scaling in the gas lift valves. In May 2014 the gas lift valves were replaced and a valve tear down post-mortem was carried out to determine the failure mode.

The gas lift valve tear down proved inconclusive as to the mode of failure but it was confirmed that there was no indication of scale on any of the unloading valves (*Figure 5)*. This is seen as further proof of the effectiveness of the unit in keeping the upper completion scale free.

Figure 5. Gas Lift Valves retrieved from well under test showing no mineral scale deposition

Conclusions

The 9 month test of the unit indicated that this method of preventing scale deposition was effective. The benefit in this case was the ability to produce ca. 200 bopd per without any noticeable deterioration of production flow rate or problems associated with mineral scale deposition that would have otherwise been expected. The unit was deployed without any intervention on the well avoiding any deferment of production or risk to well integrity and its successful operation has allowed additional production without any requirement for chemical application or discharge of chemicals to the marine environment.

This test indicates that this technology, where appropriately applied, offers the opportunity to control mineral scale deposition downhole without intervention or chemical treatment on production wells and wider application offers this operator the opportunity to increase production and avoid any environmental impact from chemical treatment.

Setting clear success criteria and being able to measure these was critical in demonstrating success and regular optimisation of the deployed unit to ensure correct and optimal operation was a key success factor.

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