25TH NORTH SEA FLOW MEASUREMENT WORKSHOP 2007

Experience with ultrasonic meters on high viscosity oil

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1 INTRODUCTION

Norsk Hydro has installed two ultrasonic metering stations for custody transfer of Grane heavy crude oil at the Sture terminal outside Bergen, Norway. The export metering station consists of five parallel meter runs with ultrasonic liquid flow meters and a 30" bi-directional ball prover with 20 m^3 volumes. The allocation metering station of Grane oil to Oseberg Transportation System has two meters in series and a bi-directional ball prover with 10 m^3 volumes. The ultrasonic liquid flow meters are respectively 12” and 6” Krohne 5-path Altosonic V.

The ultrasonic meters did not fulfil the linearity requirements of NPD. Hence it was not possible for a new K-factor to be automatically accepted by comparison with the average of the last 30 accepted K-factors with a predefined limit of acceptance of 0.3%.

Several measures were taken in order to improve linearity and gain control of development of the K-factor. The 6” allocation meters have been tested with and without the Reynolds number correction implemented in the KROHNE flow computer, and new weighing factors for high viscosities have been implemented. A test program was initiated to characterise the performance of the 12” export meters over a broad range of conditions, and a model for K-factor control limits has been established.

This paper will share the experience gained during testing and characterising of the ultrasonic heavy crude oil meters, and explains the final operating principles of the meters.

2 BACKGROUND

The Grane platform in the North Sea, in production since year 2003, sends heavy crude oil to shore through a 212 km pipeline to the Sture crude oil terminal in Norway, see Figure 1. The plateau production rate is about 40 000 Sm^3/day. The export of the heavy crude oil is through metering station named Grane Oil Handling Sture (GOHS) which consists of five parallel runs of 12” Krohne 5-path Altosonic V ultrasonic flow meters. The flow rate range of each run is 250-2500 m^3/h, however, maximum tanker loading rate is 8 000 Sm^3/h. In addition there is an allocation metering station exporting Grane oil into caverns of oil from the Oseberg Transportation System (OTS). This station, named New Oseberg Blend (NOB), consists of two 6” Krohne 5-path Altosonic V ultrasonic flow meters sin series with maximum flow rate of 600 Sm^3/h. Both metering stations have straight upstream length of 20 ID and Etoile flow conditioner. The provers are made quite large in order to ensure successful proving. The export metering station has a 30" bi-directional ball prover with 20 m^3 volumes, while the allocation station is provided with a bi-directional ball prover with 10 m^3 volumes. Schematic overview of the metering stations at Sture is shown in Figure 2.

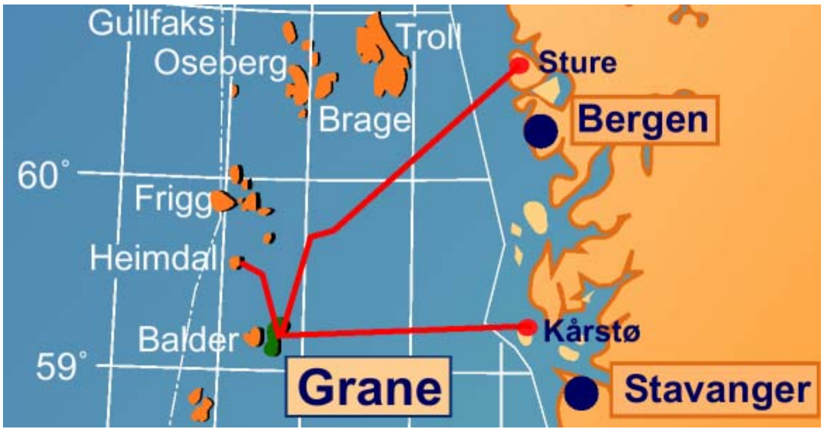

Figure 1. Location of the Grane oil field and the Sture terminal.

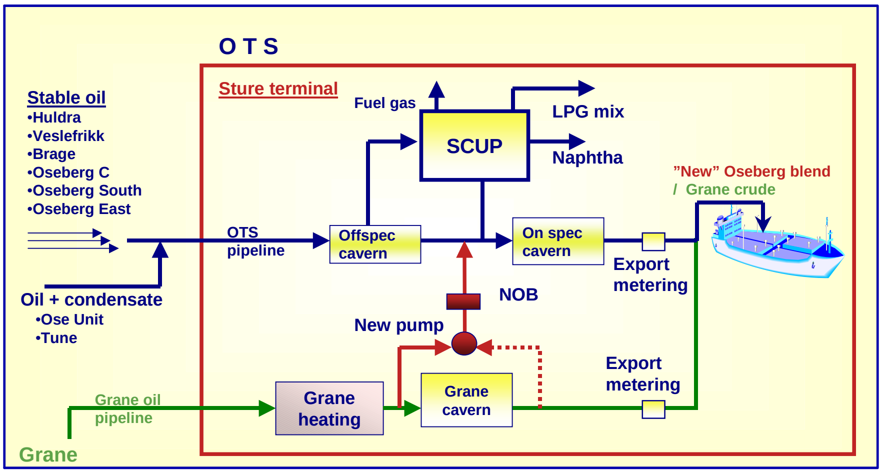

Figure 2. Schematic overview of the metering stations at Sture

3 GRANE OIL

The Grane crude oil has a viscosity during custody transfer varying between 215 and 540 mm^2/s (cSt) for temperatures between 30 ºC (normal loading temperature) and 15ºC. The density at 15 ºC is 943 kg/Sm^3 which yields an API of 18.53. A large heater system, placed upstream the two metering stations, increases the temperature of the Grane oil from nearly sea bed temperature up to 30 ºC, see Figure 2. The oil has characteristics of so called heavy crude oil, but from a metering point of view the main concern is the *conditions* during normal operation. Taking the oil properties and loading rates into account, we see that both metering stations operate at relative low Reynolds numbers, see Figure 3. Theoretically the meters will be used across three flow regimes, from laminar flow through the transition region to the preferred turbulent flow. For lower Reynolds numbers it is expected that the Krohne ultrasonic flow meters are not linear.

The two metering stations in question have a common low Reynolds-number-challenge. But due to dissimilar performance and measures taken in order control the meters long term stability, this paper describes the experience with the two ultrasonic meters separately, first the GOHS and thereafter the NOB metering station.

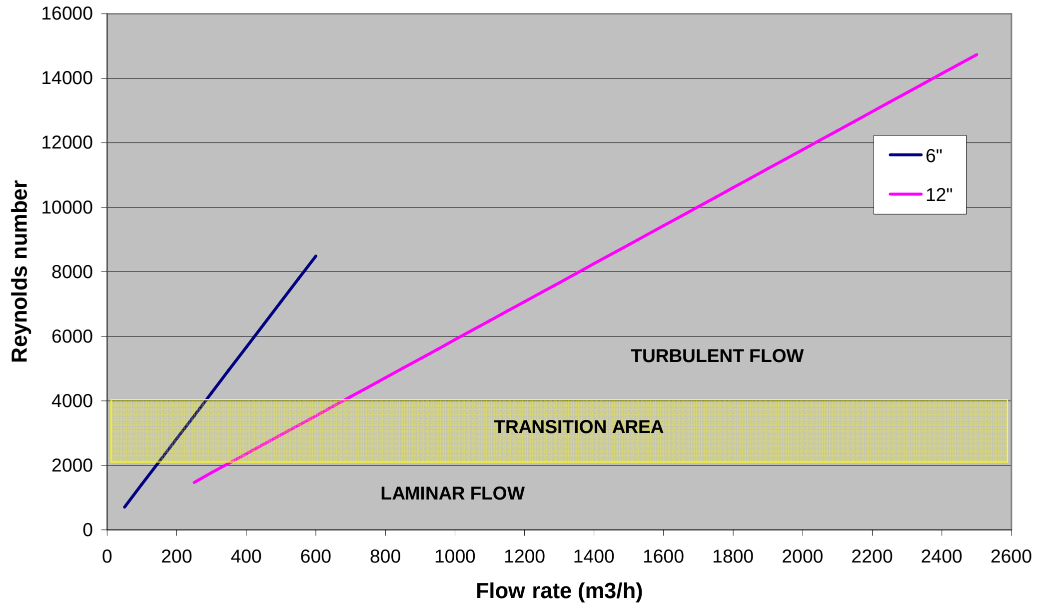

Figure 3. Reynolds number versus flow rate at normal operating conditions at GOSH and NOB

4 GOHS CHALLENGE

The Grane export ultrasonic meters went through a comprehensive testing in order to qualify the meters. The test results on heavy crude oil at SPSE in 2001 revealed a rather strong nonlinearity, as reported by Trond Folkestad at the NSFMW in 2001 [1]. Figure 4 shows an increasing K-factor with increasing Reynolds number. The Grane crude oil at Sture has lower Reynolds number at loading conditions which may enhance and invert the observed nonlinearity. The Norwegian Petroleum Directorate (NPD) required a careful k-factor follow up as part of the conditions to start using the ultrasonic metering station. Initial k-factor measurements at various loading rates certified the nonlinearity. However, opposite to the test results at SPSE the proving results on Grane crude oil show a strong decreasing k-factor with increasing flow rate, i.e. with increasing Reynolds number, see Figure 5. The Hydro repeatability requirement of 0.05% was easily fulfilled at all flow rates. Statistical method is applied.

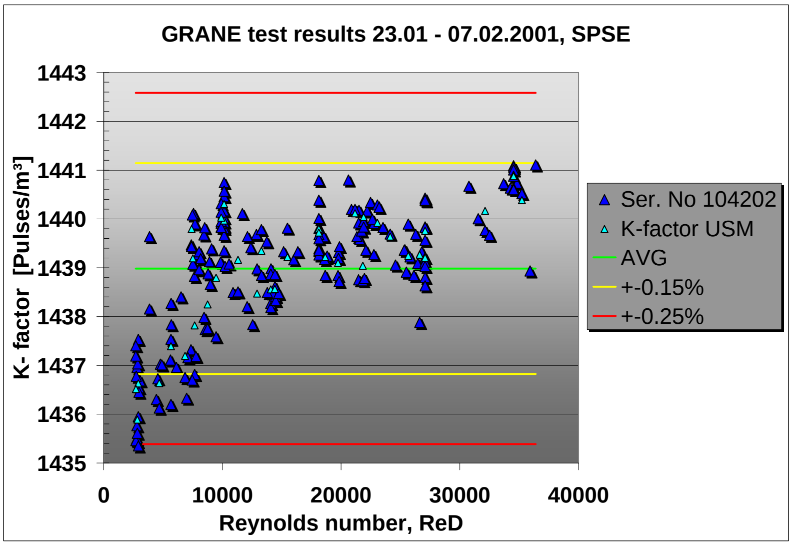

Figure 4. 12” Krohne 5-path Altosonic V ultrasonic flow meter tested on heavy crude oil

The NPD requirements for ultrasonic meters are 0.07% repeatability and 0.3% (band) linearity in 10:1 working range. On export metering stations Hydro requirements are 0.05% repeatability and the linearity requirement is defined as a long term k-factor stability of 0.15% (band). Figure 5 shows clearly that the GOHS ultrasonic meters do not fulfil the linearity requirements of neither NPD nor Hydro. Hence it is not possible for a new K-factor to be automatically accepted by comparison with the average of the last 30 accepted K-factors with a predefined limit of acceptance of 0.3%.

The GOHS challenge is to establish dynamic k-factor limits in order to have control with the ultrasonic meters long term stability. The solution is to make a k-factor model being a function of the loading conditions such as temperature, density, flow rate and so on.

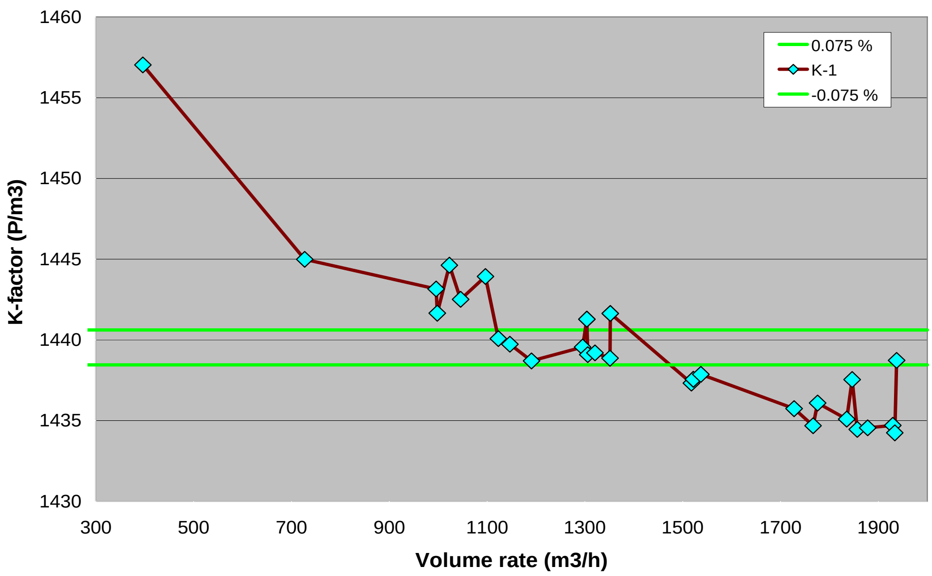

Figure 5. Initial k-factor results of the 12” Krohne 5-path Altosonic V ultrasonic flow meter, measured on Grane crude oil at Sture.

4.1 GOHS K-factor model

The first step made towards a k-factor model was to find relations between loading conditions and the k-factor it self. A test program was initiated to monitor the k-factor over a large range of flow rates, from below to above normal loading rates at 1900 m3/h. Correlations were carried out on the test results to find relations between the state variables temperature, pressure, density and flow rate, and the k-factor. Table 1 shows the correlation results for line 1. The negative correlation between temperature and density means that the density decreases with increasing temperature (of course). The results of the correlations clearly establish the most important k-factor variables, namely flow rate and temperature. Both variables have negative correlation with respect to the k-factor. In other words the k-factor decreases with increasing Reynolds number. This is also seen indirectly in Figure 5.

TABLE 1 Correlations between state variables at line 1

Correlation	***temp***	***pressure***	***Density***	***Rate***	***K-fact***
Temp	1				
Pressure	0.00668	1			
Density	**-0.862123**	0.191367	1		
Rate	0.2835064	0.564647	0.012204256	1	
K-fact	**-0.564329**	-0.41721	0.274322476	**-0.930956**	1

The next step made towards a k-factor model was to carry out a linear regression analysis based on the two main k-factor variables. Each regression analysis is based on 30 to 60 observations where each observation consist of accepted k-factor (repetition requirement fulfilled) and belonging mean value temperature and flow rate. The results of the regression analysis for all five ultrasonic meters are quite promising. Table 2 and 3 show the results for respectively line1 and 2. The R-square, which may be interpreted as the percentage explained, is for the five lines in the range 0.91 to 0.96. The linear k-factor model simply becomes the coefficients of the regression analysis times the respective measured stat variable, see Equation 1. Finally long term stability factor *limits*, ± 0.075%, are added to the calculated k-factor.

$$K\text{-}factor(T,Q)=Intercept + C_T \cdot T + C_Q \cdot Q \qquad (1)$$

where C_T is temperature regression coefficient and C_Q is volume flow rate regression coefficient, and T and Q are measured temperature and volume flow rate.

The k-factor model is applied in the following way: The measured k-factor with repeatability within the requirement of 0.05% (statistical method) is compared with the calculated k-factor, eq. 1, with belonging control limits of ± 0.075%. The new measured k-factor is accepted if it is within the calculated control limits.

TABLE 2 Linear regression coefficients and statistics for line 1

LINE 1			
	Coefficients	*Regression Statistics*	
Intercept	1473.03	Multiple R	0.97
Temp.(grC)	-0.78	R Square	**0.95**

Vol.rate (m3/h)	-0.01	Adjusted R Square	0.95

TABLE 3 Linear regression coefficients and statistics for line 2

LINE 2			
	Coefficients	*Regression Statistics*	
Intercept	1461.08	Multiple R	0.98
Temp.(grC)	-0.44	R Square	**0.96**
Vol.rate (m3/h)	-0.01	Adjusted R Square	0.96

4.2 Application of GOHS k-factor model

The GOHS k-factor model has been used by the operators at Sture since summer 2004. Measured k-factors being outside the control limits of ± 0.075% have been rejected. In the period January 2004 until august 2007 GOHS line 3 has carried out about 334 provings with successful repetition, and where 8 proving results were outside the long term stability control limits. Graphical presentation is given in Figure 6. This figure also includes simulations with fixed temperatures of 29, 31 and 33 ^{o}C and increasing flow rates. The temperature gradient yields a k-factor dependency of 0.04% per. ^{o}C for line 3. The storage of Grane export oil in large caverns improves the stability of the oil. Rarely the provings falls outside the repetition requirement of 0.05%. A histogram presentation of the proving results on line 3 is shown in Figure 7. The deviation in the histogram is the difference between calculated and measured k-factor. Similar results for line 5 are shown in Figures 8 and 9. Line 5 has a slightly broader distribution than line 3, but the gross proving results are within the long term acceptance limits.

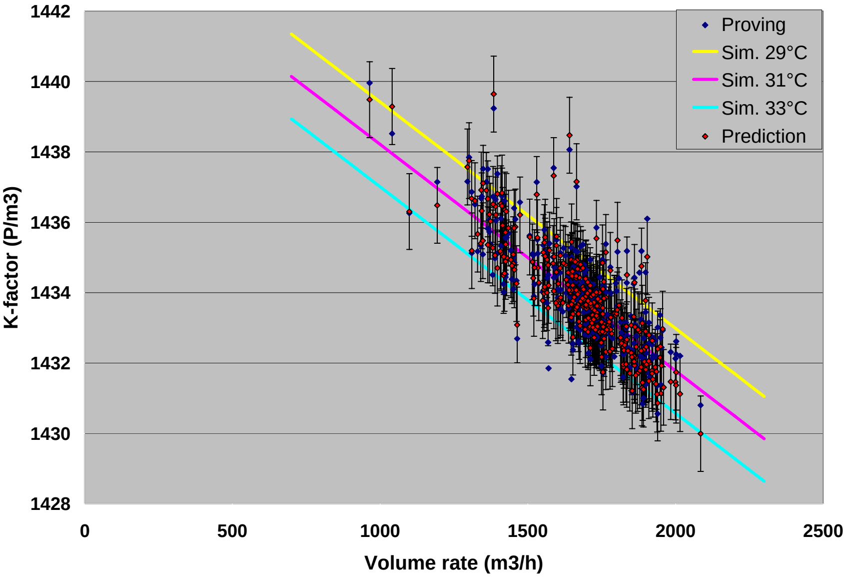

Figure 6. Measured and calculated k-factors for GOHS line 3. The error bars illustrate the control limits of ± 0.075%. The three simulations are carried out as a function of flow rates at fixed temperatures of 29, 31 and 33 ^{o}C.

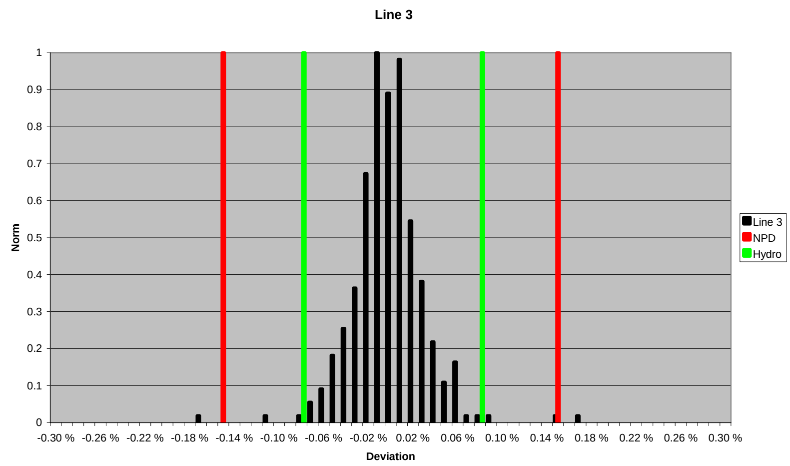

Figure 7. Histogram of the k-factor results shown in Figure 6. Deviation is the difference between calculated and measured k-factor. The Hydro and NPD long term control limits are shown respectively at ±0.075% and ± 0.15%.

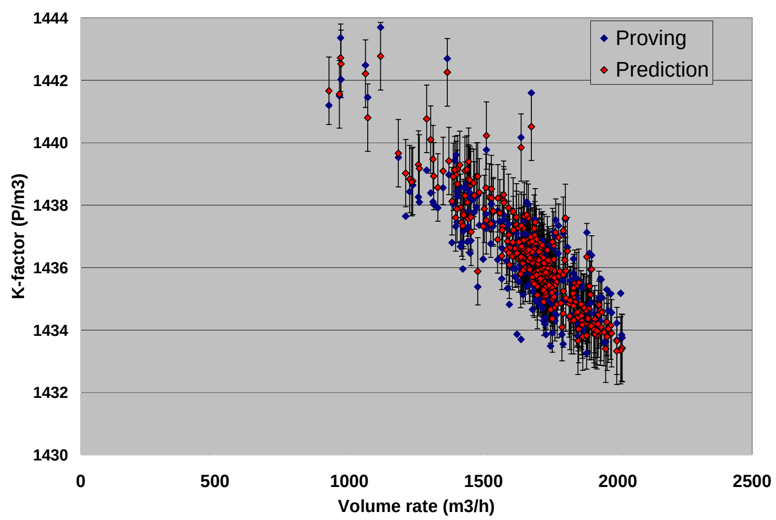

Figure 8. Measured and calculated k-factors for GOHS line 5

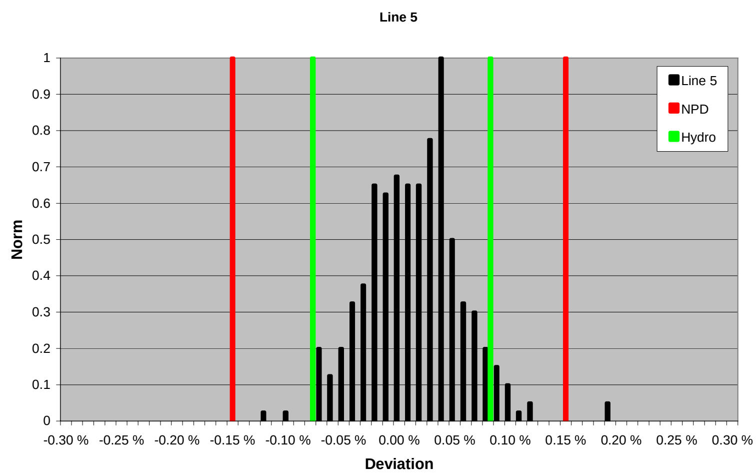

Figure 9. Histogram of the k-factor results shown in Figure 8. The Hydro and NPD long term control limits are shown respectively at ±0.075% and ± 0.15%.

4.3 Flow straightener collapse on GOHS

During the first 18 months most of the proving results on line 4 were accepted, see Figure 10. However, the slowly increasing deviation between measurement and proving model ended outside the control limits after august 2006. At the end of the year the deviation varied from -0.35% to 0.30%. Similar behaviour was also seen on line 1 at the end of year 2004, see Figure 12. By coincident an operator was present at the metering station during a proving and noticed a load metal-to-metal sound from line 4. It was assumed that the flow straightener was loose. The two lines in question were opened and the defect flow straightener assumption was verified. A picture of one of the defect flow straightener is shown in Figure 11. Once new flow straighteners were back in place most of the proving results finished within the long term stability control limits.

These results demonstrate that the k-factor model serves not only to keep control over the long term stability of the ultrasonic meters itself, but is also a mean to reveal defects on the metering stations. T the results achieved rely on a stable, hence predictable, Grane crude oil. The k-factor model has not been adjusted since initiation.

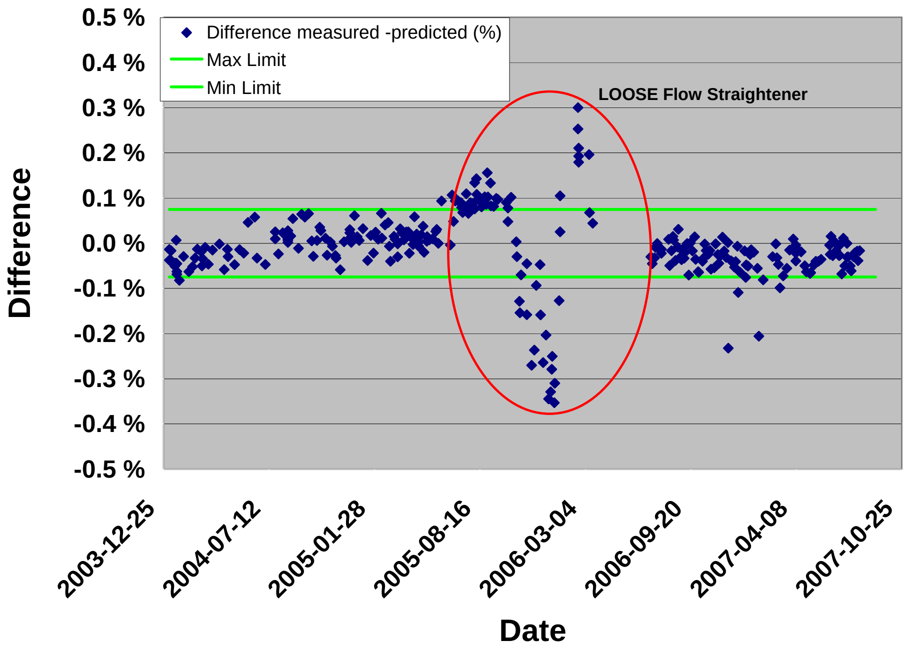

Figure 10. Deviation between measured and calculated k-factors on GOHS line 4

Figure 11. Defect flow straightener from GOHS line 4.

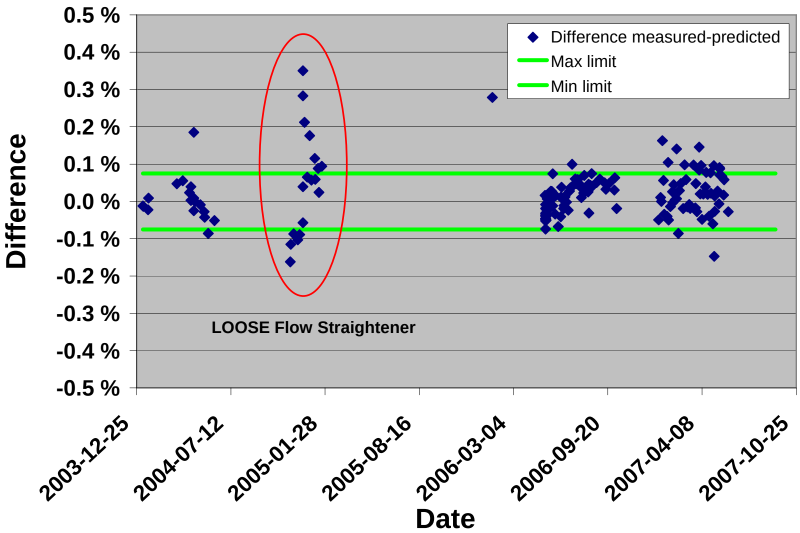

Figure 12. Deviation between measured and calculated k-factors on GOHS line 1

5 NEW OSEBERG BLEND CHALLENGE

The Krohne Altosonic V 6" ultrasonic meters went through standard FAT at Trapil metrology laboratory Paris in 2003. The calibration flow rate range was 63-630 m^3/h, see Figures 13 and 14, and the test product was Gasoil with viscosity of 3.5 to 8.0 mm^2/s at 20 ^oC. The viscosity of Grane oil is more than 25 times higher. The meters can be used with or without a Reynolds number correction which purpose is to improve the meter linearity. The correction must be applied to meet the vendor's specification. Thus the formal FAT was carried out with active Reynolds number correction. The correction, which may be interpreted as a profile correction, resembles most likely the k-factor model described for the GOHS ultrasonic liquid meters. But with active

Reynolds number correction the flow profile of the Krohne meter is *continuously* corrected. The user does not have access to neither the correction nor the correction parameters. Hydro policy for fiscal meters is to have access to all data, both fixed parameters and variable parameters. Therefore the meters were also calibrated with the Reynolds number correction turned off.

The red curve, see Figure 13 and 14, shows the formal calibration with Reynolds number correction on. The linearity of upstream and down stream meters are respectively 0,04 % and 0,02 %. The calibration without Reynolds number correction, blue curve, is close to the lower end of the NPD's linearity requirement (yellow lines). At lower flow rates the formal calibration curve of the upstream meter, see Figure 13, has an opposite trend relative to the uncorrected calibration. This may indicate that the Reynolds number correction overcompensates the true flow profile. The correction of the downstream meter yields an excellent linearity and with the same trend as the uncorrected meter, see Figure 14.

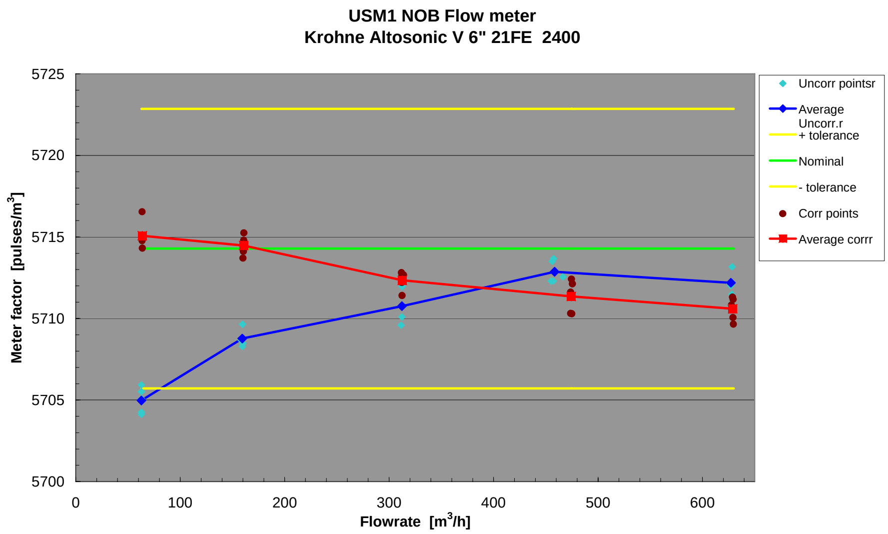

Figure 13. Pigsar calibration results of the NOB upstream ultrasonic meter. The meter was calibrated with and without Reynolds number correction.

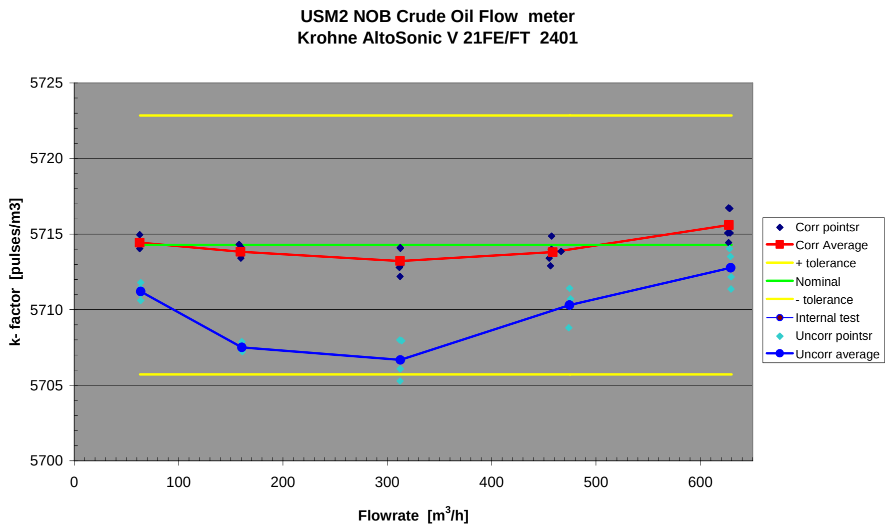

Figure 14. Pigsar calibration results of the NOB downstream ultrasonic meter. The meter was calibrated with and without Reynolds number correction.

The NOB challenge is to run the Krohne meters on Grane oil within the NPD requirements, and in accordance with the Hydro policy to have access to all applied and measured data.

5.1 NOB commissioning

Finally the commissioning phase could take place at Sture with real testing of the meters. In 2003 the Grane oil was heated up from about 7 to 30 ^{o}C with a conventional natural gas driven heat exchanger. The power consumption was about 16 MW and the Grane oil temperature varied more than 1 ^{o}C during a few minutes due to poor regulation. Initially the ultrasonic liquid meters were tested with Reynolds number correction turned off, and the meters' k-factor were characterised in the same way as the GOHS meters. Low Reynolds number in combination with unstable temperature proved to be worse than expected. It was not possible to achieve accepted k-factors because the repetition was outside the 0.07% limits. The k-factor could change as much as 0.3% from one proving trail to the next. Figure 15 shows strong correlation between temperature and k-factor. The k-factor decreases with increasing temperature. The GOHS meters possess the same relation.

The commissioning phase was scheduled to 1 month. In order to have a metering station up and running to start-up date the ultrasonic meters had to be characterised by Krohne to prepare for Reynolds number correction. Eventually with the Reynolds number correction turned on the k-factors fulfilled the repetition requirement. Statistical method was applied. Figure 16 shows a typical proving sequence. The k-factor dependency to temperature is now reversed, i.e. the k-factor decreases with decreasing temperature. Note that the new k-factor, found with statistical method, is above the traditional acceptance limits. The latter is based on the average of the 5 last proving trails.

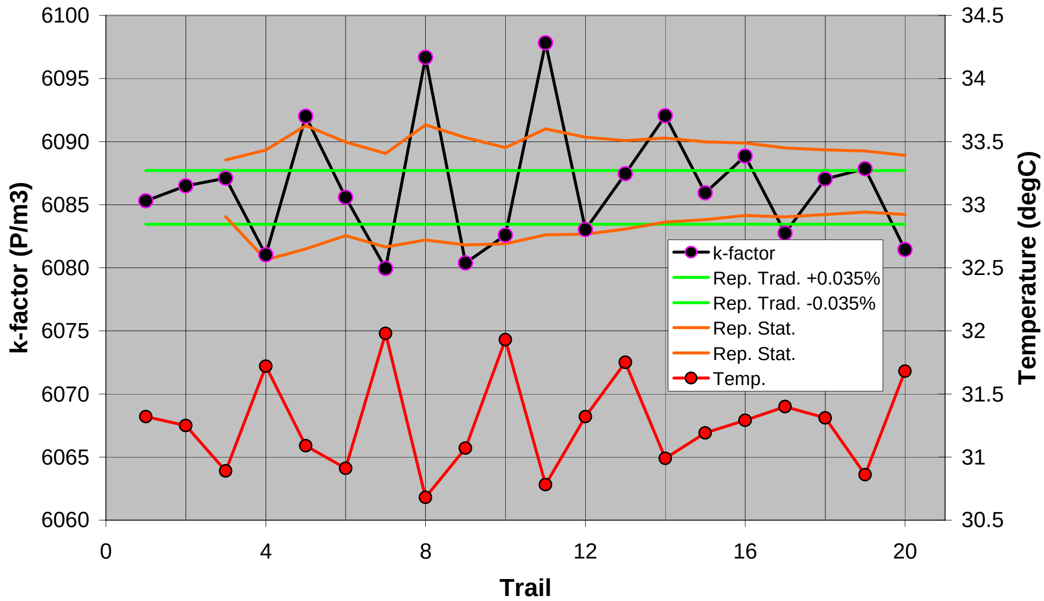

Figure 15. NOB USM1 proving sequence during commission phase. Statistical method is applied which allow maximum 20 proving trails. The flow rate is about 300 m^3/h.

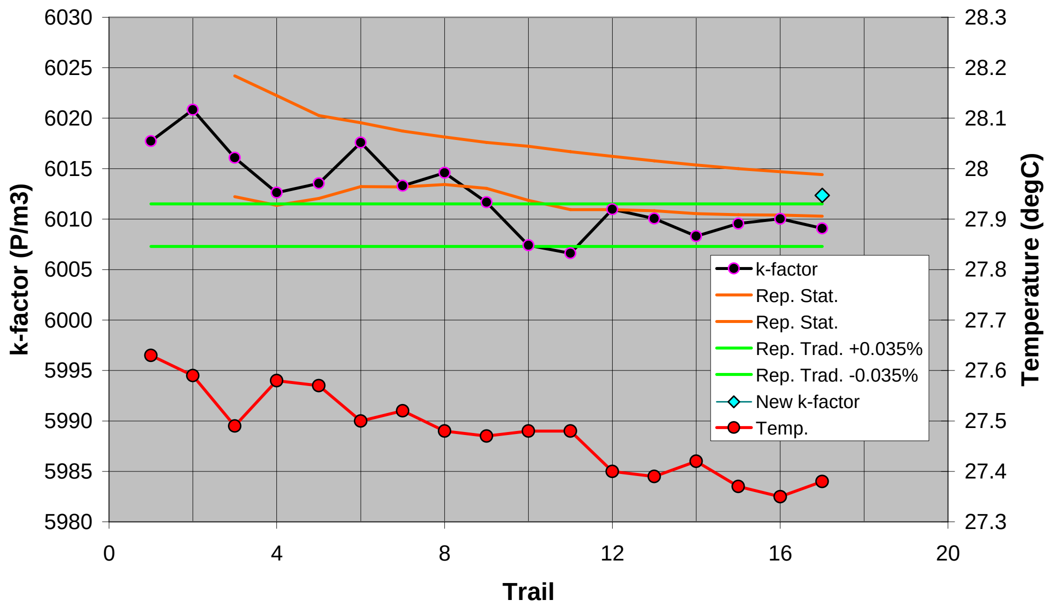

Figure 16. NOB USM1 proving sequence after start-up and Reynolds correction and statistical method are applied. The flow rate is 100 m^3/h and repetition is 0.068%.

5.2 NOB k-factor development

Krohne's Reynolds number correction was used from start-up of the New Oseberg Blend metering station. The majority of the provings fulfilled the k-factor repetition requirement of 0.07% band. However, the long term stability was not satisfied, see Figure 17. The control limits was set to 0.3%, being equal to the NPD linearity requirement. The k-factor variation was more than 3% band during the first 7 months. Thereafter in November 2004 the k-factor became more stable with a variation of about ± 0.5 %. The proving conditions did not change significantly in this period. The crude oil temperature during proving was still fluctuating, but the flow rate had decreased some. Figure 18 shows the development of temperature variation (temperature span) during proving and flow rate from start up to year 2007.

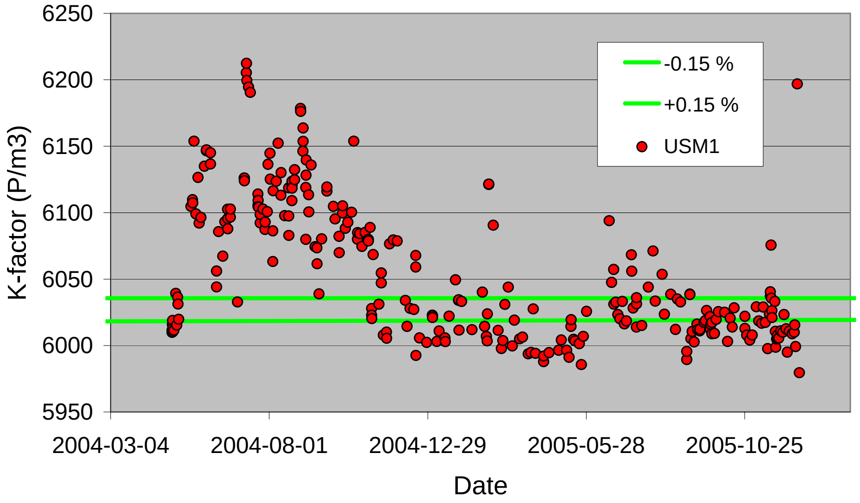

Figure 17. NOB USM1 proving results after start-up. Reynolds number correction is applied.

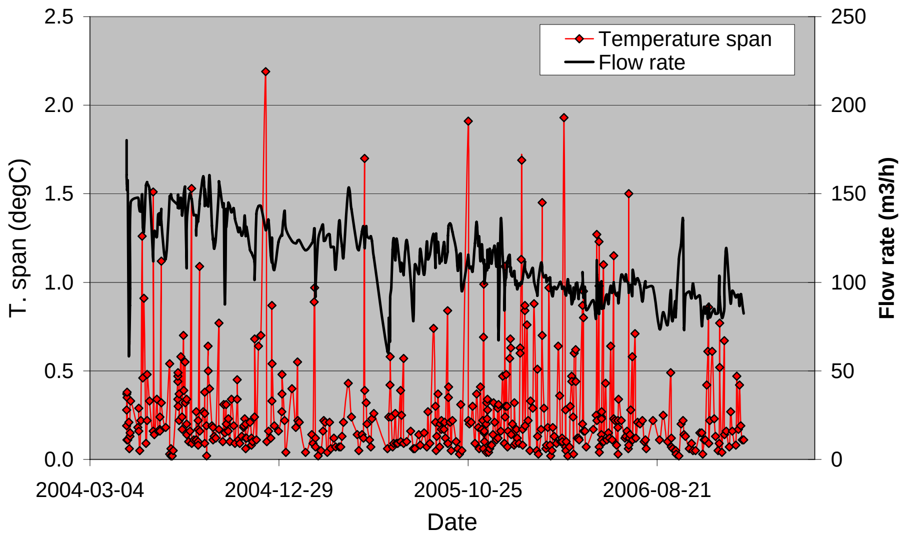

Figure 18. NOB USM1 temperature variation during proving and flow rate development from start-up to year 2007.

5.3 NOB ultrasonic path weights

The long term stability of the k-factor had to be improved. Moreover, the current Reynolds number correction partly masked the traceability of the fiscal measurements. The solution to these imperfections was to make the ultrasonic meters more *linear* at the existing conditions. The vendor Krohne carried out measurements at Sture at various flow rates and temperatures. The data were then used to estimate new weights for the ultrasonic paths. The normalised alternative weighing factors for high viscosity liquid are shown in Figure 19. The new configuration reduces weight of the centre path and increases the importance of path 1 and 5. Without using the Reynolds correction the meter should now be within the requirement of NPD. A proving sequence with new weighing factors and Reynolds correction turned *off* is shown in Figure 20.

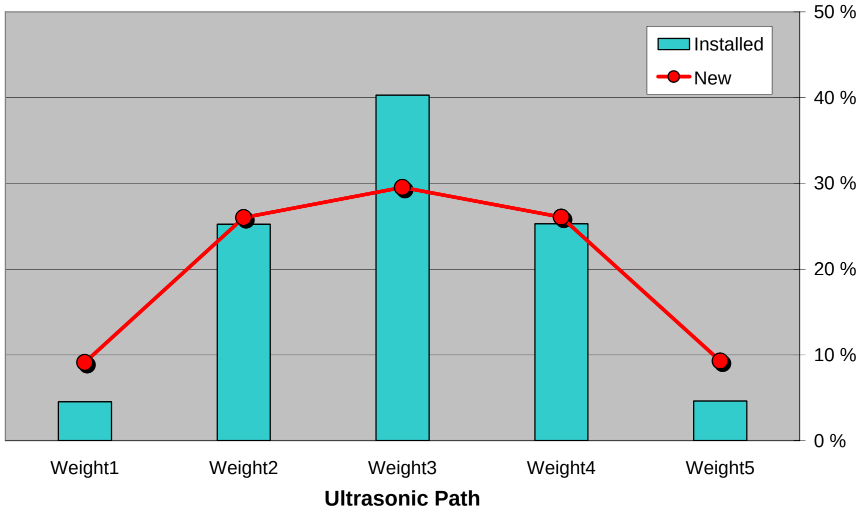

Figure 19. USM1 Old and new weighing factors

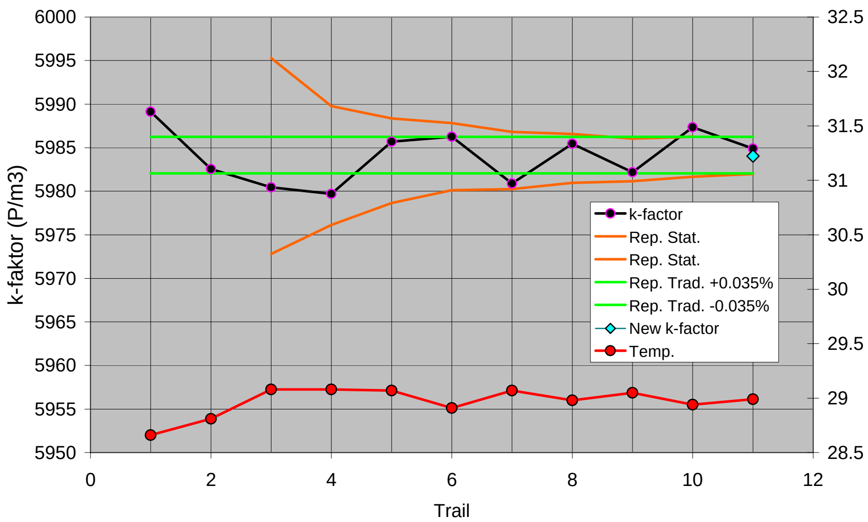

Figure 20. USM1 proving sequence with new weighing factors and without Reynolds correction. The flow rate is about 90 m^3/h.

The meters became significantly more linear with the new weighing factors. Figure 21 shows an overview of accepted k-factors since start-up until September 2007. These k-factors fulfil the repetition requirement. After implementation of new weighing factor most of the k-factors also are within the long term stability control limits of ± 0.15 %, a recent example is shown in Figure 22. The control limits are based on the average of the 30 last provings.

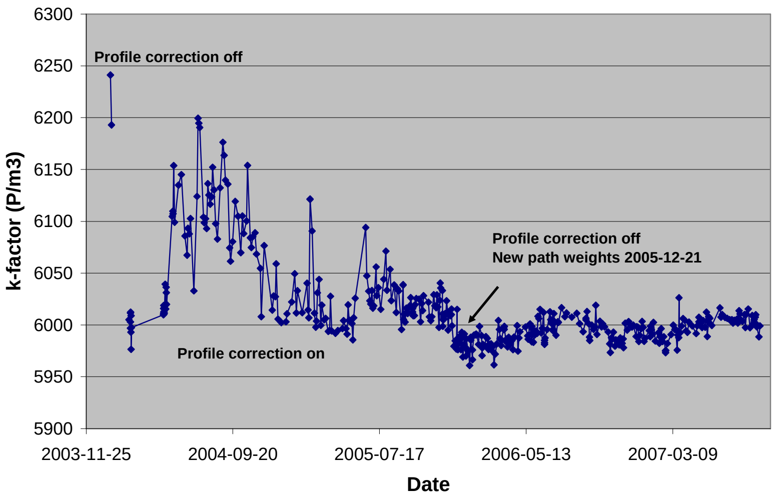

Figure 21. USM1 accepted k-factors (fulfil repetition requirement) from start-up to September 2007.

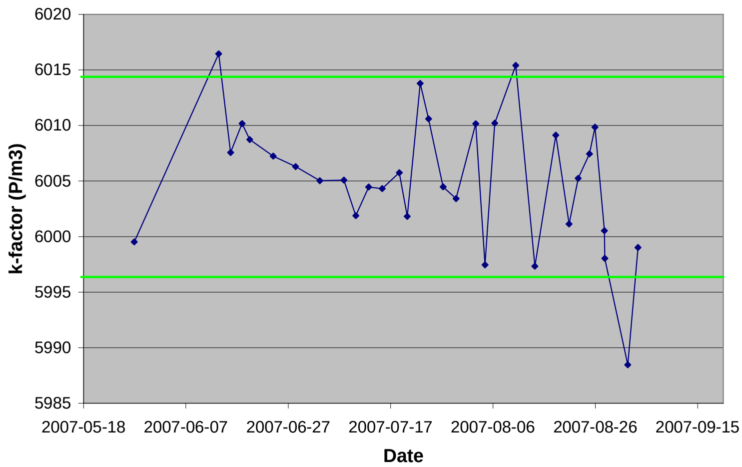

Figure 22. USM1 30 k-factors that fulfil the repetition requirement). The long term stability control limits of ± 0.15 % included.

6 CONCLUSION

Several measures were taken in order to improve linearity and gain control of the k-factor development of ultrasonic meters on high viscosity oil. The Reynolds number correction implemented in the Krohne flow computer has been turned off.

A test program was initiated to characterise the performance of the 12” export meters over a broad range of conditions. A model was made to predict the k-factor. The input to the model is temperature and flow rate, and output is long term k-factor control limits. The 12” export meters do fulfil the k-factor control limits of ± 0.075 %.

The 6” meters have got new weighing factors for high viscosities which made the meters more linear. The 6” allocation meters do now fulfil the long term stability control limits of ± 0.15 %.

REFERENCES

[1] Folkestad Trond, “Testing of a 12” Krohne 5-path Altosonic V ultrasonic liquid flow meter on Oseberg crude oil and on heavy crude oil”, NSFMW 2001.