Investigation of the use of scale risk parameters to predict failure of downhole safety valves on the Gullfaks Field

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Abstract

Although produced water from wells in the Gullfaks Field has a mild $SrSO_4$±$BaSO_4$ scaling tendency resulting from co-production of injected seawater and formation water, one of the current scale management challenges is the failure of downhole safety valves (DHSV) due to scale formation.

A pilot study has been undertaken on well A-37 to determine whether scale risk parameters can be used to predict in which wells DHSVs are more likely to fail, and if so, when? Well A-37 has had six DHSV failures (i.e. lost production due to either cleaning or replacement of the DHSV) during 17 years of water production. Several scale risk parameters for $SrSO_4$ and $BaSO_4$ have been calculated for the well at the location of the DHSV for four production periods; three ending with DHSV failure and one with no failure (121 produced water samples collected overall). These included common parameters (Saturation Ratio, SR, and the predicted precipitated mass of scale to equilibrium, SM) but also parameters combining SR, SM and produced water volume between DHSV failures.

As part of this work, a methodology was successfully developed to estimate the temperature and pressure at the DHSV at the time the samples were collected. This involved the use of a neural network trained on hydraulic production simulation results for the well. The estimated pressure and temperature data were used in thermodynamic scale predictions to calculate SR and SM at the DHSV for each water sample.

The results showed that the primary cause of the DHSV failures is most likely $SrSO_4$ scale deposition although minor $BaSO_4$ deposition at the DHSV cannot be discounted. The primary factor determining the scaling potential at the DHSV at any point in time is the produced water composition and the effects of pressure and temperature at the DHSV are secondary.

The SR and SM results for $SrSO_4$ have been evaluated to determine whether DHSV failure is likely to occur as a result of ‘critical values’ for these parameters being exceeded during production. Depending on the assumptions made, the critical values for SR_{SrSO4} may be less than 1.5-1.9 and those for SM_{SrSO4} less than 66-169 mg/L. Alternatively, over sustained production DHSV failure may occur when SR_{SrSO4} exceeds 1.6 (±0.1) and SM_{SrSO4} exceeds 73 mg/L (±10 mg/L).

When these critical values are exceeded, DHSV failure may still not occur for significant periods of time (up to 4 years) suggesting that the produced water volume may be an additional factor in the timing of the failures. To allow for this factor the cumulative scaling risk (CSR) for DHSV failure was calculated. This is the cumulative sum of the produced water volume (with scaling potential) multiplied by SR or SM for the production period between DHSV failures. Under this approach, it would be expected that CSR_{SR} and CSR_{SM} will be approximately constant for each production period ending in DHSV failure.

The CSR for $SrSO_4$ was found to be consistent for some production periods but not for others. The inconsistencies may reflect faster DHSV failure when $BaSO_4$ is deposited on the DHSV before $SrSO_4$. Equally, scale may not have formed on the DHSV unless SR_{SrSO4} and SM_{SrSO4} exceeded ~1.5 and ~145 mg/L respectively (in which case the CSR for DHSV failure would have been consistent for the production periods).

These results show that there is potential to use these different approaches for prediction of DHSV failures, and possibly even the prediction of the timing of failures, but further results are required from additional wells to help better refine their predictive capability.

Introduction

The Gullfaks Field is located in Block 34/10 of the Norwegian North Sea (Figure 1) (Fossen and Hesthammer, 1998). One of the current scale management challenges of the field is the failure of downhole safety valves (DHSV) as a result of scale formation under mild scaling conditions. The scale is believed to be $SrSO_4$ plus some $BaSO_4$ resulting from co-production of injected seawater and formation water. Not only is this a safety concern but it also results in loss of production. A better understanding of the conditions leading to the failures is required before monitoring and management plans can be developed to prevent future failures. To this end, an initial study was undertaken in which the history of failures in each well were reviewed and a ‘snapshot’ of the scaling conditions in the production wells was obtained (Fleming, 2010). This study showed that:

a) Given the formation water compositions at Gullfaks, $BaSO_4$ scale was expected at <10% seawater (SW) cut and $SrSO_4$ between 10 and 80% SW cut.

b) All the water-producing wells had a relatively low scaling risk but the greatest DHSV scaling risk was present at 40-60% SW cut.

c) DHSV failure occurs across a large range in SW cut (between 5 and 85%) and often downhole safety valve failures only start after years of production of water with a higher scaling risk.

d) Wells that have scale-related DHSV failures when the SW cut is low, have a greater risk of further failures as the SW cut and produced water volumes increase. In contrast, wells that have their first DHSV failures at higher SW cuts have lower risk of scale-related failures during the remaining life of the well.

e) There is no correlation between scale-related DHSV failure and field segment or producing intervals.

Based on a review of these results, it was hypothesised that it is longer-term, very slow build-up of scale in the wells that leads to DHSV failure. If this hypothesis is correct, a combination of both the historical scaling potential and the volume of water produced over time, together reflecting the ‘cumulative scaling risk’ (CSR), are predicted to correlate with the occurrence and timing of DHSV failures. To test this hypothesis, a pilot study has been undertaken on well A-37 which has been affected by scale-related DHSV failures. The objectives of the study were:

a) To develop a methodology for calculating scale potential parameters (Saturation Ratio, SR, and the predicted precipitated mass of scale to equilibrium, SM) at the DHSV from historical data (over a period of 18 years in some cases).

b) To choose appropriate parameters that can be used to estimate the CSR.

c) To apply them on well A-37 for $BaSO_4$ and $SrSO_4$ scale and to evaluate the results to determine whether the CSR hypothesis is supported.

d) To determine, if similar studies were undertaken on additional wells at Gullfaks, whether the CSR approach might be improved/refined sufficiently to allow it to be used to monitor and manage the DHSV scale risk in wells.

In addition, other studies have suggested that ‘critical’ values of SR and SM need to be exceeded for scale mitigation to be required in wells. A further objective of the study was to determine whether ‘critical’ values of SR and SM might be required for DHSV failure to occur in well A-37. This paper summarises the work undertaken and the results obtained.

Background: Well A-37

Well A-37 was drilled in 1992 to 1983.8m TVDRKB (3548m MDRKB), completed in the Cook Formation (Cook-2 unit) and production was started in October 1992. The well was re-perforated in the shallower Cook-3 unit in July 1998. The DHSV is located at 541.3m TVDRKB (544.8m MDRKB) and a downhole pressure and temperature gauge (DHG) is located at 1722.2m TVDRKB (3020m MDRKB). Fluid rates, wellhead pressure (WHP), GOR and water cut have been measured daily throughout production. DHG measurements are available for much of the period between April 1997 and April 2008 when the gauge failed. Subsequently, temperature measurements were undertaken at the wellhead (WHT).

The first evidence of minor water breakthrough occurred in September 1993. The formation water composition for the well is shown in Table 1. Some produced water samples were collected between September 1993 and 1997 but regular (approximately monthly) sampling only began in January 1997. The samples were not preserved before dispatch onshore for analysis. The produced water compositions primarily reflect the fraction of injected SW present in the produced water, as shown by the opposing trends in Cl and SO_4 concentrations (Figure 2). Reactions have also affected the produced water compositions; Figures 3 and 4 show that Ba, Sr and SO_4 have been lost from the produced water. Scaling predictions (see below) suggest that these losses reflect precipitation of $BaSO_4$ and $SrSO_4$ in the well/reservoir although souring in the reservoir also contributes to SO_4 loss. Some losses may have occurred in the sample bottles due to lack of sample preservation. The samples were filtered before analysis so the original Sr, Ba and SO_4 concentrations could have been higher in the produced water than measured.

Scale was first noted in this well when some scale (type not recorded) was recovered from the well in a Venturio junk basket during unsuccessful Cook-3 perforation operations in 1997. Tight spots associated with scale were also identified below 3303m MDRKB in July 1998 during re-perforation operations. These were probably $BaSO_4$ (see below) because given the low reservoir temperature (79°C) and the low drawdown into Gullfaks wells, calcite scale does not occur in the deeper completions (nor shallower in the well where production is from the Cook Formation). Later, in 2004, the well started producing large fragments of scale to surface. These were analysed and found to be mainly $SrSO_4$, with some minor amounts of $BaSO_4$.

The DHSV was tested at least once per week during production. For the purposes of this study, a DHSV 'failure' is defined as an event whereby it was necessary to stop production to either clean or replace the DHSV due to known or suspected scale build-up. The first scale-related problems occurred on 14 June 2001 with a DHSV failure (see Table 2). Scale dissolver was subsequently injected into the well and a brush was used to clean the DHSV. Five other failures occurred prior to 18 December 2010 which was the cut-off for this study (Table 2). These are all thought to be scale-related except for that on 9 December 2003 (Event 5) where there is some uncertainty regarding the cause of the control line leakage. In this case, and on 7 October 2003, the DHSV was replaced. In all the other cases, the DHSV was cleaned by brushing in the presence of KCl and/or scale dissolver.

As the CSR hypothesis envisages gradual scale build-up on the DHSV, it was initially assumed that whenever the DHSV was cleaned or replaced, the DHSV has been left scale-free. Based on this assumption, 7 periods of production were identified during which scale may have gradually developed on the DHSV (Table 2). Over this period, the water cut varied between ~70 and 90%, the water rate between ~500 and 1600 Sm^3/day and the produced water SW fraction (from Cl) between approximately 20 and 70%. The volumes of water produced during these periods are shown in Table 2.

Methodology for calculating DHG and DHSV pressure and temperature

In the absence of a downhole temperature and pressure gauge at the DHSV, one of the challenges of this work was to obtain estimates of the pressure and temperature at this location when produced water samples were collected. This was achieved using a combination of PROSPER (Petroleum Experts Limited, 2007) and a neural network program (QNET v2000) (http://www.qnetv2k.com/, 2012). These were also used to estimate the pressure and temperature at the location of the DHG so that the predictions could be compared with actual downhole measurements for validation purposes. The methodology used for these calculations was:

a) Interrogate the production database to identify ranges of WHP, liquid rate, gas-oil ratio (GOR) and water cut for the well.

b) Select values for WHP, liquid rate, GOR and water cut that cover these ranges (Table 3) and use all combinations of these in PROSPER to predict pressure and temperature at both the DHG and DHSV locations in a number of 'sensitivity' calculations.

c) Enter the PROSPER input data (WHP, liquid rate, GOR and water cut) and output data (pressure and temperature at the DHG and DHSV locations) into QNET v2000 and use the data to train the neural network.

d) Use the trained network to estimate the pressure and temperature at the DHG and DHSV on sampling days given the WHP, liquid rate, GOR and water cut.

For the PROSPER calculations the well dimensions were taken from the well completion diagram. The fluid was assumed to enter the well at the mid-perforation depth of Cook-2 and Cook-3 (1786m TVD MSL). The entry temperature of the fluid was estimated to be 79°C as this provided a better match to the measured temperatures at the DHG. As there were no periods when both BHT and WHT were measured, it was necessary to estimate the heat transfer coefficient by using PROSPER to model well test results during the periods when either downhole or wellhead temperature were measured. These calculations indicate that the heat transfer values may be between 24 and 35 $W/m^2/K$ so a value of 30 $W/m^2/K$ was used in the sensitivity calculations.

The sensitivity calculations showed that:

- Temperature at the DHSV is strongly related to the water cut and fluid flow rate reflecting the higher specific heat capacity of water relative to oil and the inverse correlation between heat loss and flow rate during production respectively.
- Pressures at the DHG and DHSV are primarily related to WHP and less so to GOR, water cut and total liquid flow rate.

Prior to training the neural network, trial calculations were undertaken to optimise the number of hidden layers and nodes in the network and the number of iterations allowed so as to minimise the pressure and temperature prediction uncertainty. The trained network was capable of predicting the downhole and wellhead pressures and temperatures obtained by PROSPER to within ±2.6bar and ±0.1°C respectively.

Pressures and temperatures measured at the location of the DHG are compared with the predicted values obtained from the trained neural network in Figures 5 and 6. Uncertainties in the estimated pressures (±16 bar) and temperatures (±2°C) are displayed. Uncertainties in the estimated pressure were determined from the differences between the estimated and measured pressures (95% of the estimated pressures are within 16 bar of measured pressures). Uncertainties in the estimated temperatures were calculated using PROSPER which showed that uncertainties in the heat loss coefficient translate into uncertainties in the wellhead temperature of ±2°C.

Allowing for these uncertainties, it can be seen in Figures 5 and 6 that there is good correspondence between the measured and predicted values. Also, based on the observed temperatures at the DHG and the location of the Cook-2 perforations, the estimated temperature at the DHG during production from Cook-2 only (i.e. before Cook-3 perforation) is expected to be ~78-79°C. This is consistent with the predicted temperatures before Cook-3 perforation. There are a few ‘outliers’ where the agreement between measured values and predicted values falls outside the estimation uncertainty. Outliers might be the result of:

a) Errors in measured liquid flow rates.

b) Data ‘mismatch’ because the production data used in the neural network are averages obtained over the day and the DHG pressure measurements are spot measurements taken only once per day.

Also, during the period between July 1998 and May 1999, measured temperatures at the DHG were lower than in later periods but were also increasing over time. This may reflect (a) cooling of the well as a result of the well perforation activities (July 1998) and possibly (b) initial high production from Cook-3 but with an increasing proportion of production from Cook-2 relative to Cook-3 over time. The predicted DHG temperatures were corrected by -2°C to provide a better fit to those measured at the DHG. The corrected DHG predicted temperatures are shown in Figure 6.

The uncertainties and corrections applied to the predicted DHG data have also been applied to the DHSV predictions. Actual temperatures and pressures are expected to lie within the range of the predicted values with their uncertainty because:

a) The PROSPER pressure predictions are constrained by the wellhead pressure, so it is anticipated that the uncertainty at the DHSV will be less than ±16 bar for most samples due to the DHSV being closer to the wellhead than the DHG.

b) Uncertainties in wellhead temperature arising from the heat loss coefficient can be expected to be applicable to DHSV temperatures too.

It can be seen in Figures 5 and 6 that the predicted pressures at the DHG vary between 175 and 283 bar (mean = 216 bar) and at the DHSV they vary between 90 and 170 bar (mean = 108 bar). Temperatures vary between 76.3 and 78.3°C (mean = 78.5°C) at the DHG and between 43 and 69°C (mean = 61°C) at the DHSV.

Scale predictions

SR (Eq. 1) and SM values for $SrSO_4$ and $BaSO_4$ for every produced water sample were calculated using MultiScale^{TM} 7.1 (Petrotech, 2006) under the estimated pressure and temperature conditions at the DHG and DHSV. To estimate the uncertainty in these values arising from the uncertainties in predicted pressures and temperatures, 9 samples were selected to cover the range in scaling potentials exhibited by the produced water from the well. Scaling predictions were undertaken on these samples where the predicted temperatures and pressures were varied by ±2°C and ±16bar respectively about the predicted values.

$$\mathrm{SR}_{\mathrm{MX}} = \frac{\mathrm{a}_{\mathrm{M}+}.\mathrm{a}_{\mathrm{X}-}}{\mathrm{K}_{\mathrm{SP}}^{\mathrm{o}}(\mathrm{MX})} \qquad \text{Eq.1}$$

Where:

SR_{MX} = Saturation ratio of salt MX.

a = ion activity.

$K_{SP}{}^{o}(MX)$ = Solubility product of salt MX.

M^+ = Cation.

X^- = Anion.

Uncertainties in pressure and temperature translate into uncertainties of approximately ±4-7% for SR_{BaSO4}, ±4% for SR_{SrSO4}, ±0.15 mg/L for SM_{BaSO4} and ±12 mg/L SM_{SrSO4}. These uncertainties were not so large that important results could not be obtained from the study.

Additional calculations were undertaken for some samples to determine SR and SM under ambient surface (sample bottle) conditions.

CSR parameters

The SR and SM data along with produced water volume data were used to calculate the values of two CSR parameters at the DHG and DHSV (CSR_{SR} and CSR_{SM}; Eqs. 2 and 3).

$$CSR_{SR,n} = \sum_{n=0}^{n=i} \left(\frac{SR_n + SR_{(n-1)}}{2}\right).\left(V_n - V_{(n-1)}\right) \qquad \text{Eq. 2}$$

Where:

CSR_{SR} = Cumulative SR scaling risk (m^3).

n = Produced water sample number.

i = Total number of produced water samples.

V_n = Volume of water with scaling potential (SR>1) produced up to collection of sample n (m^3).

SR_n = Saturation Ratio of sample n.

$$CSR_{SM,n} = \sum_{n=0}^{n=i} \left(\frac{SM_n + SM_{(n-1)}}{2x1000}\right).\left(V_n - V_{(n-1)}\right) \qquad \text{Eq. 3}$$

Where:

CSR_{SM} = Cumulative SM scaling risk (kg).

SM_n = Mass of scale precipitated to equilibrium from sample n (mg/L).

When calculating these values it was assumed that:

a) Fluid volumes produced when SR and SM are less than 1 and 0 respectively do not contribute to the CSR parameters (i.e. no scale was forming under these conditions). So, the water volumes considered are only those with scaling potential.

b) Scale did not dissolve in the well when SR<1 or erode after deposition. This reflects the resistive nature of sulphate scales once formed.

When calculating CSR_{SR} and CSR_{SM} the water volume produced from the well over time was calculated from the daily water rates. The mean SR and SM between sampling dates was calculated and multiplied by the water volume with scaling potential produced during this period. When SR declined below 1 or increased above 1 between sampling dates, the produced volume at which the decline/increase occurred was estimated assuming the SR varies linearly with produced volume between the sampling dates.

Results

Scaling potential in the well

In well A-37, SR_{BaSO4} is primarily determined by the concentrations of both Ba and SO_4 whilst the primary control on predicted scale mass of $BaSO_4$ is the Ba concentration due to the elevated SO_4 content of the produced water samples. The effects of pressure and temperature variations at each location (i.e. DHG and DHSV) are secondary for both SM and SR.

Figures 7 and 8 show SR and SM over time for $BaSO_4$ at the DHSV. As the solubility of $BaSO_4$ decreases with a decrease in temperature and pressure, SR_{BaSO4} and SM_{BaSO4} increase with a decrease in temperature and pressure and so are higher at the DHSV than at the DHG and even more so under sample bottle (ambient surface) conditions. Despite the absolute differences in SR and SM at the different locations, the trends in Figures 7 and 8 over time are also seen at the DHG and ambient surface conditions.

Prior to Cook-3 perforation and until April 1999, the sole scaling risk at the DHSV was from $BaSO_4$ precipitation. SR_{BaSO4} varied between 1.9 and 6.9 (average = 4.6) and SM_{BaSO4} between 1.6 and 8.4 mg/L (average = 5.5 mg/L). Despite the risk, during this period there were no problems with the DHSV suggesting that either $BaSO_4$ scale deposition did not occur at the DHSV during this time or any deposition was insufficient to cause problems. After April 1999, SR_{BaSO4} and SM_{BaSO4} are even lower (<~3.5 and <~0.5 mg/L respectively) at the DHSV reflecting the low produced water Ba concentration (average ~0.5 mg/L). This suggests that $BaSO_4$ precipitation is unlikely to have been a primary factor in the later DHSV failures although minor deposition cannot be discounted (see below).

In contrast, scale was identified 126m (TVD) below the DHG before Cook-3 perforation. Again, the sole scaling risk at the DHG at that time was from $BaSO_4$ precipitation so it is likely that the scale was $BaSO_4$. SR_{BaSO4} varied between 1.3 and 3.4 and SM_{BaSO4} between 0.6 and 7.0 mg/L at the DHG prior to Cook-3 perforation. The values might have been even higher because of (a) $BaSO_4$ deposition deeper in the well and (b) $BaSO_4$ deposition could have occurred in the sampling bottles. After April 1999, SR_{BaSO4} and SM_{BaSO4} are lower (<~2.2 and <~0.5 mg/L respectively) at the DHG again reflecting the low produced water Ba concentration and much higher SO_4 content of the produced water. Therefore, later in well life build-up of scale deeper in the well was likely to have been less.

In well A-37, SR_{SrSO4} is primarily controlled by the concentrations of both Sr and SO_4 (e.g. Figure 9) whilst the primary control on predicted scale mass of $SrSO_4$ is the Sr concentration due to the elevated SO_4 content of the produced water samples. Again, the effects of pressure and temperature variations at each location are secondary for both SM and SR.

Figures 10 and 11 show how SR_{SrSO4} and SM_{SrSO4} vary over time at the DHSV. Although $SrSO_4$ solubility also decreases with decrease in pressure, its solubility increases with a decrease in temperature. As a result, there is little change in SR_{SrSO4} and SM_{SrSO4} as the temperature and pressure decrease during production between the DHG and DHSV (e.g. see Figure 12). At ambient conditions, SR_{SrSO4} is only marginally lower than that at the DHG and DHSV due to the greater effect of temperature versus pressure decline. At all three locations, the trends in SR_{SrSO4} and SM_{SrSO4} over time are similar.

Up to April 1999, the average SR_{SrSO4} at the DHSV was 0.9 but after this time, when SO_4 increased significantly (>360 mg/L), SR_{SrSO4} and SM_{SrSO4} also increased to averages of 1.8 and 114 mg/L respectively. As it was after April 1999 that problems with the DHSV started to occur, and given the large predicted $SrSO_4$ scale masses relative to those of $BaSO_4$ (reflecting the very low Ba concentrations in the produced water after this time; Figure 3), by implication the problems are likely to be primarily related to $SrSO_4$ scale. This is confirmed by the scale produced in 2004 (mainly $SrSO_4$, with some minor amounts of $BaSO_4$) and is consistent with the scale predictions where for much of the time after April 1999 both $SrSO_4$ and $BaSO_4$ are predicted to be deposited at the DHSV (Figure 13).

Scaling risk during production periods

Because there was only a $BaSO_4$ scaling risk at the DHSV before Cook-3 perforation and because $SrSO_4$ was probably the primary scaling mineral at the DHSV after April 1999, these two periods and the associated scale types have been considered separately. Tables 4 and 5 summarise the SR and SM and CSR_{SR} and CSR_{SM} results respectively for each production period. In each case, to avoid biases arising from outlier data these have not been considered when calculating these results. Similarly, to avoid biases associated with production periods during which few samples were collected, results for these periods are not presented or discussed further (i.e. production periods 3, 4 and 5 which have low produced water volumes; see Table 2).

Discussion

Critical values approach

Within the industry, a number of companies have adopted scale mitigation guidelines which set out, in terms of SR and/or SM, when sufficient scale deposition may be expected given temperature and pressure conditions at the location of interest, such that mitigation is required. These guidelines usually state that mitigation will be required when SR and/or SM exceed certain ‘critical values’ (Mackay et al., 2005; Ramstad et al., 2005).

In the context of this study, the critical values are those which, when exceeded, result in DHSV failure. The ‘critical values’ concept is potentially useful at Gullfaks because although it cannot be used to constrain the timing of DHSV failure, it might provide an indication of which wells are more likely to have a failure so that mitigation measures could be undertaken to prevent this.

Prior to Cook-3 perforation and during production period 7, by definition, the critical values for SR and/or SM for $BaSO_4$ and $SrSO_4$ respectively were not exceeded at the DHSV although minor deposition might have occurred. With respect to $BaSO_4$, prior to Cook-3 perforation $BaSO_4$ scale has probably formed deeper in the well, depleting Ba in the produced water whilst in period 7, the Ba concentration was very low. In contrast, during production periods 1, 2 and 6, scale deposition at the DHSV has occurred and resulted in DHSV failure so the critical SR and/or SM for $SrSO_4$ have been exceeded. Therefore, the SR and SM results for well A-37 might be used to constrain the critical values for these two types of scale under the pressure and temperature conditions at the DHSV. But, use of these results is complicated by (a) the variation of SR and SM during each period, (b) lack of sample preservation and (c) the possibility that scale was building up on the DHSV prior to Cook-3 perforation and during production period 7 such that given additional production during these periods, DHSV failure might have occurred.

For example, assuming no scale formed at the DHSV prior to Cook-3 perforation, the lower limit of the critical values could be 6.8 and 8 mg/L for SR_{BaSO4} and SM_{BaSO4} respectively. These values are the maximum observed during this period and assume that scale only deposits above these values. Alternatively, the mean and standard deviation for SR_{BaSO4} (4.6±1.3) and SM_{BaSO4} (5.8±1.9 mg/L) could be used to show how low the critical values might be over a sustained period of production. But, if scale deposition was occurring on the DHSV during this period, and DHSV failure did not occur due to insufficient production, the critical values could be lower than suggested above.

The same arguments apply to the results for $SrSO_4$ during production period 7 where the maximum SR_{SrSO4} (1.9) and SM_{SrSO4} (92 mg/L) shows what the lower limit of the critical values could be and the mean and standard deviation for SR_{SrSO4} (1.6±0.1) and SM_{SrSO4} (73±10 mg/L) show what the lower limit of the critical values could be over a sustained period of production (but again if scale deposition was occurring on the DHSV during this period, the critical values could be lower).

For production periods 1, 2 and 6 the minimum SR_{SrSO4} (1.5) and SM_{SrSO4} (66 mg/L) observed in any period may represent a maximum estimate of the critical values if it is assumed that scale deposition was occurring throughout each period (i.e. scale deposition might occur at even lower values). Alternatively, the maximum SR_{SrSO4} (1.9) and SM_{SrSO4} (169 mg/L) observed in all periods may also represent a maximum estimate of the critical values if it is assumed that scale deposition was only occurring when these peaks were reached.

Depending on the assumptions made, the critical values for SR_{SrSO4} and SM_{SrSO4} may therefore be ≤1.5-1.9 and ≤66-169 mg/L respectively. Based on the above results, it is those from long duration production periods where no DHSV failure has occurred which are likely to best constrain the critical values whilst those from periods where failures have occurred can be used to verify these values. For example, if no further failures were to occur in well A-37 and SR_{SrSO4} and SM_{SrSO4} were to remain within recent limits it would be notable that SR_{SrSO4} is similar during periods 1, 2, 6 and 7 but SM_{SrSO4} is lowest during the latter period. This would suggest that both SR and SM may need to exceed the critical values for scale to precipitate at the DHSV and the mean and standard deviation for SR_{SrSO4} (1.6±0.1) and SM_{SrSO4} (73±10 mg/L) would provide reasonable estimates of the lower limit of these critical values for a sustained period of production. Such results are confirmed by the result for periods 1, 2 and 6.

Evidently, calculating scaling potentials for produced waters from other wells in the same way as undertaken on well A-37 would help constrain the critical values for Gullfaks wells. One factor not considered above is the lack of preservation of the produced water samples. If $BaSO_4$ and $SrSO_4$ precipitated in the sample bottles before analysis, the critical values identified above may underestimate the actual values. It would therefore also be beneficial to undertake field tests to determine to what extent precipitation of $BaSO_4$ and $SrSO_4$ in samples bottles may have affected these results.

In summary, critical values may be important in determining whether scale causes DHSV failures on Gullfaks wells. But, the produced waters were within limited ranges of SR_{SrSO4} and SM_{SrSO4} for significant periods of time (up to 4 years) during Production Periods 1, 2 and 6 before the DHSV failures occurred. This supports the suggestion that the produced water volume may be an additional factor in the timing of the failures.

CSR approach

Under this approach, the produced water volumes considered are only those with scaling potential (i.e. where SR > 1 and SM > 0). For example, CSR_{SM} represents the potential mass of scale (kg) that could precipitate (to equilibrium) from produced water, with scaling potential, over time. In effect, this approach assumes that the critical values for SR and SM are 1 and 0 respectively.

It is evident that little of the predicted scale masses actually deposits at the DHSV over time. For example, during production period 2 (moderate SO_4 in produced water, ~800-1100 mg/L), 60,500 kg $SrSO_4$ is predicted to be precipitated; more than enough to cause a rapid failure of the DHSV. So, this approach assumes that a constant fraction of the potential scale mass will actually precipitate and so the rate of scale build-up will correlate linearly with SM and produced water (with scaling potential) rate. Similarly, for CSR_{SR} which is a multiple of SR and cumulative produced water (with scaling potential) volume. Under these circumstances, it would be expected that CSR_{SR} and CSR_{SM} will be approximately constant for each production period ending in DHSV failure.

It can be seen in Table 5 that the CSR_{SR} and CSR_{SM} results for $SrSO_4$ for production periods 1 and 2 are reasonably consistent as predicted by the model. But, they are much lower than those for periods 6 and 7 (moderate/high SO_4 in produced water, ~800-2000 mg/L), and in the latter case, despite its higher values, no DHSV failure has occurred. These discrepancies from the expected results might reflect the effects of conditions which do not form part of the CSR model as implemented in this study. For example, to explain the low results for production periods 1 and 2, and high results for periods 6 and 7, it may be that:

a) The DHSV has been ‘conditioned’ by some minor deposition of $BaSO_4$ before Cook-3 perforation.

b) This has increased the rate of deposition of $SrSO_4$ during production periods 1 and 2.

c) Cleaning the DHSV at the end of production period 1 has not removed this conditioning effect (i.e. cleaning was not 100% effective).

d) After installation of the new DHSV at the start of period 6, SR_{BaSO4} and SM_{BaSO4} were very low and so conditioning of the DHSV by $BaSO_4$ scale did not occur.

Under this scenario, the lack of DHSV failure during period 7 can be explained by insufficient time for CSR_{SR} and CSR_{SM} to reach the high values required for DHSV failure. If this is the case, failure of the DHSV might occur when CSR_{SR} and CSR_{SM} values similar to those obtained in period 6 are achieved.

Another possible explanation of the inconsistent CSR_{SR} and CSR_{SM} results is that it may be that different critical values for precipitation need to be allowed for in the model. For example, had the critical values for SR_{SrSO4} and SM_{SrSO4} were ~1.5 and ~145 mg/L respectively, it is estimated that CSR_{SR} and CSR_{SM} for periods 1, 2 and 6 would be similar and significantly greater than the values for period 7 (hence no failure occurring during this period).

Because there is only one CSR result for $BaSO_4$ from this well (pre-Cook 3 perforation production period), it cannot be interpreted with respect to the timing of DHSV failure but if additional data can be obtained (i.e. for production periods when there is only a $BaSO_4$ scaling risk, see below) the result could be considered with the new data in the same way as described above for the $SrSO_4$ results.

In summary, based on the results from well A-37, the CSR approach shows promise as a tool for predicting the approximate timing of DHSV failure but it requires further development and refinement before that capability can be reached. Additional CSR_{SR} and CSR_{SM} results from other wells where DHSV failures have (and have not) occurred after periods of production are required to aid this model development and refinement.

Implications for well A-37

For well A-37, it is a challenge to predict whether there will be future failures of the DHSV. Based on the critical values approach, it is possible that future failures will not occur whilst SM_{SrSO4} remains at the low values currently exhibited, but if they increase above 73±10 mg/L, it is possible that failures will occur.

Under the CSR approach, failure could occur when CSR_{SR} and CSR_{SM} for $SrSO_4$ approach those values exhibited for production period 6. If the critical values for precipitation under this model are higher than 1 and 0 for SR_{SRSO4} and SM_{SRSO4} respectively, then the time to reach the CSR_{SR} and CSR_{SM} values for production period 6 will be greater (and might never be reached).

Conclusions

Deposition of scale under mild scaling conditions in wells of the Gullfaks Field is causing DHSV failures. Not only is this a safety concern but it also results in loss of production.

A methodology has been developed to calculate the scaling potential of the produced water at the DHSV and this has been applied to the produced waters of well A-37 where scale-related DHSV failures have occurred. These show that the failures are probably due to $SrSO_4$ deposition although minor $BaSO_4$ deposition cannot be discounted.

The scaling potential at the DHSV over time has been evaluated to determine whether failures can be predicted from ‘critical values’ or ‘cumulative scaling risk’ approaches.

It has been found that the critical values approach may be important in determining whether scale is likely to cause DHSV failures on Gullfaks wells whilst the CSR approach shows promise as a tool for predicting the approximate timing of DHSV failure. But, further results are required from additional wells to help better refine their predictive capability.

Acknowledgements

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Table 1 Composition of Cook formation water (well A-37).

Constituent	Concentration (mg/L)
Na	15,023
K	344
Ca	1,341
Mg	413
Ba	12
Sr	390
Cl	27,528
SO_4	40
B	122

Table 2 Scale-related DHSV activities.

Event No.	Date	Activity	Production period	Production volume (m^3)
1	14 June 2001	Inject scale dissolver, brush DHSV	1	912,583
2	18 July 2003	Inject KCl, brush DHSV	2	408,785
3	15 August 2003	Inject scale dissolver, brush DHSV	3	27,829
4	7 October 2003	Replace DHSV	4	6,124
5	9 December 2003	Replace DHSV (control line leakage).	5	40,005
6	17 December 2007	Inject KCl/scale dissolver, brush DHSV	6	1,844,574
7	18 December 2010	End of data set	7	985,807

Table 3 Variables and values used in the PROSPER sensitivity calculations.

Variable	Values used in sensitivity calculations			
Total liquid flow rate (Sm^3/day)	500	1000	1662	
WHP (bar)	60	90	120	
GOR (Sm^3/Sm^3)	70	100	200	
Water cut (%)	0	20	50	90

Table 4 Results for SR and SM at the DHSV.

Production period	Scale	Pressure Range (bars)	Temp. Range (°C)	SR Mean	SR Standard Deviation	SR Range	SM Mean (mg/L)	SM Std. Dev. (mg/L)	SM Range (mg/L)
Pre-Cook-3	$BaSO_4$	90-159	43-64	4.6	1.3	1.9-6.8	5.8	1.9	1.6-8.0
1	$SrSO_4$	91-107	53-65	1.8	0.1	1.6-2.0	143	17	121-188
2	$SrSO_4$	96-110	46-63	1.7	0.1	1.5-1.9	148	16	111-169
6	$SrSO_4$	103-170	60-69	1.9	0.2	1.5-2.2	118	35	66-197
7	$SrSO_4$	105-109	54-67	1.6	0.1	1.4-1.9	73	10	49-92

Table 5 CSR_{SR} and CSR_{SM} results.

Production period	Scale type	Produced volume with scaling potential (m^3)	CSR_{SR} (m^3)	CSR_{SM} (kg)
Pre-Cook-3	$BaSO_4$	390,002	1,889,796	2,197
1	$SrSO_4$	449,486	775,305	57,262
2	$SrSO_4$	408,786	674,975	55,273
6	$SrSO_4$	1,843,745	3,517,887	220,538
7	$SrSO_4$	986,875	1,990,577	82,351

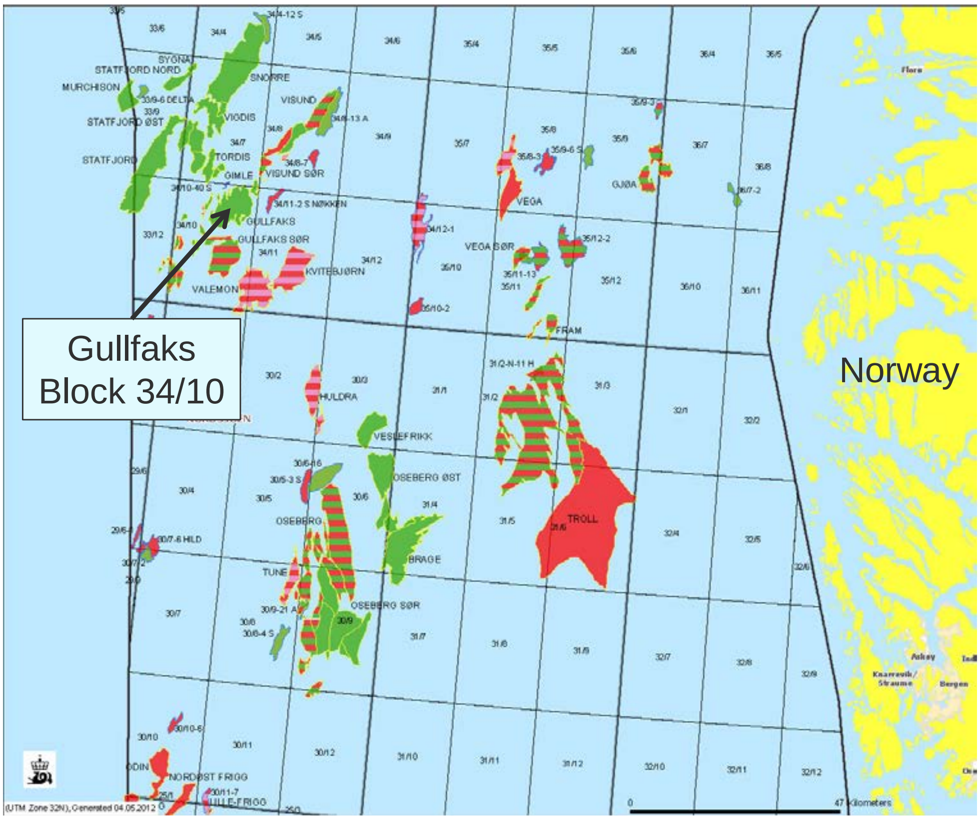

Figure 1 Location of the Gullfaks Field.

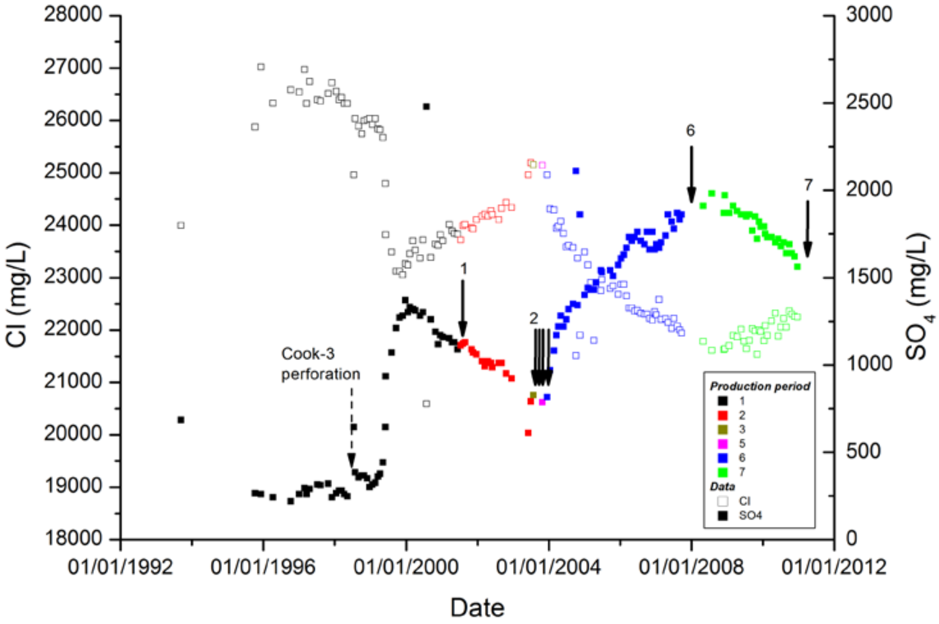

Figure 2 Variation of Cl and SO_4 in produced water over time. Black arrows show end of ‘production periods’ (see main text).

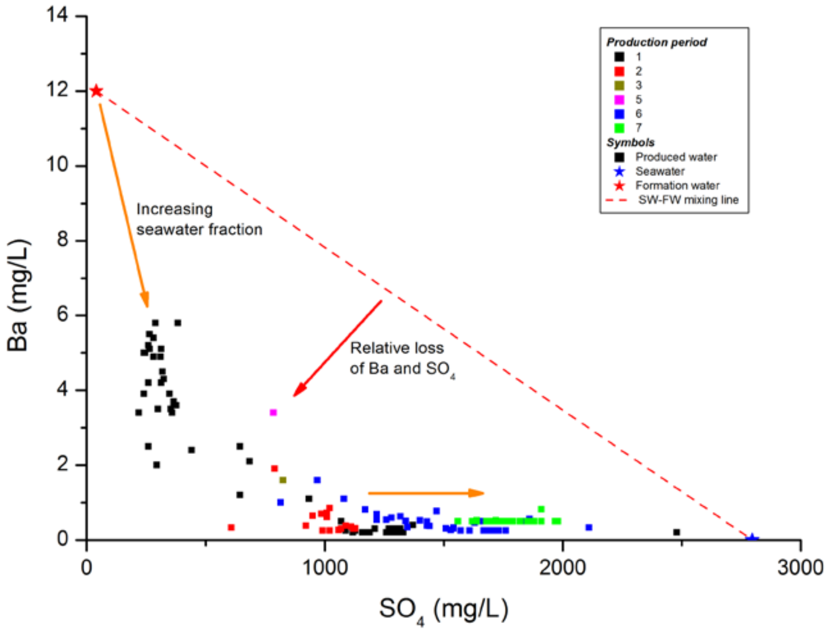

Figure 3 **Variation of SO_4 and Ba in produced water. Note the apparent loss of Ba and SO_4 relative to seawater-formation water mixtures and the increase in seawater fraction with increase in SO_4.**

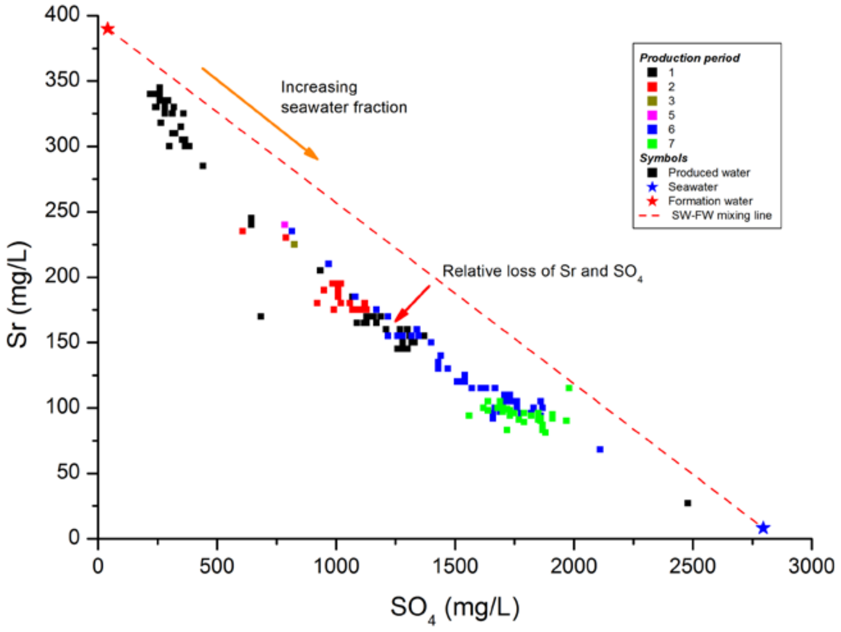

Figure 4 **Variation of SO_4 and Sr in produced water. Note the apparent loss of Sr and SO_4 relative to seawater-formation water mixtures and the increase in seawater fraction with increase in SO_4.**

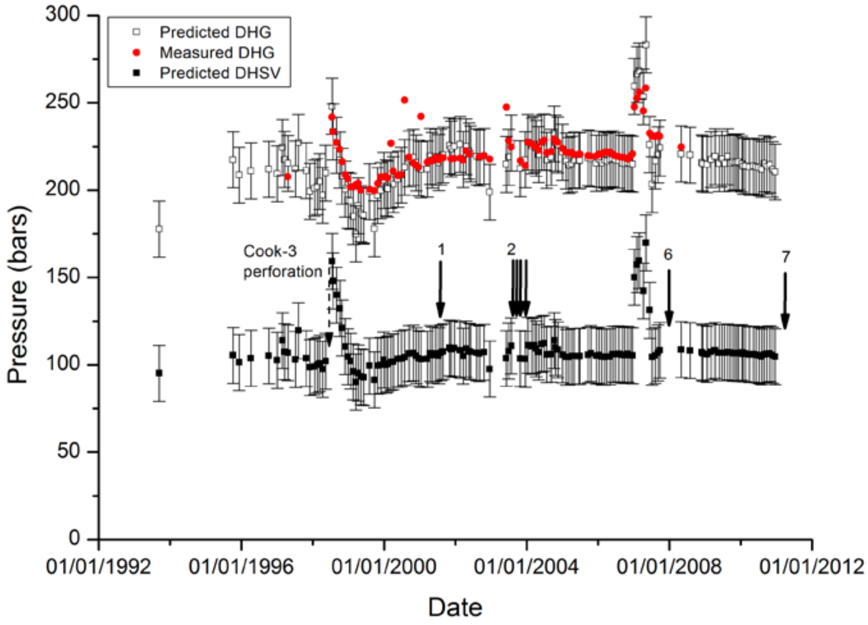

Figure 5 Comparison of predicted and measured pressure at the downhole gauge, and predicted pressure at the DHSV.

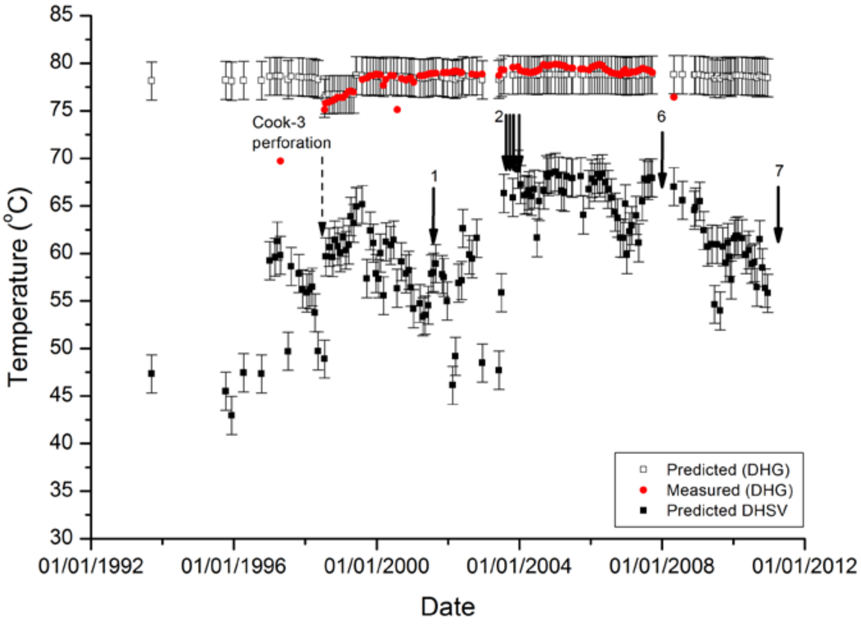

Figure 6 Comparison of predicted and measured temperature at the downhole gauge, and predicted temperature at the DHSV.

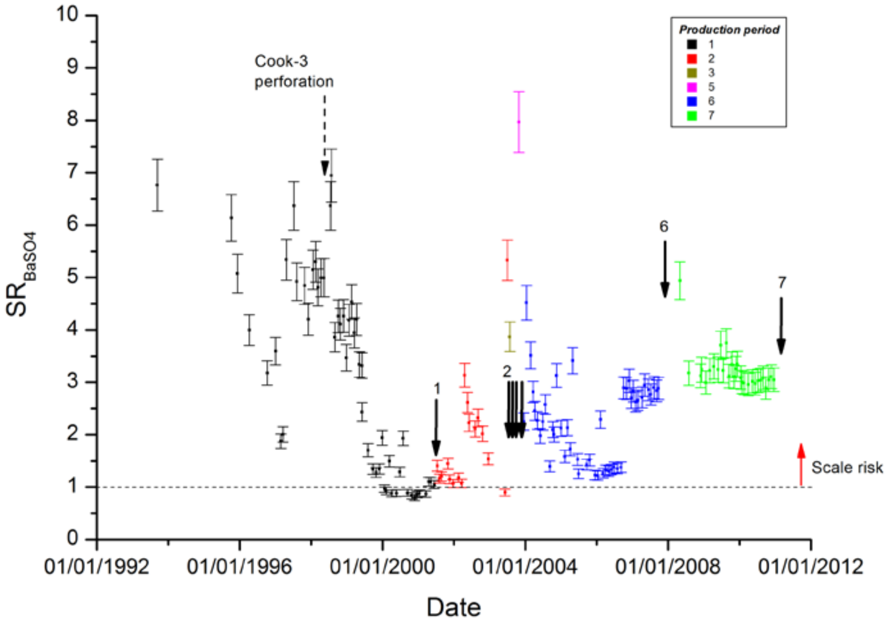

Figure 7 Variation of SR_{BaSO4} over time at the DHSV. Solid black arrows identify the end of production periods.

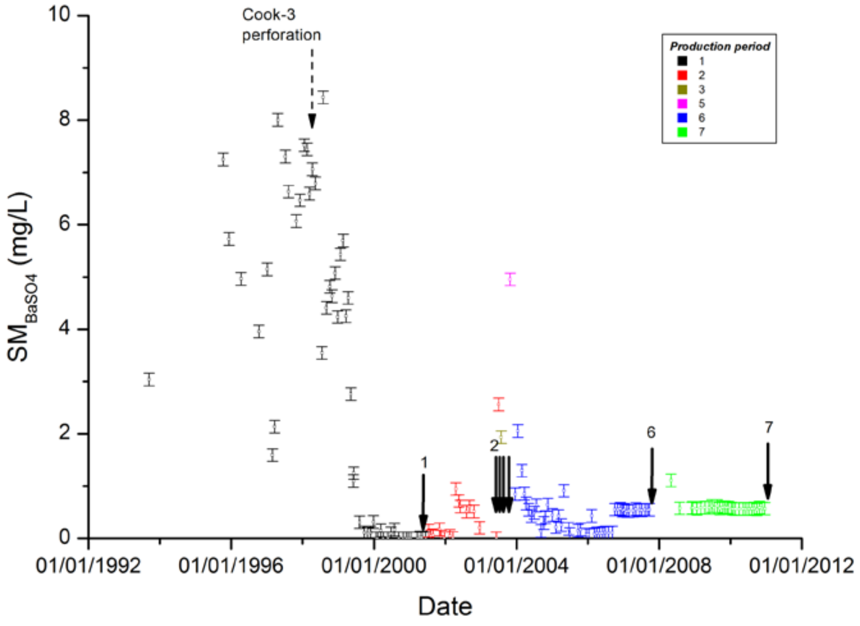

Figure 8 Variation of SM_{BaSO4} over time at the DHSV. Solid black arrows identify the end of production periods.

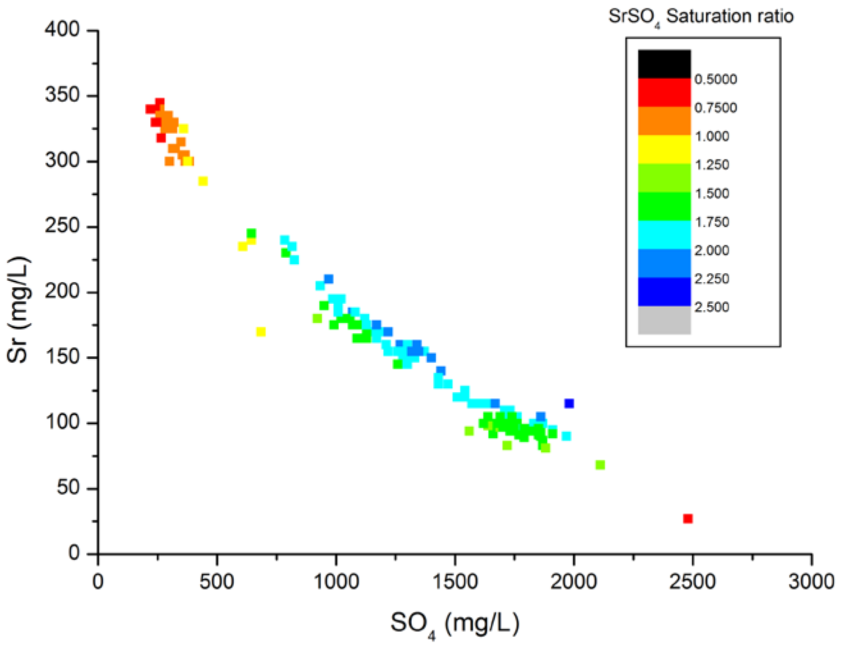

Figure 9 Variation of produced water SO_4 and Sr with SR_{SrSO4} at DHSV.

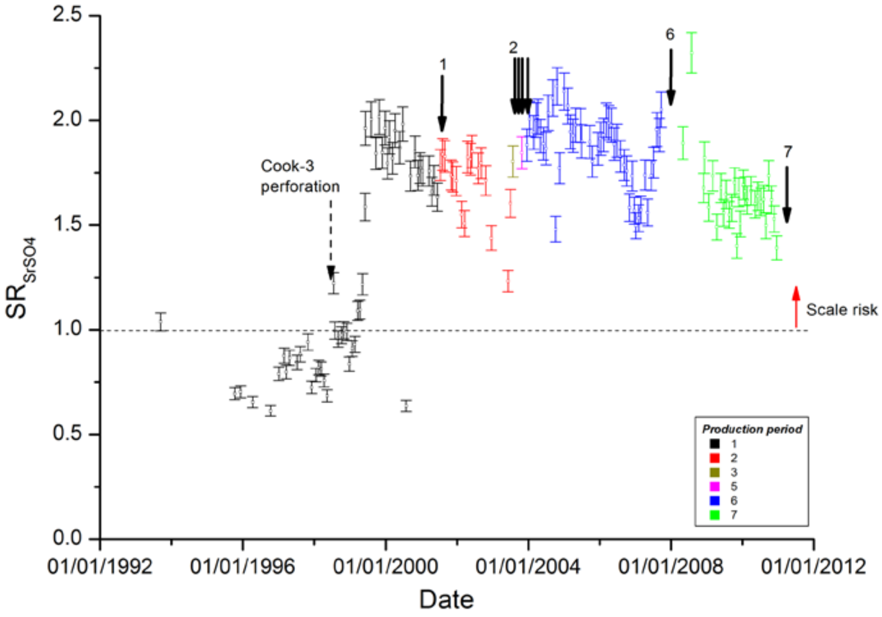

Figure 10 Variation of SR_{SrSO4} over time at the DHSV. Solid black arrows identify the end of production periods.

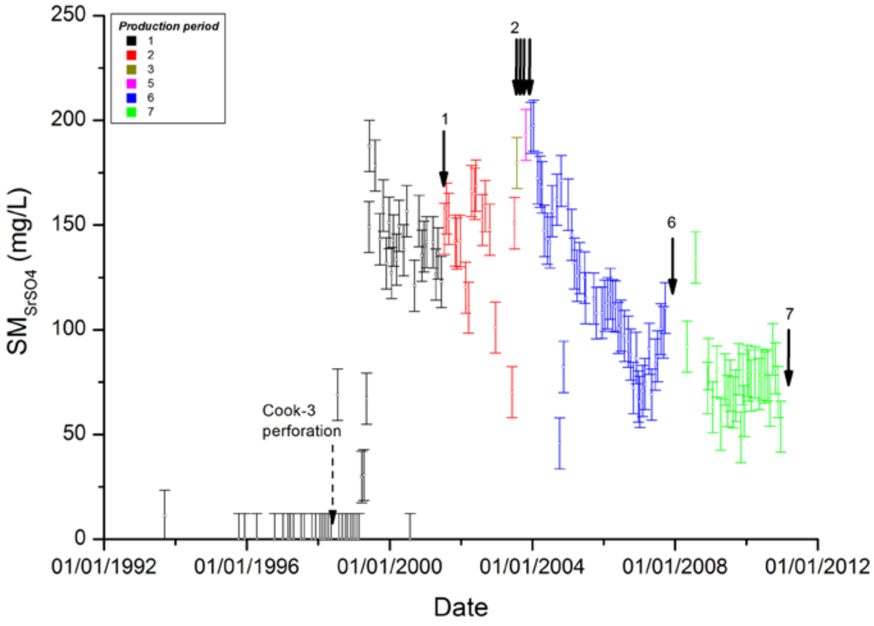

Figure 11 **Variation of SM_{SrSO4} over time at the DHSV. Solid black arrows identify the end of production periods.**

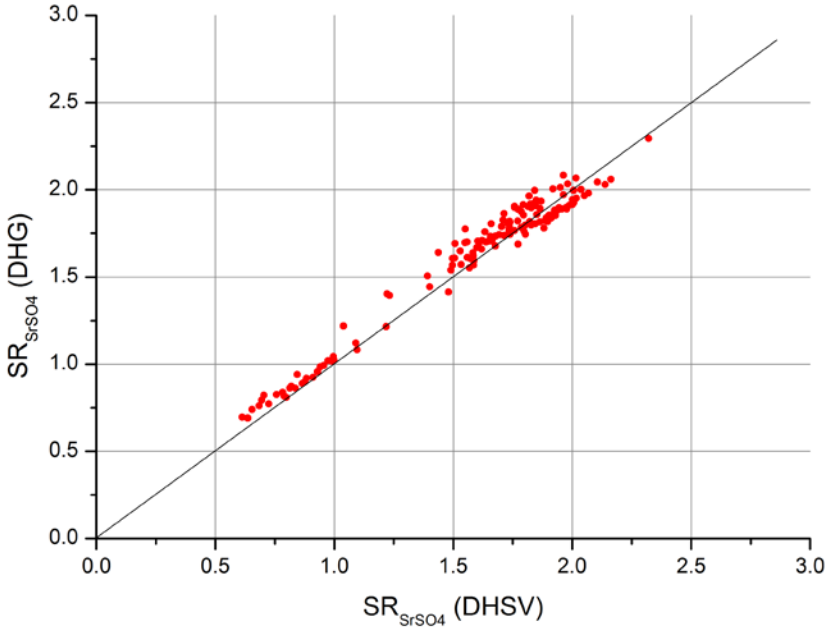

Figure 12 **Comparison of SR_{SrSO4} at the DHSV and DHG.**

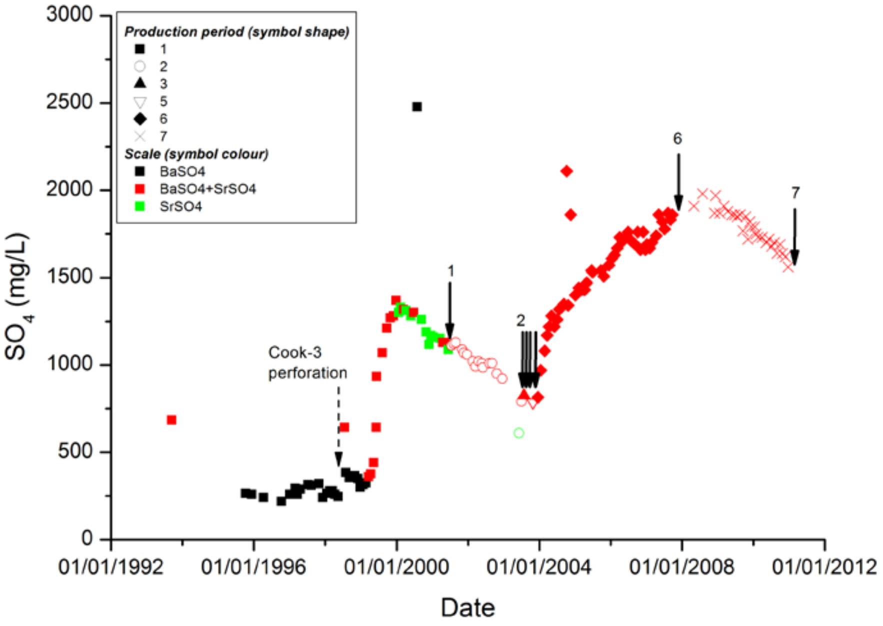

Figure 13 Predicted type of scale deposition over time at the DHSV. Solid black arrows identify the end of production periods.