19^{TH} NORTH SEA FLOW MEASUREMENT WORKSHOP 2001

TESTING A 12" KROHNE 5-PATH ALTOSONIC V ULTRASONIC LIQUID FLOW METER ON OSEBERG CRUDE OIL AND ON HEAVY CRUDE OIL

Trond Folkestad, Norsk Hydro ASA

1 INTRODUCTION

Norsk Hydro is going to install its first ultrasonic crude oil metering station for custody transfer at the Sture terminal in Norway, to be used for export of Grane heavy crude oil. The metering station will have five meter runs with ultrasonic liquid flow meters and a 30" bi-directional ball prover with 20 m^3 volumes. The ultrasonic liquid flow meters will be 12” Krohne 5-path Altosonic V.

To determine the design of the export metering station for heavy crude oil from Grane and achieve approval from the Norwegian Petroleum Directorate (NPD) a series of tests, evaluations and deliberations were needed.

This paper will share the experience gained from two test series on one 12" Krohne ultrasonic liquid flow meter. First, the meter was tested for over three months at Norsk Hydro's Sture crude oil export terminal in Norway. Then the meter was tested for six days at the Société du Pipeline Sud-Européen's (SPSE) test site in Fos sur mer in France on various heavy crude oils. The paper will conclude with some recommendation for using and proving this type of ultrasonic liquid flow meter.

2 BACKGROUND

The Grane platform in the North Sea, in production in the year 2003, will send heavy crude oil to shore through a 212 km pipeline to the Sture crude oil terminal in Norway, see Figure 1. Expected production rate is 34 000 Sm^3/day. Custody transfer of the heavy crude oil will be through a dedicated metering station at the Sture terminal with a maximum tanker loading rate of 8 000 Sm^3/h.

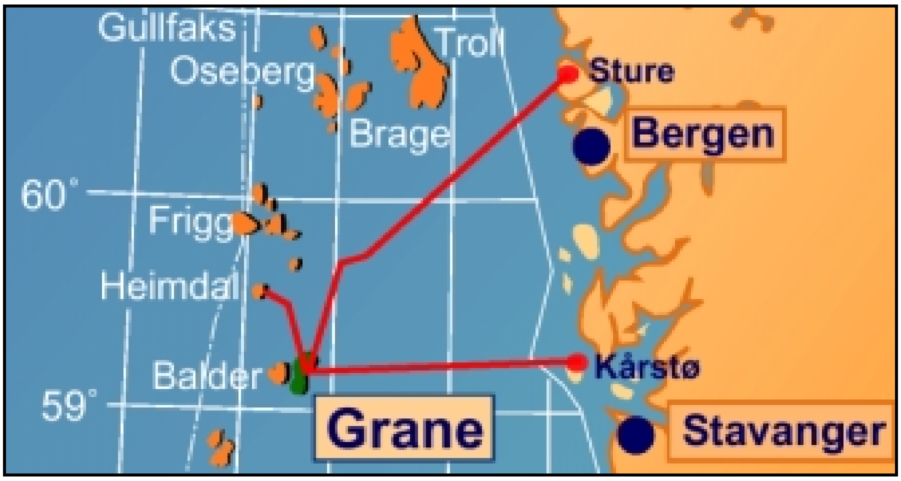

Figure 1. Location of the Grane oil field and the Sture terminal.

3 CHALLENGE

With expected crude oil viscosity during custody transfer varying between 215 and 540 mm^2/s (cSt) for temperatures between 30ºC (normal loading temperature) and 15ºC, the design of the metering station was in no way straight forward. After some evaluations and deliberations, Norsk Hydro decided to try to qualify using ultrasonic liquid flow meters with a large bi-directional ball prover.

Gaining acceptance from the NPD was a crucial constraint so NPD was approached and a program for qualifying an ultrasonic liquid flow meter was discussed. A test program was decided with NPD as observer and participant in the steering committee for the test at the Sture terminal.

4 TEST PROGRAM

Since there was (and still is) little prior experience with using and proving ultrasonic liquid flow meters on heavy crude oil, two test series were planned to determine if using ultrasonic liquid flow meters were at all feasible.

One test aimed at determining operability, "long term" stability and probability of consistently proving an ultrasonic liquid meter within NPD requirements and took place at Norsk Hydro's Sture terminal in Norway on Oseberg Crude oil. The second test was strictly functional and should determine that an ultrasonic liquid flow meter could measure and be proven at high viscosity and took place at SPSE's test site in France.

5 FACTORY CALIBRATION

The 12" Krohne 5-path ultrasonic liquid flow meter was calibrated using a water tower at Krohne Altometer in Dordrecht, the Netherlands, prior to shipment, see Figure 2.

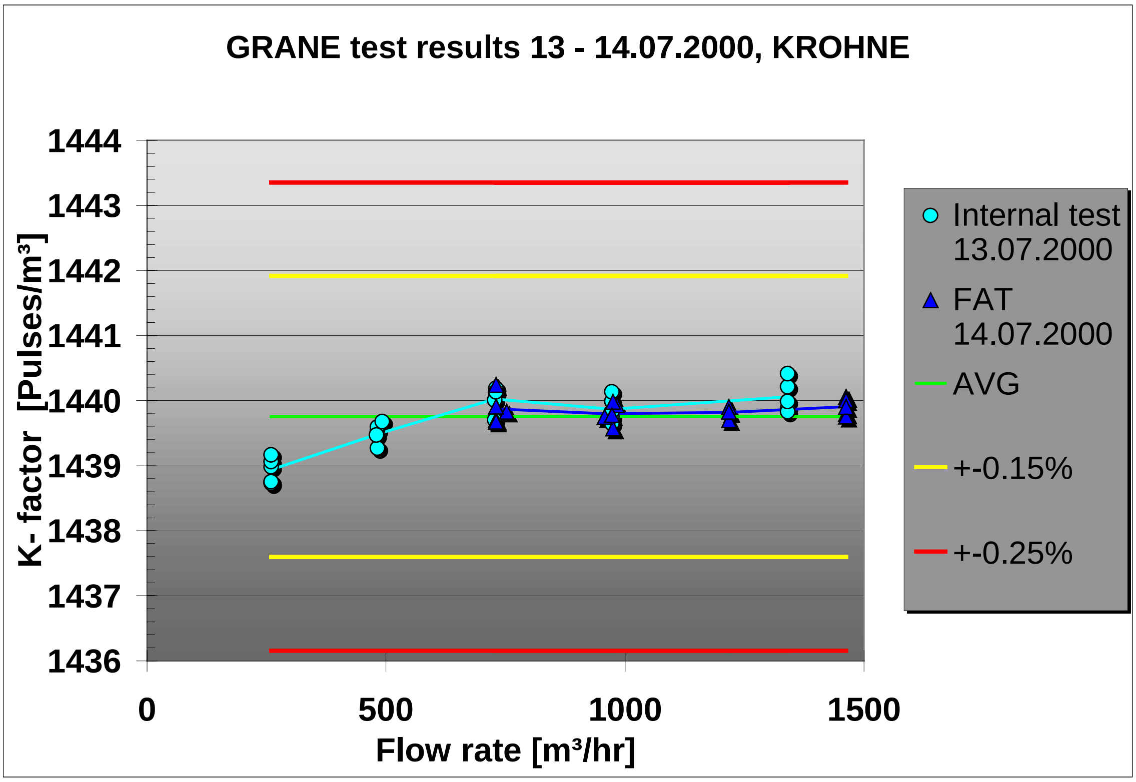

Figure 2. Calibration results, 12" Krohne 5-path ultrasonic liquid meter, with water.

The ultrasonic liquid flow meter's linearity was excellent, well within the NPD linearity requirements for a turbine meter of ± 0.25% (flow range 10:1) and ± 0.15% (flow range 5:1) and the repeatability was acceptable (±0.020%). The ultrasonic liquid flow meter was however not tested over the full flow range of 250 to 2500 m^3/h. Nominal meter factor is 1440 pulses/m^3.

6 TESTING AT THE STURE TERMINAL

Norsk Hydro's Sture terminal in Norway is a crude oil storage and processing facility with storage caverns in the rock base at Sture, LPG and Naphtha export stations, two crude oil export stations and two jetties. The crude oil export stations each consists of 8 meter runs containing 12" Daniel turbine meters and tube bundle flow conditioners. The bi-directional ball provers are 30" with 15 m^3 volumes.

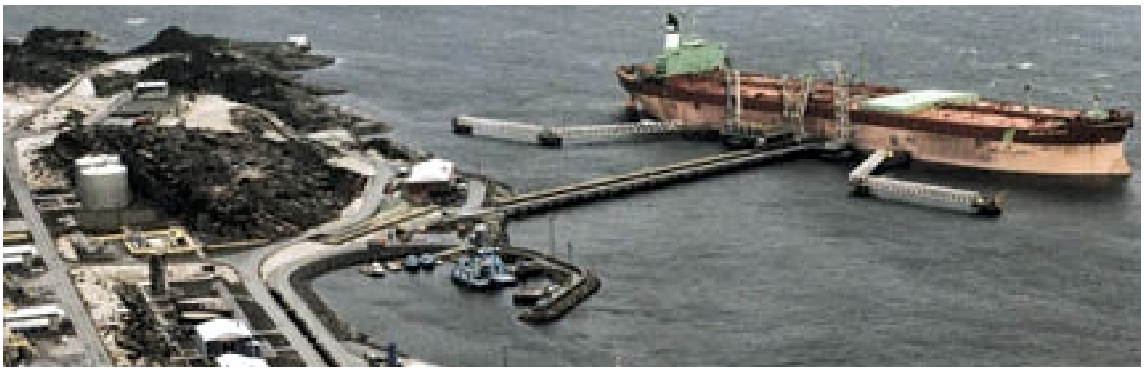

Figure 3. Jetty no. 1 and Export metering station no. 1 at the Sture terminal.

The 12” Krohne 5-path Altosonic V ultrasonic liquid test meter temporarily replaced the turbine meter in meter run 8 in export metering station no. 1. The filter was removed and a new ISO tube bundle flow conditioner was placed approx. 10D upstream the meter, see Figure 3 and 4.

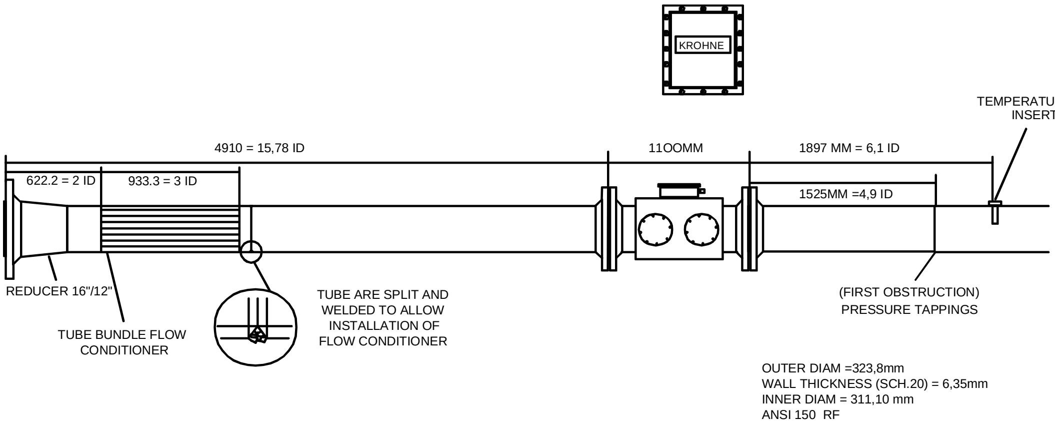

Figure 4. Meter run 8 with test meter installed at the Sture terminal.

The ultrasonic transmitters were located out in field in an EExd enclosure while the Krohne flow computer was located in the local instrument room, sending two pulse trains to the flow computer on meter run 8.

The test series at the Sture terminal lasted from 01.08.2000 until 06.11.2000. This was a "long term" test including 38 oil tanker calls at Sture and 39 batch loading operations during which 2930 proving trials were performed, representing 2 to 4 years of normal proving.

The ultrasonic liquid flow meter should be demonstrated operable within the present NPD requirements for a turbine meter with respect to repeatability, linearity and stability. I.e. repeatability within 0.050% (band), linearity within ± 0.25% (flow range 10:1) and ± 0.15% (flow range 5:1) over the flow range of 250 to 2500 m^3/h and long term stability at normal loading flow rates within ± 0.15%.

6.1 Linearity

The linearity for the ultrasonic liquid flow meter was determined at the start of the test period, see Figure 5. Linearity was compared to the NPD linearity requirements for a turbine meter, for five different flow rates between 250 and 2500 m^3/h. The meter factor was almost constant with flow rate but showed some odd variations. The linearity is well within the NPD linearity requirements for a turbine meter.

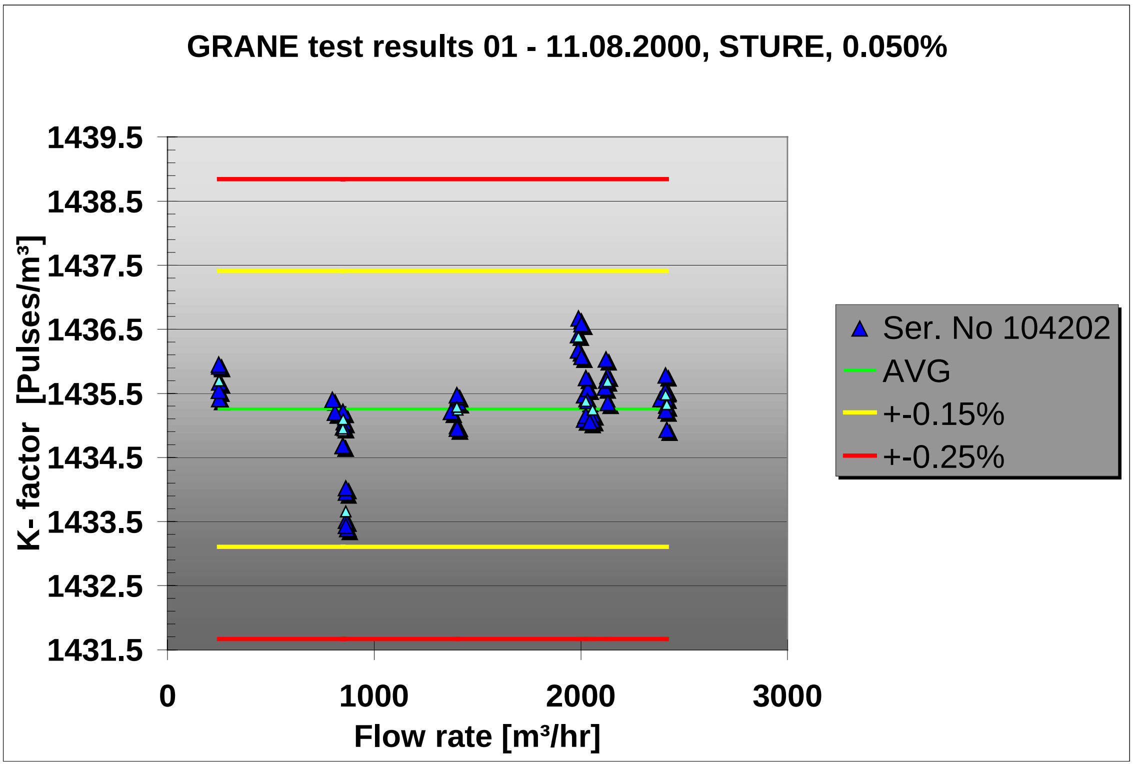

Figure 5. Linearity based on the average of five single proving trials.

Nominal meter factor for this ultrasonic meter is 1440 pulses/m^3. The achieved meter factors on crude oil are lower than the meter factors from the factory calibration on water, ref. Figure 2.

6.2 Proving result summary

A valid meter factor was achieved for the ultrasonic liquid flow meter for every loading operation adhering to the NPD regulation for proving turbine meters. This was also the only method implemented in the flow computer. However, it was surprisingly difficult to achieve valid meter factors using the established proving method for turbine meters. Using a bi-directional prover with volumes of 15 m^3, proving was expected to be unproblematic, but only about 31% of the proving sequences gave valid meter factors within the NPD requirement.

A valid meter factor is the average meter factor from a sequence of five consecutive proving trials when these five meter factors lie within a band of 0.050% of the average meter factor, according to the NPD regulation for proving turbine meters. If this is not true after five proving trials, up to ten proving trials can be made, always using the last five meter factors to calculate a valid meter factor. If no valid meter factor can be established after ten proving trials, a new proving sequence must be started.

Proving results were obtained using the established method for meter factor acceptance for a turbine meter, here called "five consecutive proving trials method". For the month of October 2000, all proving results were manually re-evaluated using statistical methods. In addition, the operation of the meter was evaluated with respect to stability using trend data and proving results from the turbine meters in the other meter runs.

A brief summary of all proving results is given in Table 1 and 2.

Table 1. Comparison of valid meter factors. (For various test periods.)

<table>
<tr><th>Proving sequences in test period</th><th>Proving sequences giving Valid meter factors</th><th>Rejected Proving sequences</th><th>95% confidence interval for Valid meter factors (band)</th><th>Average of all Valid meter factors [p/m^3]</th></tr>
<tr><td colspan="5">"Five consecutive proving trials method" in the test period 01.08 - 06.11.2000.
(5 - 10 single proving trials per proving sequence).</td></tr>
<tr><td>401</td><td>124 (30.9%)</td><td>277 (69.1%)</td><td>0.209%</td><td>1434.91</td></tr>
<tr><td colspan="5">"Five consecutive proving trials method" in the test period before and after the period with presumed "very light" crude oil, 01.08 - 25.08.2000 and 13.09 - 06.11.2000.
(5 - 10 single proving trials per proving sequence).</td></tr>
<tr><td>238</td><td>73 (30.7%)</td><td>165 (69.3%)</td><td>0.107%</td><td>1435.34</td></tr>
<tr><td colspan="5">"Five consecutive proving trials method" during stable test period, 01.10 - 31.10.2000.
(5 - 10 single proving trials per proving sequence).</td></tr>
<tr><td>129</td><td>35 (27.1%)</td><td>94 (72.9%)</td><td>0.117%</td><td>1435.28*</td></tr>
<tr><td colspan="5">Statistical method (Uncertainty at 95% confidence level for the estimator for the Mean meter factor) during stable test period, 01.10 - 31.10.2000.
(5 - 20 single proving trials per proving sequence).</td></tr>
<tr><td>74</td><td>55 (74.3%)</td><td>19 (25.7%)</td><td>0.089%</td><td>1435.43*
(*0.010%)</td></tr>
<tr><td colspan="5">Turbine meter run no. 7, during stable test period, 01.10 - 31.10.2000.
(5 - 10 single proving trials per proving sequence).</td></tr>
<tr><td>48</td><td>43 (89.6%)</td><td>5 (10.4%)</td><td>0.071%</td><td>-</td></tr>
</table>

Using a statistical method to determine meter factors for the ultrasonic liquid flow meter clearly improves proving performance. In Table 1, the difference between the two methods of evaluating proving results is extremely small (0.010%) for the month of October 2000. However, using the statistical method the number of valid meter factors increases with a factor three from 27% to 74% and the scatter is also significantly reduced to give performance that are comparable to a turbine meter. Only normal loading rates are included in Table 1.

Table 2. Comparison of average meter factors from all proving trials, with the average of all valid meter factors from Table 1. (For various test periods.)

Proving trials in test period	95% confidence interval for all meter factors (band)	Meter factors from all proving trials		Average of all Valid meter factors [p/m^3]	Average repeatability of 5 consecutive trials (band)
		MAX MIN [p/m^3]	AVG [p/m^3]		
All meter factors from all proving trials in the test period 01.08 - 06.11.2000.					
2 930	0.305%	1438.24 1431.17	**1434.99**	**1434.91** (a) (**-0.006%**)	0.105%
All meter factors from all proving trials before and after the period with presumed "very light" crude oil, 01.08 - 25.08.2000 and 13.09 - 06.11.2000.					
2 200	0.241%	1438.24 1431.28	**1435.36**	**1435.34** (a) (**-0.001%**)	0.107%
All meter factors from all proving trials during stable test period, 01.10 - 31.10.2000.					
944	0.211%	1438.24 1432.65	**1435.47**	**1435.28** (a) (**-0.013%**) **1435.43** (b) (**-0.003%**)	0.106%

a) Established proving method for a turbine meter
b) Statistical proving method

Again, the differences are so small as to be statistically insignificant between the average meter factors from all proving trials and the average of all valid meter factors. This shows that it is not critical which evaluation criterion is used to determine a valid meter factor as long as it based on a method that gives a true average meter factor. A purely statistical method will ensure this better than the established proving method for a turbine meter and will give less scatter.

The small differences are also a good indication that the variability in meter factors is stochastic.

The results in Table 1 and 2 also indicate that the metering system with the ultrasonic liquid flow meter and pipe prover has good long-term reproducibility.

6.3 Proving results - long term stability

In Figure 6, 7 and 8 the long term stability of the meter factor for the whole test period is compared to the NPD linearity requirements for a turbine meter of ± 0.25% (flow range 10:1) and ± 0.15% (flow range 5:1). The confidence interval at 95% confidence level and the NPD repeatability requirement is also indicated. All valid meter factors were determined using the established proving method for a turbine meter.

The NPD operating requirement for a turbine meter states that: "The calibration factor for the turbine meter shall be validated by control limits according to a recognised standard."

A recognised standard is the American Petroleum Institute's Manual of Petroleum Measurement Standards (API MPMS) recommending that action limits with confidence level of 95% to 99% are to be calculated. However, these action limits will vary from meter run to meter run and are therefore found impractical in use.

During normal operation of a turbine meter, the established validation method is to use fixed control limits as a percentage around the average of at least 30 valid meter factors. The metering system is considered to be in control within ± 0.15% of this average.

The long term stability of the meter factor is quite acceptable, see Figure 6.

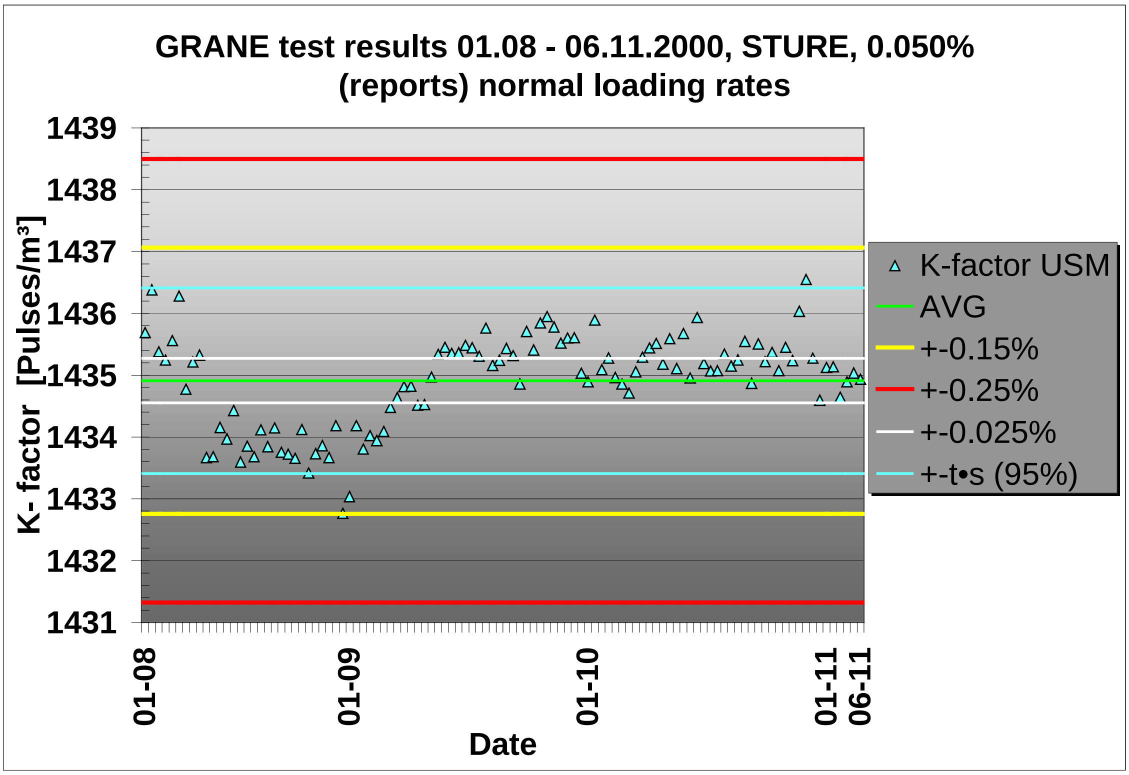

Figure 6. All valid meter factors during the whole test period 01.08 - 06.11.2000.

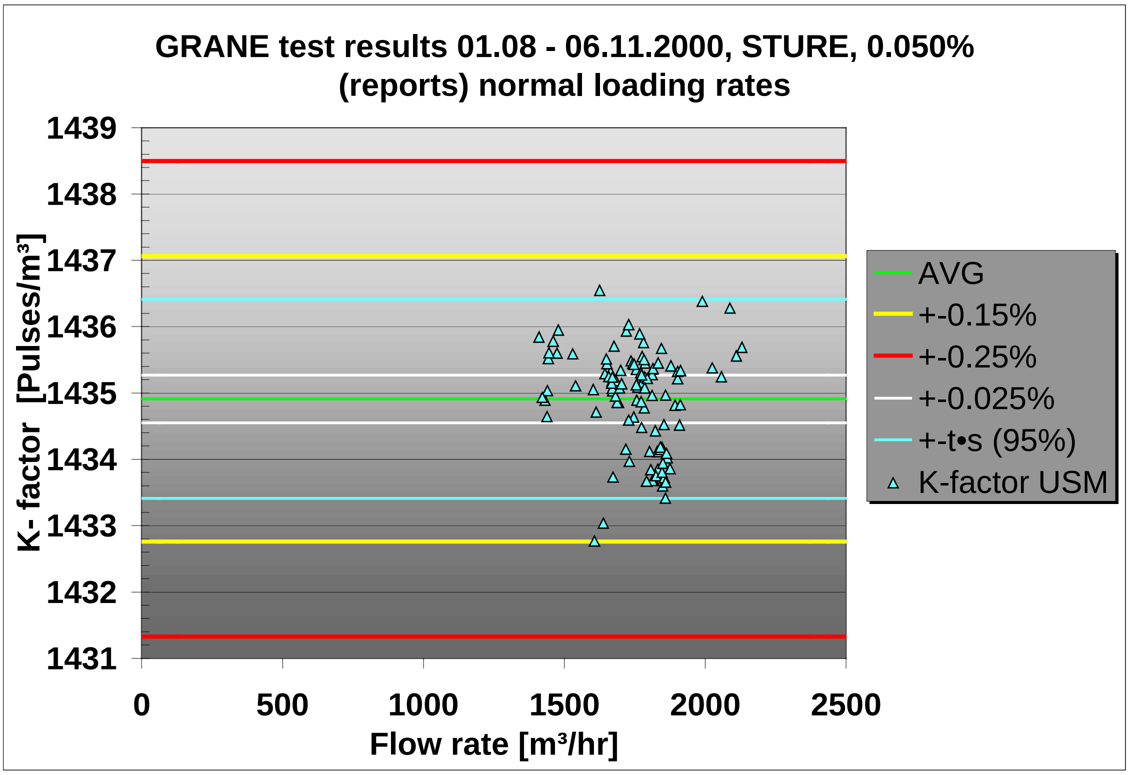

Figure 7. All valid meter factors during the whole test period 01.08 - 06.11.2000.

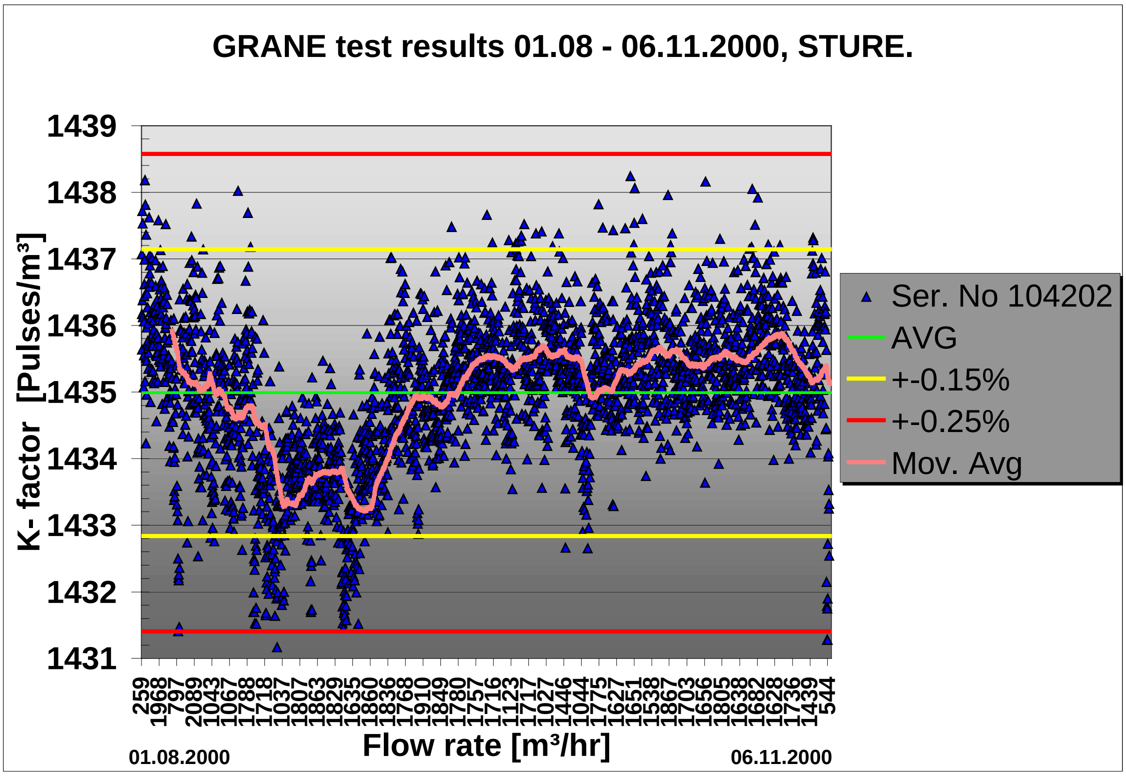

Figure 8. All meter factors from every proving trial during the whole test period 01.08 - 06.11.2000.

However, there is an odd dip in the meter factor in the test period from 26.08. - 12.09.2000, see Figure 6 and 8. It was later established that in this period the exported oil probably had a different consistency than normal and consisted of a "very light" crude oil.

This was due to several unfortunate circumstances happening simultaneously. The delivery of lighter than normal crude oils from the offshore oil platforms and long periods of down time for the process plant at the Sture terminal designed to remove most of the LPG and Naphtha components from the crude oil prior to export.

To further verify that it was the consistency of the crude oil that affected the ultrasonic meter, the turbine meters in the other meter runs were examined to see whether they has reacted to the change as well. Indeed, they had. In Figure 9 the turbine meter in meter run 6 show a significant increase in meter factor in exactly the same test period.

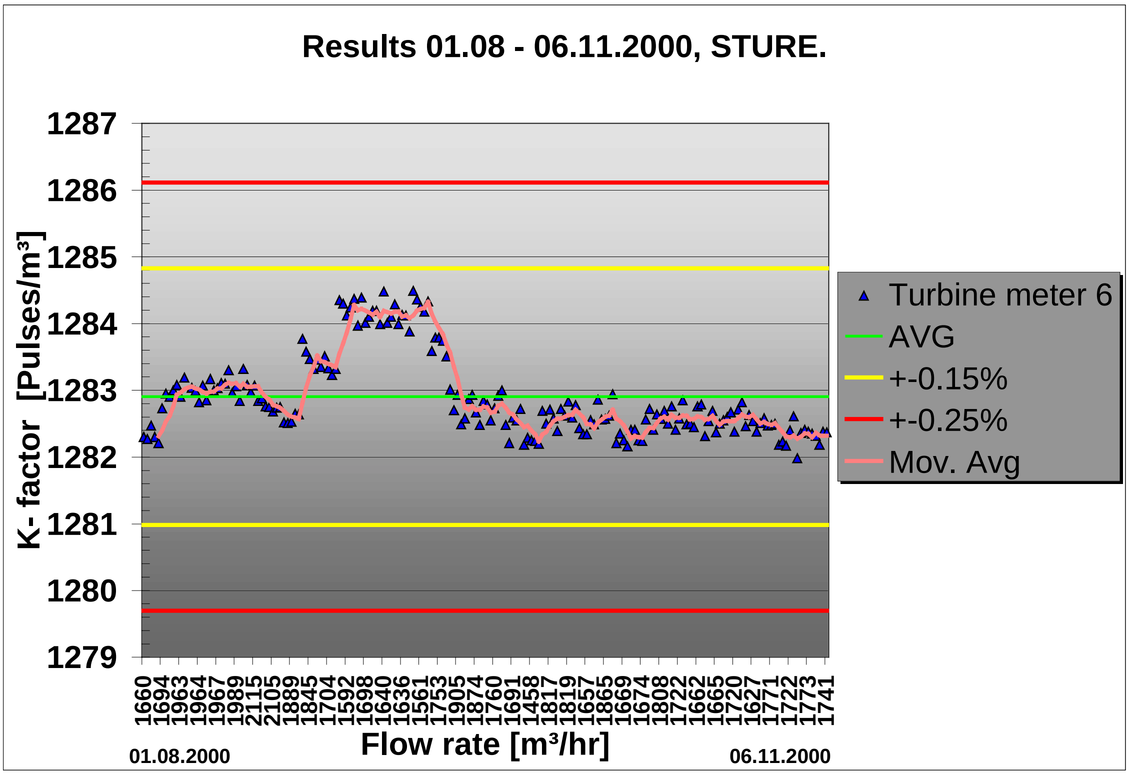

Figure 9. All meter factors from every proving trial during the whole test period 01.08 - 06.11.2000 for the turbine meter in meter run 6.

Removing all meter factors from the period with presumed "very light" crude oil, the resulting plot show that the meter factor was very stable for the rest of the test period, see Figure 10 and 11.

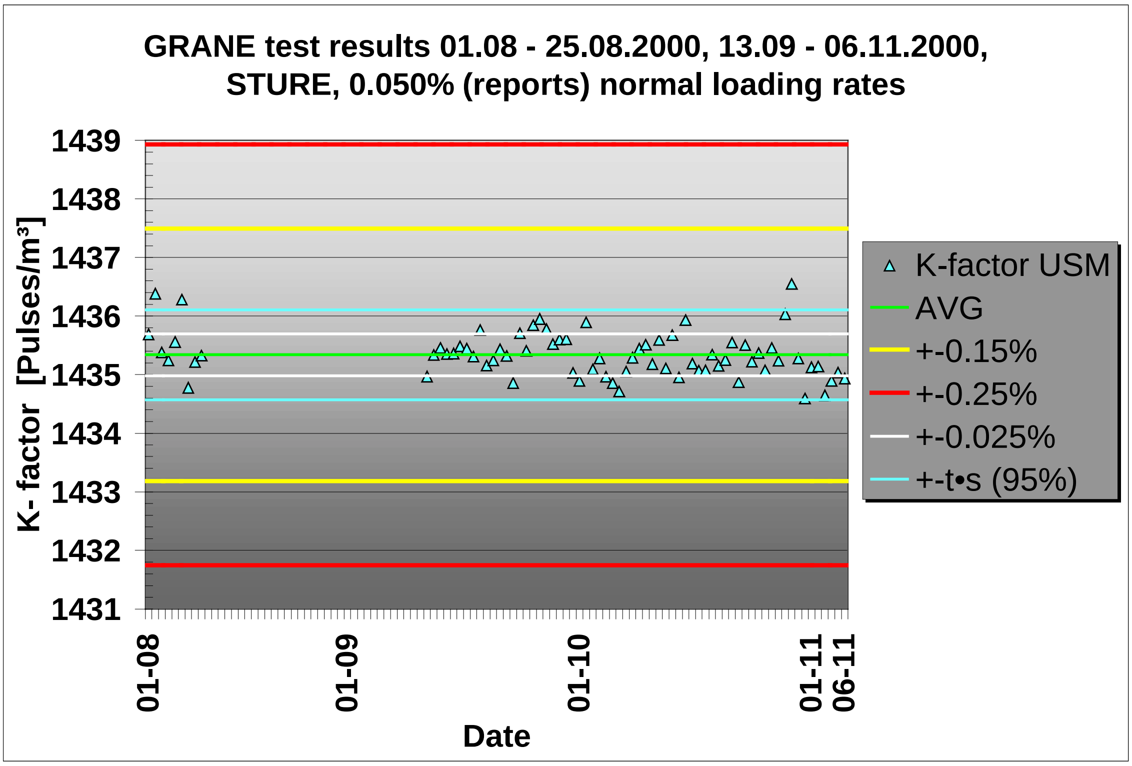

Figure 10. All valid meter factors during the test period before and after the period with presumed "very light" crude oil, 01.08 - 25.08.2000 and 13.09 - 06.11.2000.

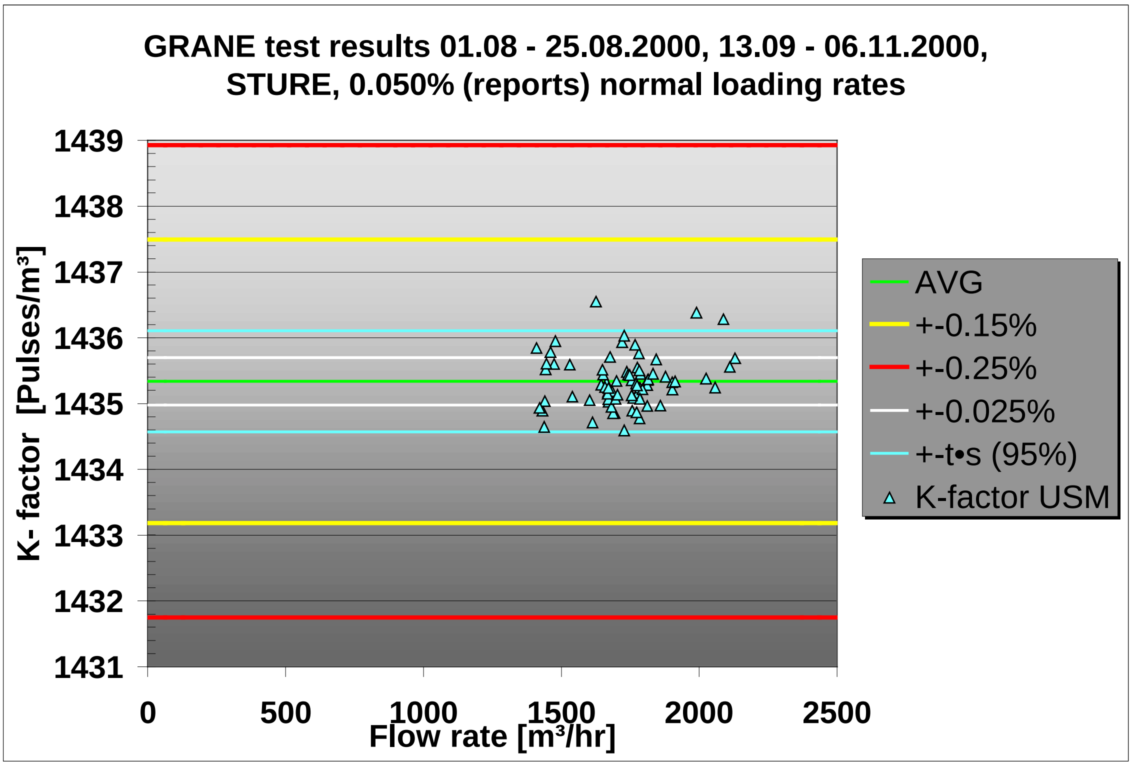

Figure 11. All valid meter factors during the test period before and after the period with presumed "very light" crude oil, 01.08 - 25.08.2000 and 13.09 - 06.11.2000.

6.4 Pulsating flow affecting repeatability

Only about 31% of the proving sequences gave valid meter factors within the NPD requirement using the established proving method for a turbine meter, ref. Table 1.

Typical meter factors from single proving trials showing the larger than expected scatter and consequently poor repeatability compared to the NPD requirement, are given in Figure 12 for a normal loading flow rate.

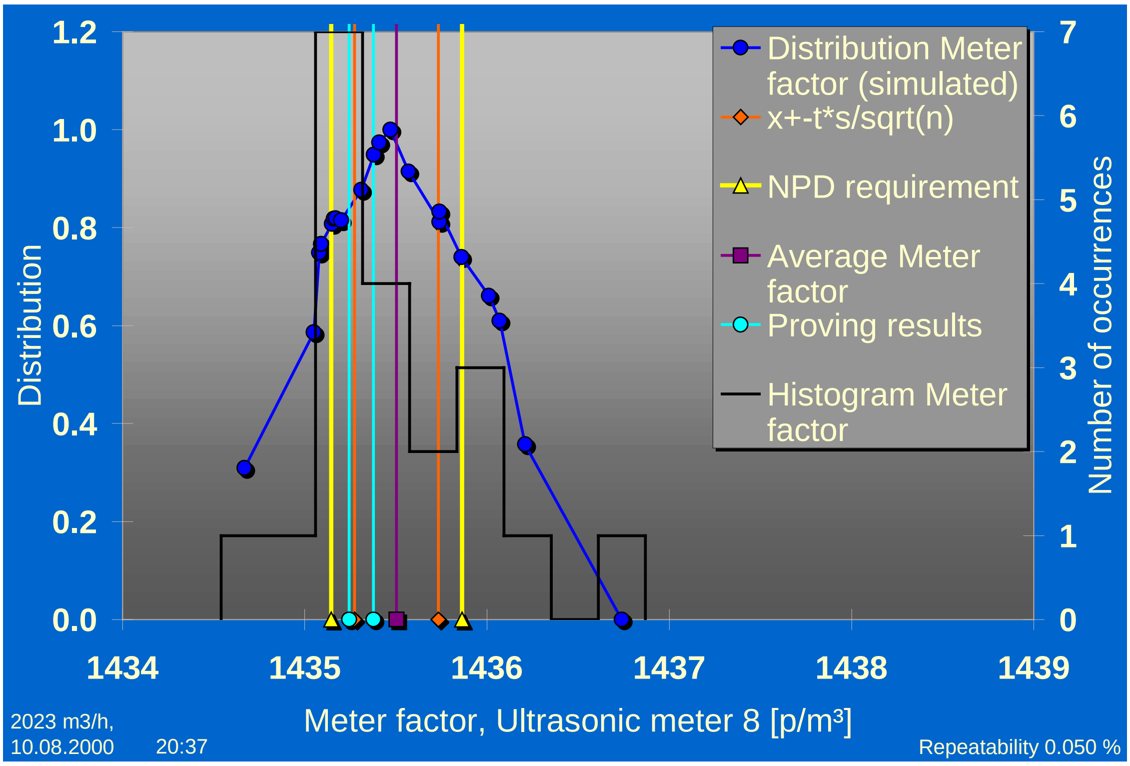

Figure 12. Typical distribution of meter factors from single proving trials at normal loading flow rate. The uncertainty of the Estimator for the Mean meter factor is calculated at 95% confidence level.

Typical variation in meter factor during several proving sequences is given in Figure 13. The relative repeatability could typically vary from 0.5 to 3.8 times the NPD requirement.

A lot of effort was put in to find possible causes for the poorer than expected repeatability. No fault could be found either in the prover or in the pulse transmission from the Krohne flow computer to the FMC Kongsberg Metering flow computer.

Pulse transmission was evaluated and signal strength, shape, noise and error counting was checked. No errors could be found.

Krohne Altometer personnel performed alternative proving by re-routing the detector switch signals to the Krohne flow computer. The same repeatability results during proving were achieved as seen with the FMC Kongsberg Metering flow computer.

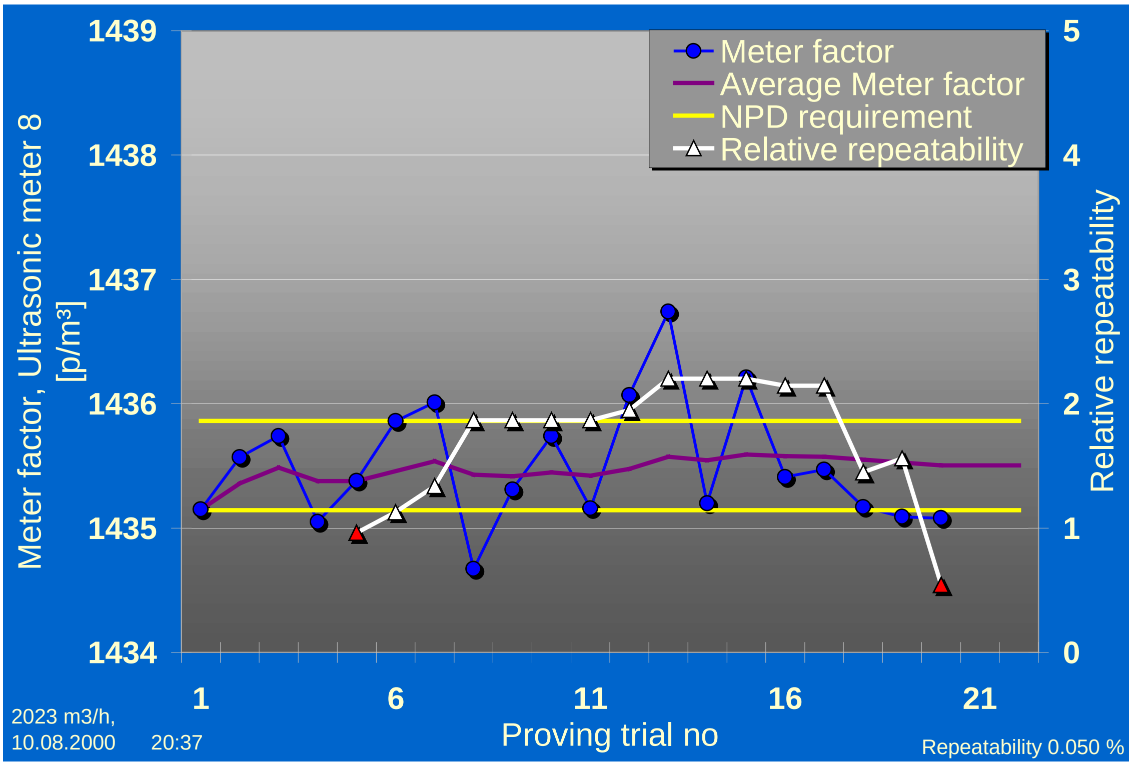

Figure 13. Typical variation in meter factor from single proving trials at normal loading flow rate.

Based on the experience from Oseberg Sør the prover performance was evaluated [2], by logging the counter values from the proving hardware. The scatter in the meter factors calculated from these counter values for all four volumes simultaneously was less than 0.012% (band). This was well within the NPD calibration requirement for a prover of 0.020% (band). The prover performance was acceptable. The poor repeatability was not due to the prover.

The flow profile through the meter was examined on the Krohne flow computer display. The flow profile was not severely skewed and no significant swirl or cross flow effects were present. The profile was fairly symmetrical but pulsating.

As part of the test of the ultrasonic meter at the Sture terminal, the time series of measured flow velocities were logged on file. From this, flow stability could be determined and frequencies of any pulsations in the flow could be identified, performing the same analysis as during the Oseberg Sør tests [1] [2].

According to the theory developed in [1], pulsating flow during meter proving will lead to variation in the meter factor. Critical pulsating flow frequencies that will influence proving stability the most can be determined as the pulsations that oscillate 0.5 to 3.5 times during a single pass of the prover ball, see Table 3.

Table 3. Critical pulsating flow frequencies.

Proving flow rate [m^3/h]	One-way proving time [s]	Maximum critical pulsating flow frequency [Hz]	Minimum critical pulsating flow frequency [Hz]
2 500	10.7	0.33	0.05
250	107	0.033	0.005

Krohne Altometer personnel logged the time series of measured flow velocities (35 ms sampling time = 28.6 Hz). Analysis of the time series showed pulsating flow with frequencies well below 0.33 Hz, see Figure 14, 15, 16 and 17.

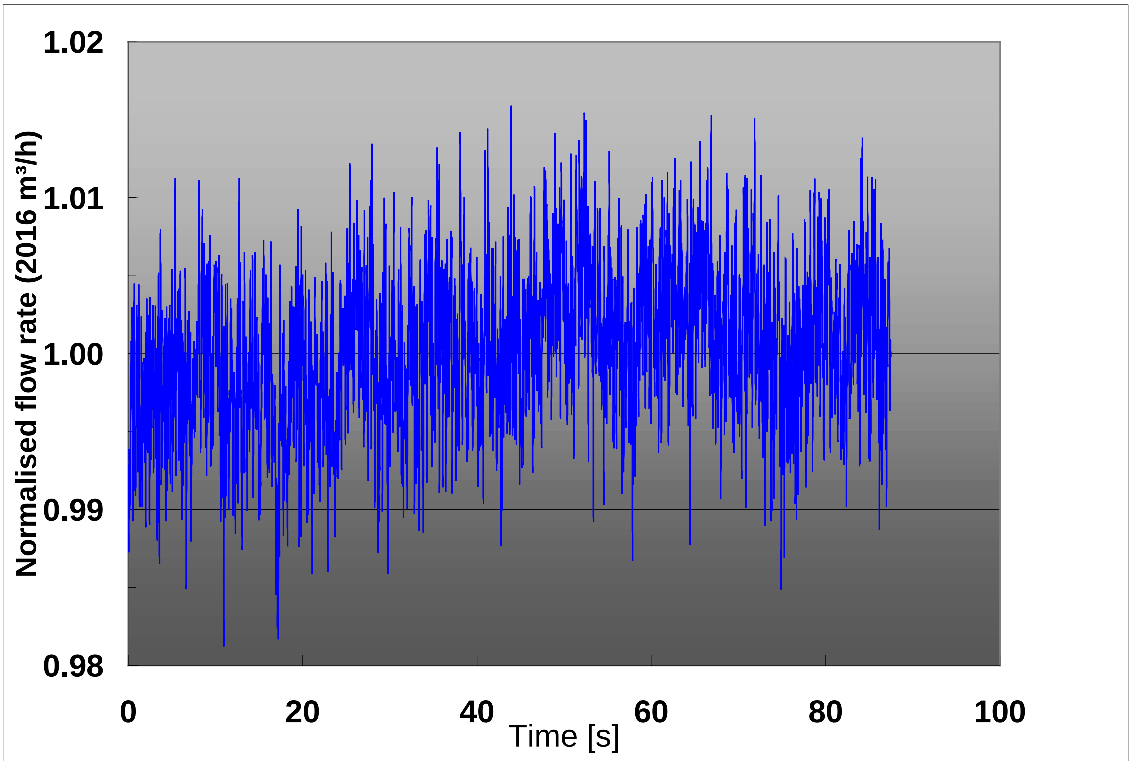

Figure 14. Typical time series at normal loading flow rate show pulsating flow.

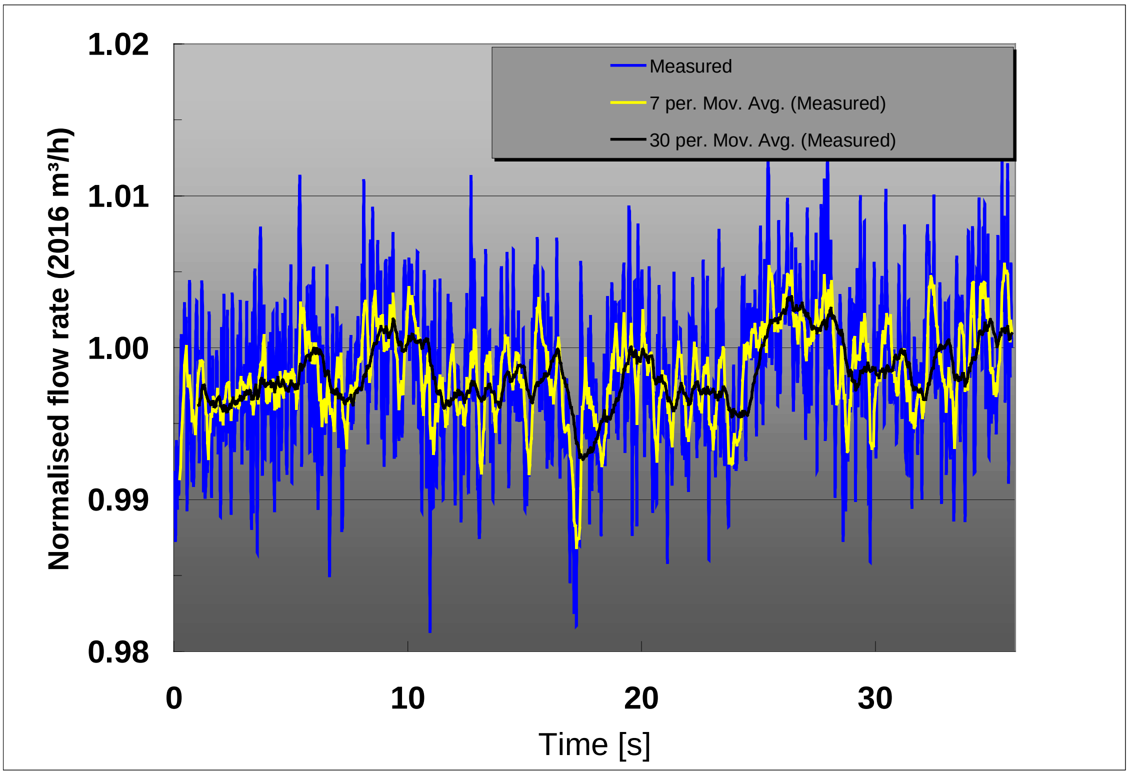

Figure 15. Typical time series at normal loading flow rate indicates periodic pulsation with significant amplitude.

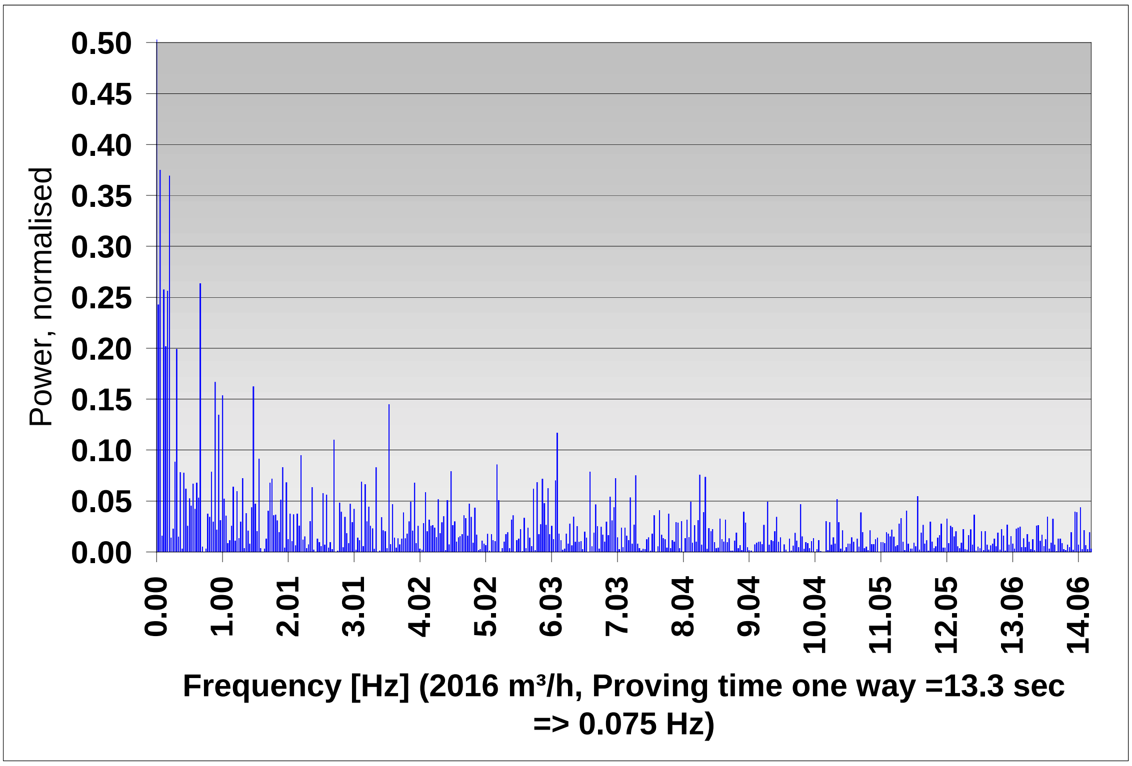

Figure 16. FFT on time series identifies pulsation frequencies at normal loading flow rate.

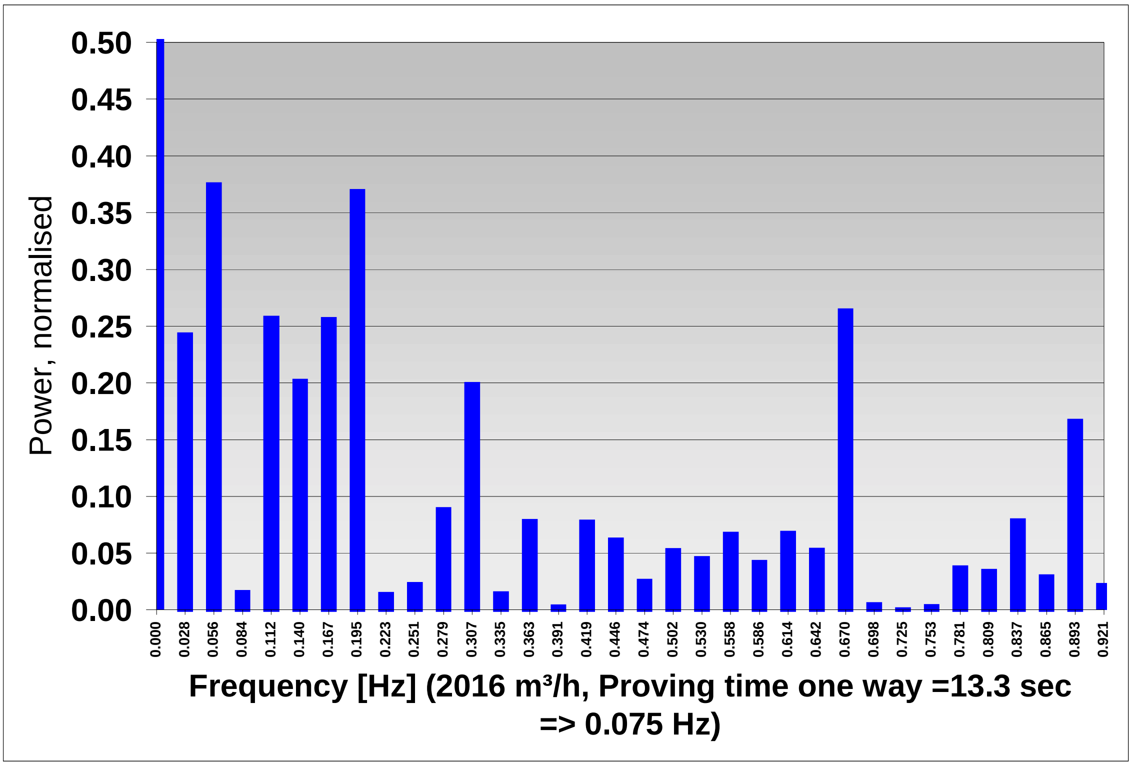

Figure 17. FFT on time series identifies pulsation frequencies at high flow rate. Blow-up.

The flow was much more stable and the energy of the pulsation much smaller than during the Oseberg Sør tests [1] [2] and this concurs with the much smaller variability in meter factor.

Again we can conclude that the ultrasonic meter seems to give a reasonably good indication of the true variation in average flow rate over the cross-section of the pipe below 14 Hz (the sampling theorem). The variability in meter factor is largely due to pulsating flow.

The pulsating flow was probably generated by pumps and control valves in the export line.

6.5 Statistical evaluation of meter factors

The process stability at the Sture terminal was not sufficient for proving an ultrasonic meter consistently in adherence with the NPD requirement for a turbine meter.

However, the purpose when proving a meter is to arrive at an average meter factor that represents the meter's performance under operating conditions. Acknowledging that a significant proportion of the variability in meter factor observed during the tests at the Sture terminal were not due to the meter's intrinsic repeatability but to the variation in process conditions during the meter proving. Using a statistical method for determining the average meter factor of an ultrasonic meter seems the obvious improvement to the established proving method for turbine meters, as discussed in [1].

Using statistical methods the maximum acceptable uncertainty band at 95% confidence level (the 95% confidence interval) is equalled to the NPD repeatability requirement of 0.050% (band). At least 5 and maximum 20 proving trials constitutes a proving sequence.

Several statistical methods can be used for evaluating meter factors and some were given in [1]. See also API MPMS Chapter 13.2.

The uncertainty band, δ, (confidence interval) at 95% confidence level $(\alpha = 5\%)$ for a test sample of **n** meter factors is given by Equation 1. Assuming that all meter factors, **X**, follow a normal distribution with standard deviation, **s**, and average, $\overline{X}$, the test sample of **n** meter factors will follow a Student-t distribution with (**n-1**) degrees of freedom.

$$\delta = 200 \cdot t_{\frac{\alpha}{2},n-1} \frac{s}{\overline{X}} \qquad [\%] \qquad \textbf{(1)}$$

An estimator for the Mean meter factor, μ, is given by Equation 2. Assuming that all meter factors, **X**, follow a normal distribution with standard deviation, **s**, and average, $\overline{X}$, the estimator for the Mean meter factor, μ, will follow a Student-t distribution with (**n-1**) degrees of freedom.

$$P\left(\overline{X} - t_{\frac{\alpha}{2},n-1} \frac{s}{\sqrt{n}} < \mu < \overline{X} + t_{\frac{\alpha}{2},n-1} \frac{s}{\sqrt{n}} \right) = 1 - \alpha \qquad \textbf{(2)}$$

The uncertainty band, δ, (confidence interval) at 95% confidence level $(\alpha = 5\%)$ for the estimator for the Mean meter factor, μ, is given by Equation 3.

$$\delta = 200 \cdot t_{\frac{\alpha}{2},n-1} \frac{s}{\overline{X} \cdot \sqrt{n}} \qquad [\%] \qquad \textbf{(3)}$$

Equation 1 gives an estimate for the scatter in the test results while Equation 3 gives an uncertainty band for the average of the test results.

Both these methods may in some cases require a large number of proving trials (more than 20) to give a valid meter factor. In other words, these methods have slow convergence. However, experience show that the average meter factor stabilises quite rapidly and varies little after 5 to 10 proving trials. A more rapidly converging method was given in [1] and repeated here for convenience.

The method is a two-step convergence method for the average meter factor where the criteria for convergence are:

- If there is less than ± 1/10 of the NPD repeatability requirement (± 0.0050%) change from previous calculated average meter factor, then perform a new proving trial
- and if there is less than ± 1/20 of the NPD repeatability requirement (± 0.0025%) change to the next calculated average meter factor, then there is convergence and this average meter factor is a valid meter factor.

If no valid meter factor can be established after 20 proving trials then a new proving sequence must be started.

Looking at the meter factors from each proving sequence, we see that the two last methods normally both give valid meter factors, see Figure 18. However, the preferred statistical method is to evaluate the uncertainty band at 95% confidence level for the estimator for the Mean meter factor, since this is the most robust method.

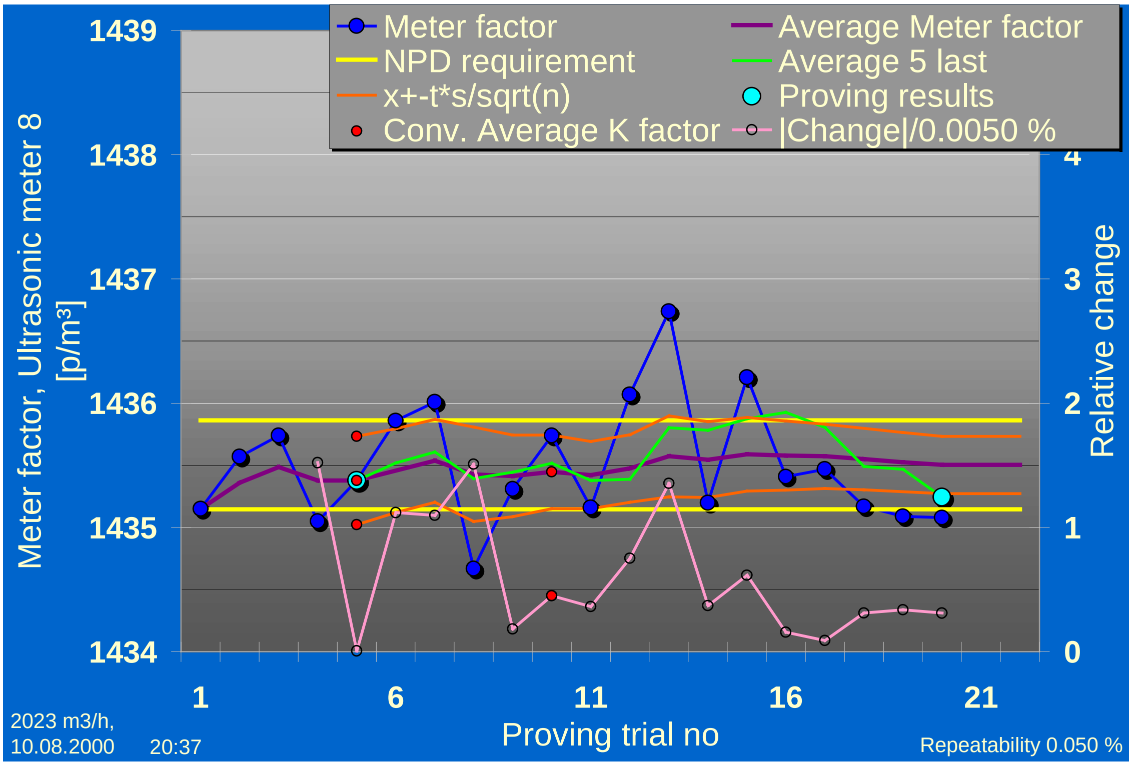

Figure 18. Typical variation in meter factor from single proving trials at normal loading flow rate. Statistical evaluation.

The stability of the average meter factor was very good during the test and a statistically determined meter factor could normally be achieved after 5 to 12 proving trials.

6.6 Using statistical method and comparing with turbine meter

After valid meter factors were achieved for all meter runs in operation during each loading operation, proving continued alternately for the ultrasonic meter in meter run 8 and the turbine meter in meter run 7. Proving was performed at normal loading flow rates throughout the rest of the loading operation. This was done in order to get as many test results as possible to enable comparison of proving results from the ultrasonic meter with those from the turbine meter, under similar process conditions.

Using the established proving method for a turbine meter could give some odd shifts in the meter factor from consecutive proving sequences and as many as 69% of the proving sequences were rejected. Because of this, it was decided to re-evaluate all the proving trials for the month of October 2000 using a statistical method. The method selected is based on the uncertainty band at 95% confidence level for the estimator for the Mean meter factor, given in Equation 3.

The valid meter factors for the ultrasonic meter established using these two evaluation methods were compared with the meter factors from the turbine meter in meter run 7, see Figure 19, 20, 21, 22, 23 and 24.

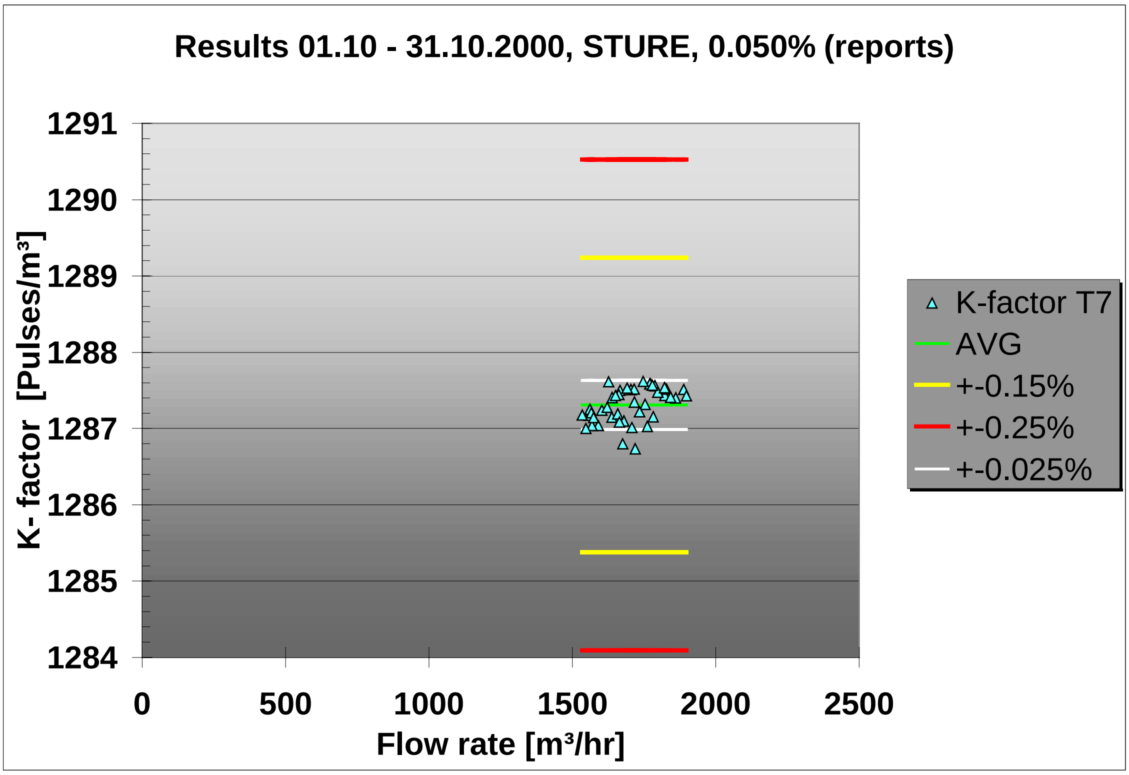

Figure 19. All valid meter factors during the test period 01.10 - 31.10.2000 for turbine meter in meter run 7.

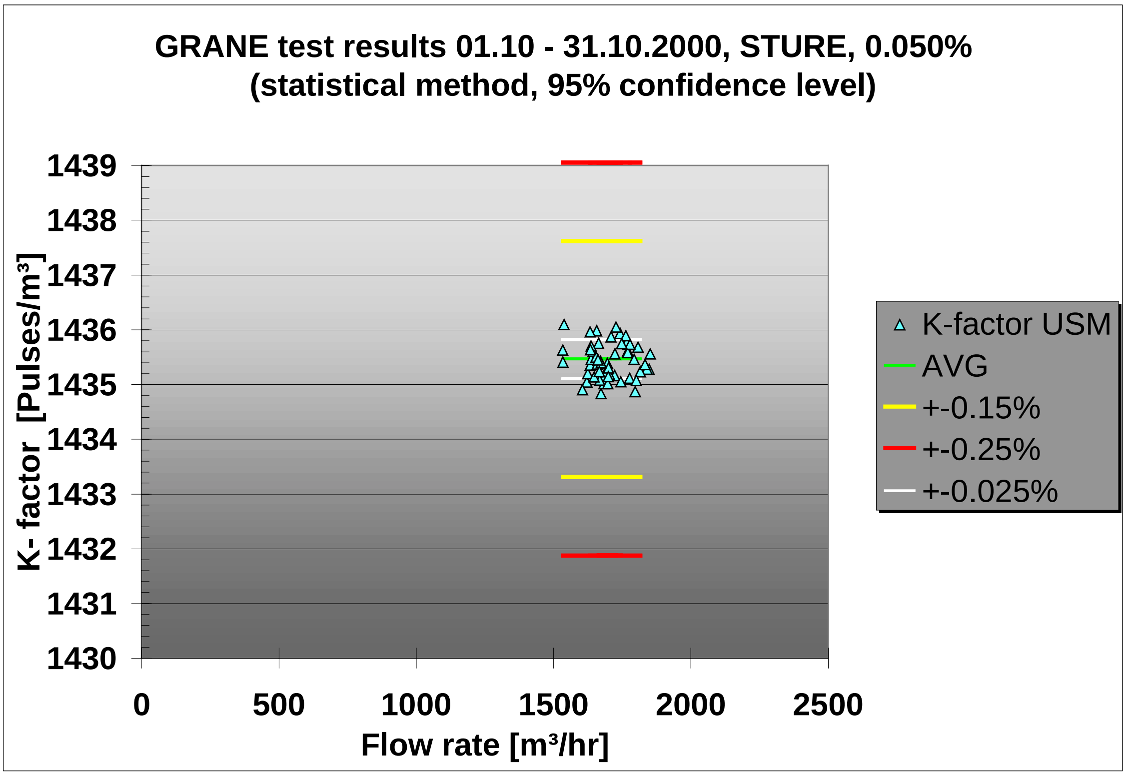

Figure 20. All valid meter factors during the test period 01.10 - 31.10.2000 using a statistical method for evaluation of meter factors.

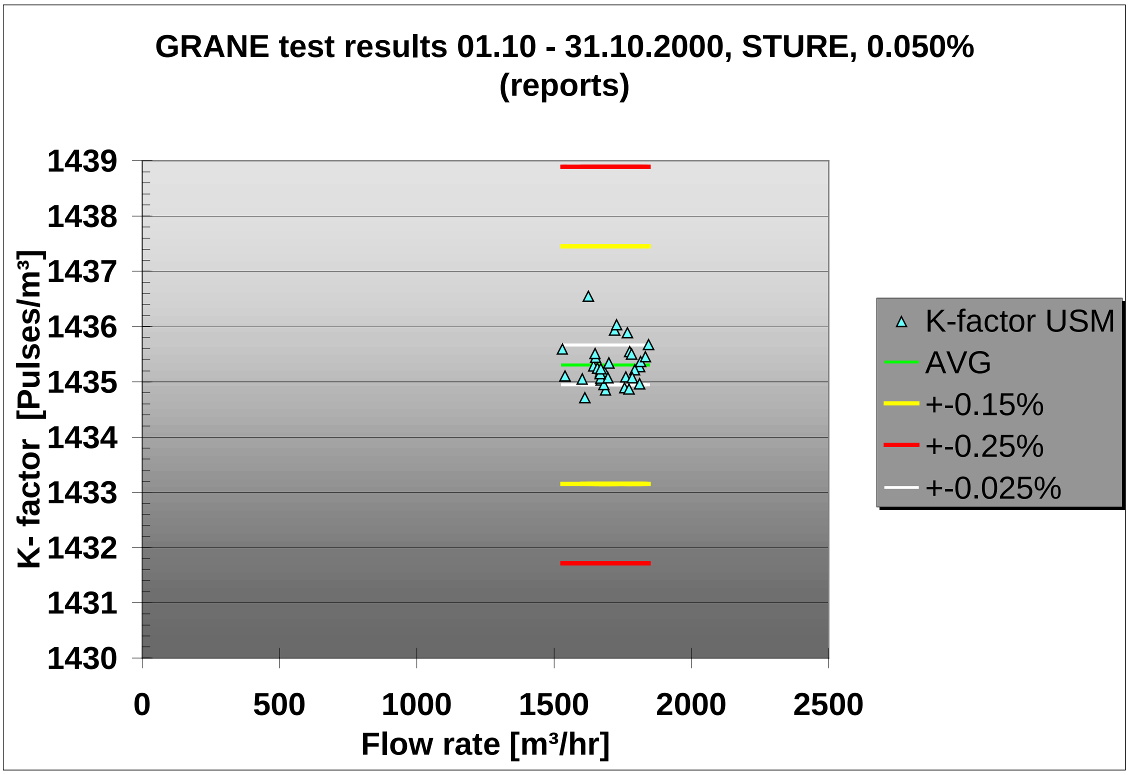

Figure 21. All valid meter factors during the test period 01.10 - 31.10.2000 using the established proving method.

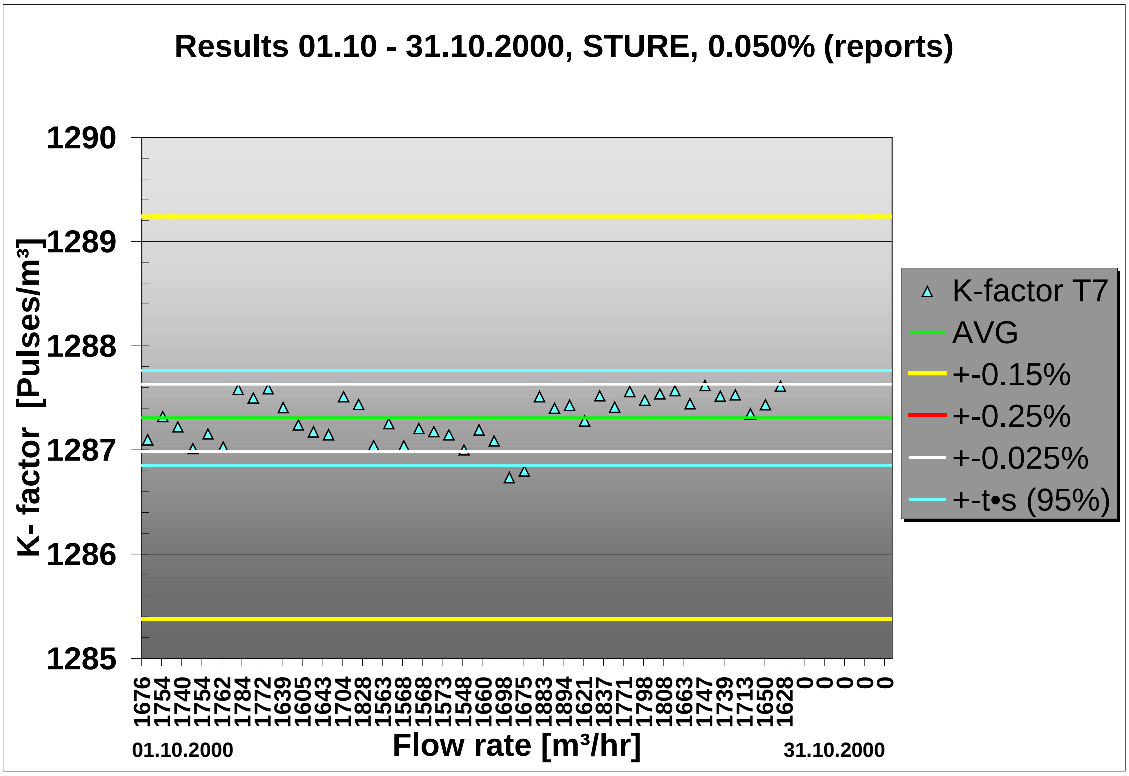

Figure 22. All valid meter factors during the test period 01.10 - 31.10.2000 for turbine meter in meter run 7.

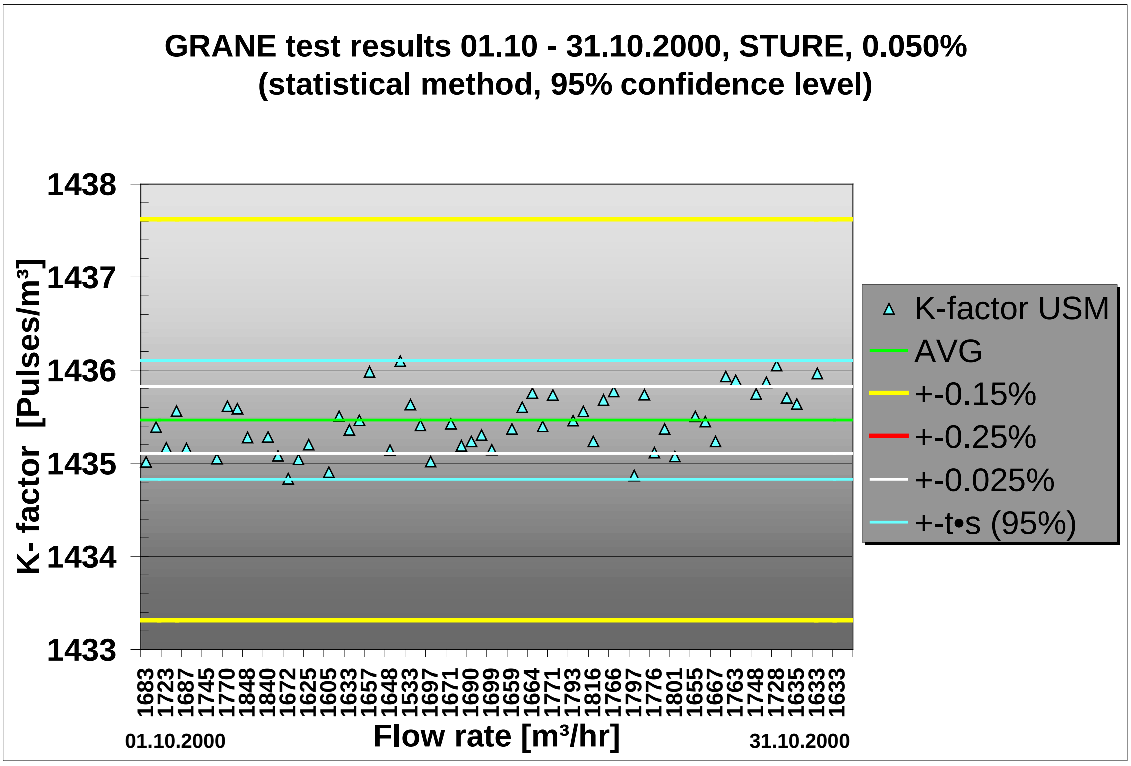

Figure 23. All valid meter factors during the test period 01.10 - 31.10.2000 using a statistical method for evaluation of meter factors.

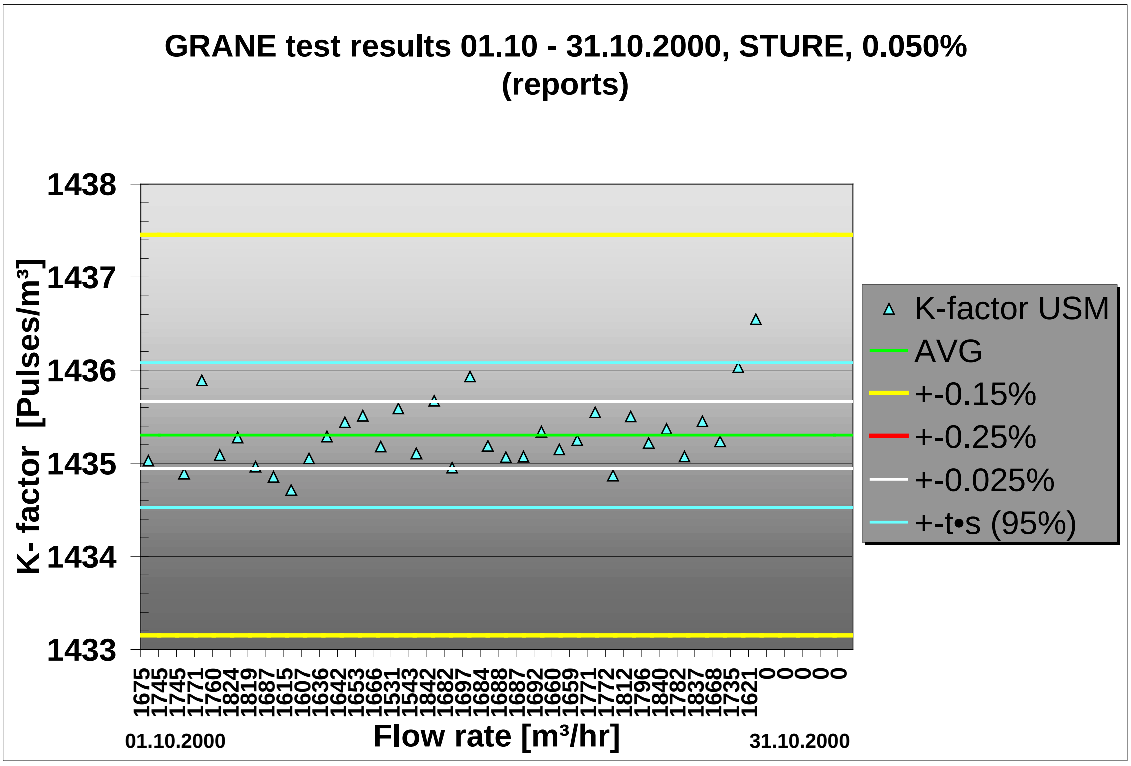

Figure 24. All valid meter factors during the test period 01.10 - 31.10.2000 using the established proving method.

The stability of the meter factor for the ultrasonic meter was excellent for the month of October 2000 compared with the long term stability requirement (control limits) for a turbine meter of ± 0.15%.

Using a statistical method for evaluating meter factors the stability (95% confidence interval of 0.089%) was more than 3 times better than the requirement and almost as stable as the meter factors for the turbine meter in meter run 7 (95% confidence interval of 0.071%). The statistical method also gave significantly (57%) more valid meter factors than the established proving method for a turbine meter using the same 944 proving trials.

Based on this evidence one can argue that the established proving method for a turbine meter is not the optimum method to use proving an ultrasonic meter against a pipe prover.

7 TESTING AT SPSE

The same 12" Krohne 5-path Altosonic V ultrasonic liquid flow meter that had been tested at Norsk Hydro's Sture terminal in Norway, was installed in one of the two test sections at the SPSE test site in Fos sur mer in France, see Figure 25.

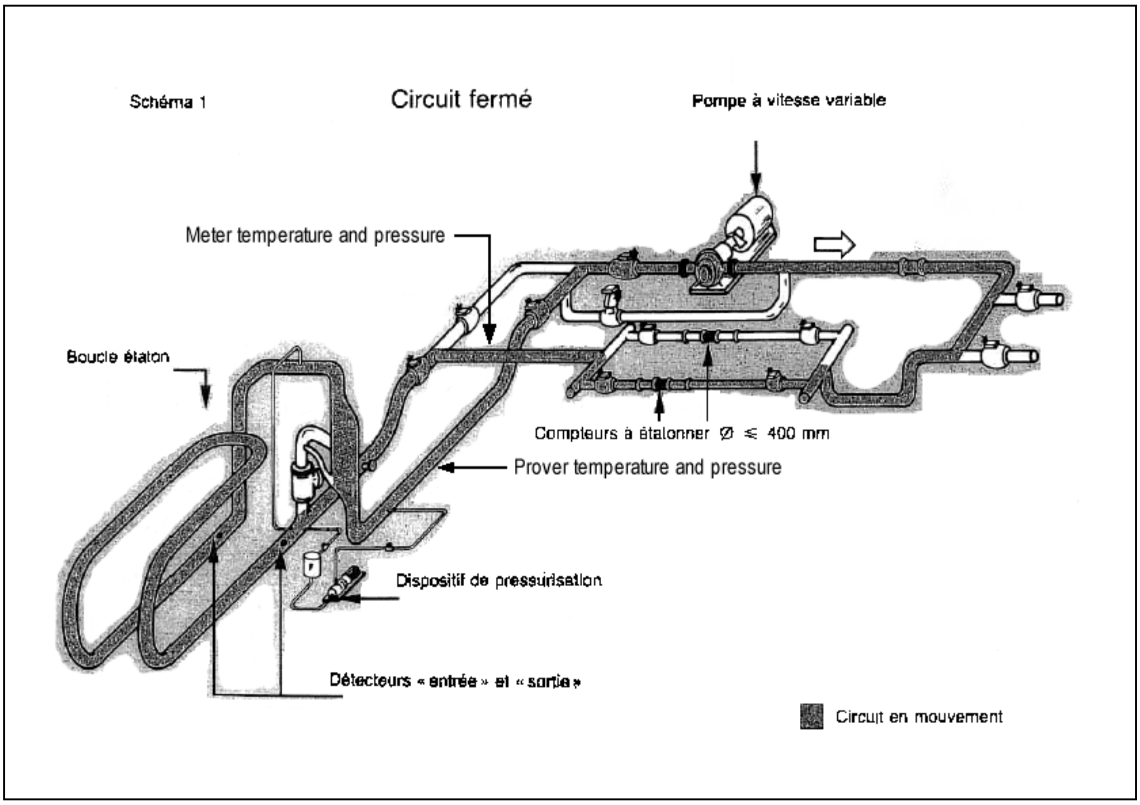

Figure 25. Test loop at SPSE test site in Fos sur mer in France.

The piping and prover in the test loop had no heat insulation or weather protection. The number and placement of temperature and pressure transmitters were not sufficient to in any way compensate for this lack of stable conditions, see Figure 25 and 26. It was therefor expected that there could be some problems obtaining good repeatability and reliable results at all flow rates during testing.

The uni-directional prover had volumes of 15 m^3.

The ultrasonic test meter from Krohne was installed without flow conditioner but with sufficient straight upstream piping to avoid significant swirl or cross flow through the meter.

The test series at the SPSE test site lasted from 23.01.2001 until 26.01.2001 and from 06.02.2001 until 07.02.2001 during which 222 proving trials were performed.

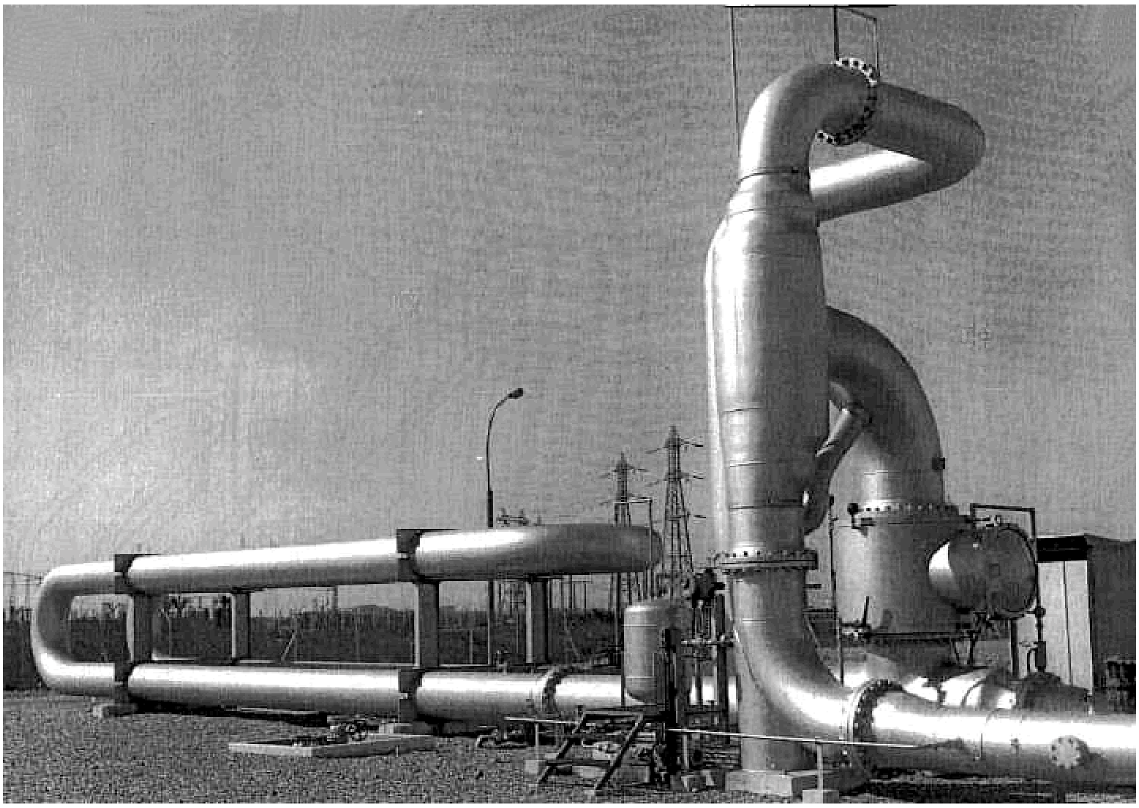

Figure 26. Uni-directional prover in test loop at SPSE Fos sur mer.

7.1 Test result summary

The tests at SPSE were strictly functional and demonstrated that the ultrasonic meter was able to measure and be proven for all tested values of kinematic viscosity between 7 and 584 mm^2/s (cSt) at flow rates from 235 to 2700 m^3/h.

The flow was slightly more stable and the energy of the pulsations in flow rate was smaller than during the Sture tests. This concurs with the higher kinematic viscosity and smaller variability in meter factor observed. However, for some flow rates more severe pulsation in flow rate could be seen.

Neither linearity nor repeatability could be demonstrated fully within the NPD requirements for a turbine meter over the entire flow range and viscosity range.

The temperature rise and the consequent viscosity drop during testing were very large due to the high viscosity oil. It was therefore very difficult to get five consecutive proving trials with sufficiently similar conditions to verify repeatability, not to mention linearity. See Figure 27 for a typical test series with kinematic viscosity changing from 415 to 215 mm^2/s during 20 consecutive proving trials.

However, by combining proving results from various test series the ultrasonic liquid flow meter was found to be fairly linear and within ±0.15%, over the flow range 235 to 2700 m^3/h for a large variation in kinematic viscosity (change of more than 100 mm^2/s).

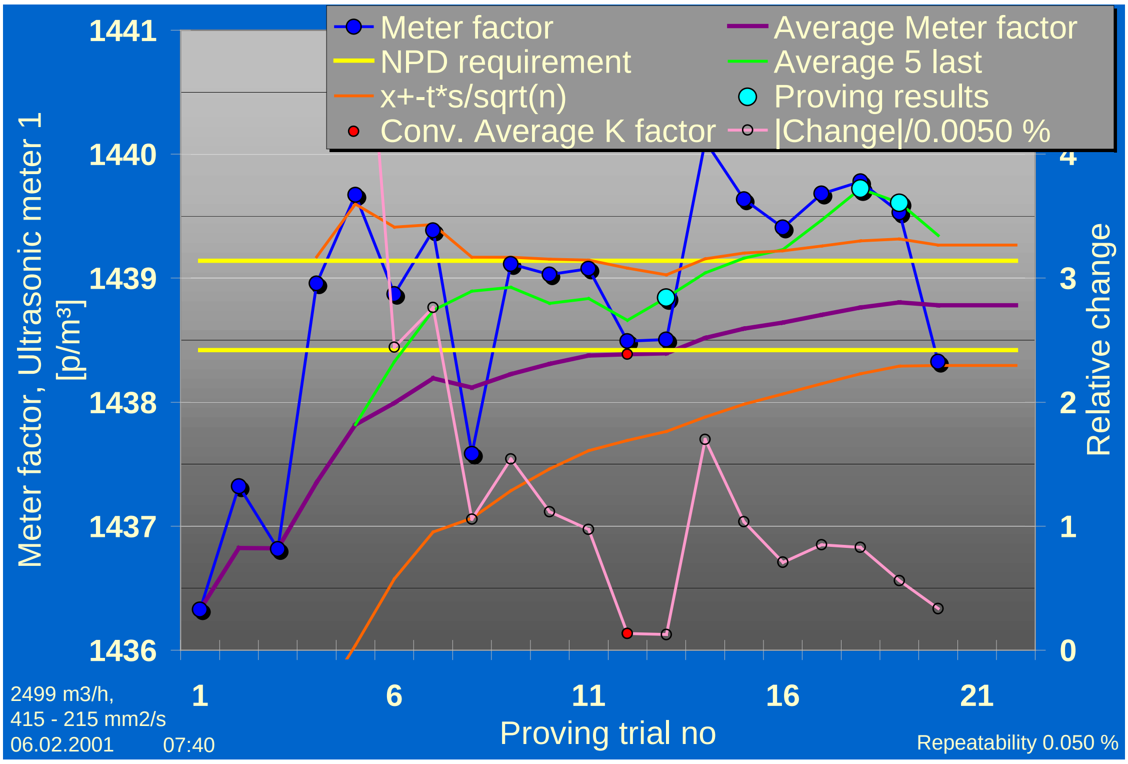

Figure 27. Statistical evaluation - typical variation in proving trial results at 2499 m^3/h and kinematic viscosity ranging from 415 to 215 mm^2/s.

7.2 Evaluation - combining proving results from various test series

All meter factors from all 8 test series at SPSE are plotted in Figure 28 and compared to the NPD linearity requirements for a turbine meter for kinematic viscosity ranging from 75 to 584 mm^2/s and flow rates between 235 and 2700 m^3/h, a total of 222 test results.

The repeatability varied a lot, sometimes within requirement and sometimes even way out.

The meter factors were over all fairly constant but showed many large variations. The linearity was acceptable at low kinematic viscosity below 140 mm^2/s (test 0 - 4) but not at high kinematic viscosity (test 5 - 7).

In Figure 29, the same results are plotted against flow rate. Above 1000 m^3/h, the meter factors for the ultrasonic meter were fairly constant while the large variations all occurred at lower flow rates.

In Figure 30, the same results are plotted against kinematic viscosity.

In Figure 31, the same results are plotted against Reynolds number (ReD). The meter factors were fairly constant but showed large spread at low Reynolds numbers.

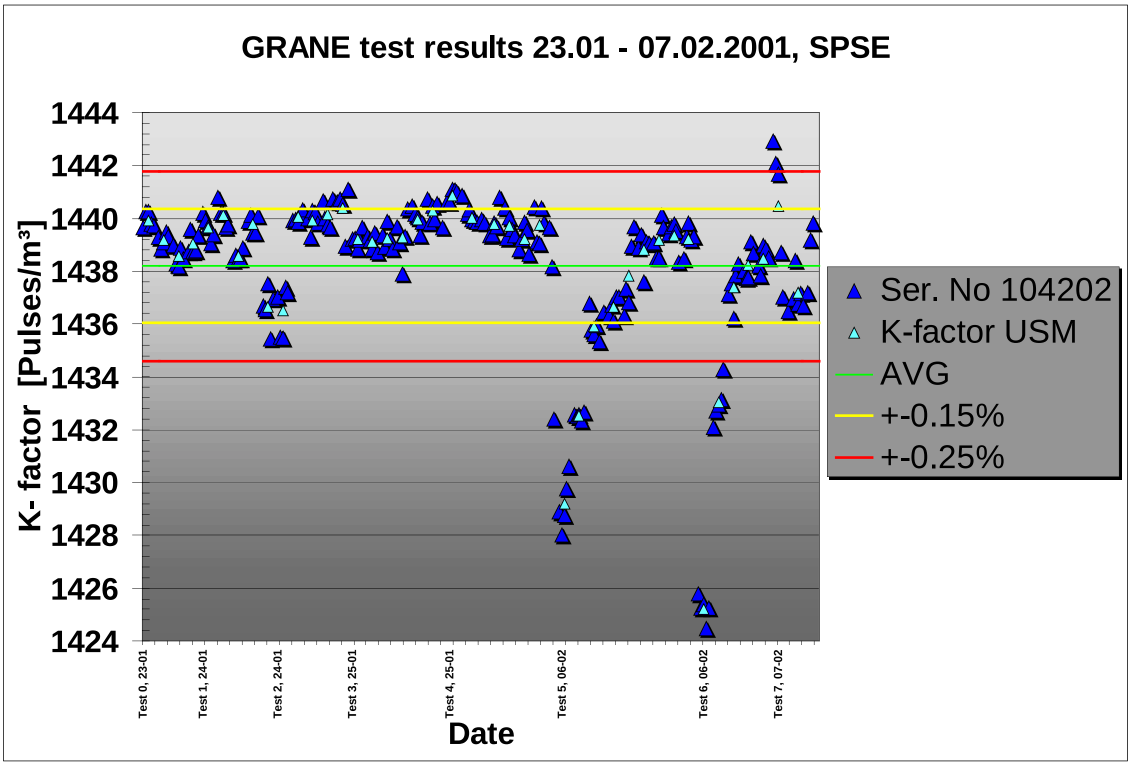

Figure 28. All meter factors from all 8 test series at SPSE.

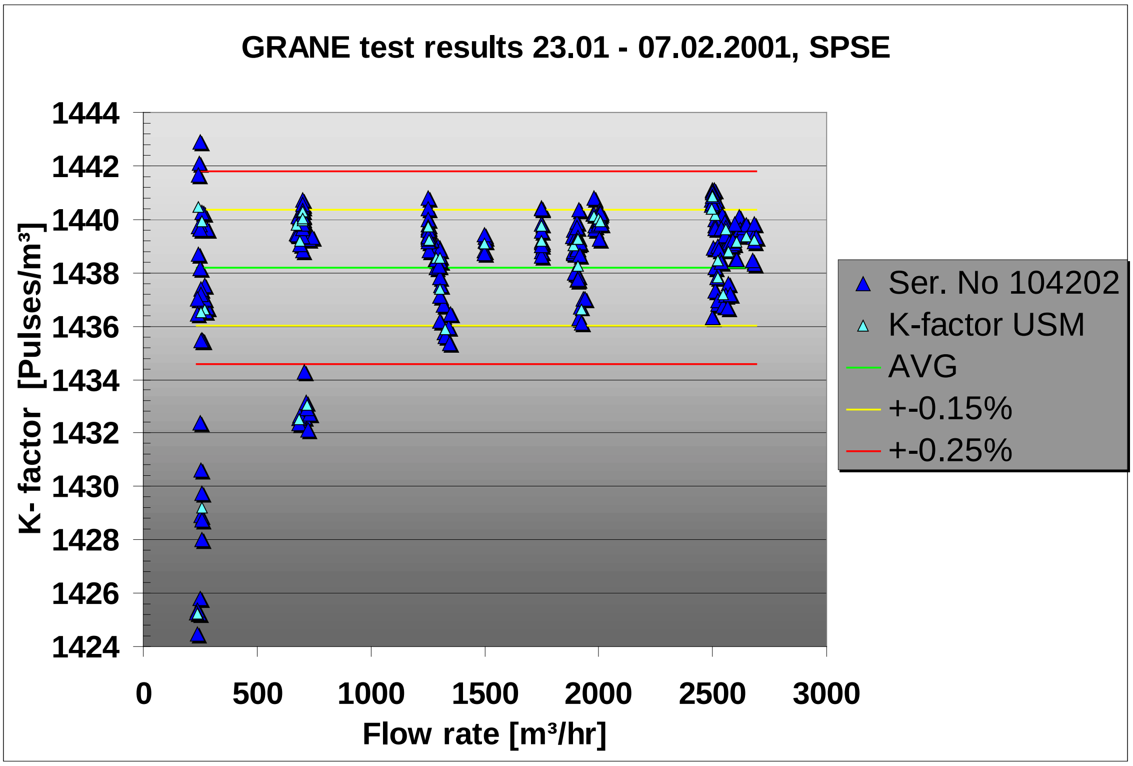

Figure 29. All meter factors from all 8 test series at SPSE.

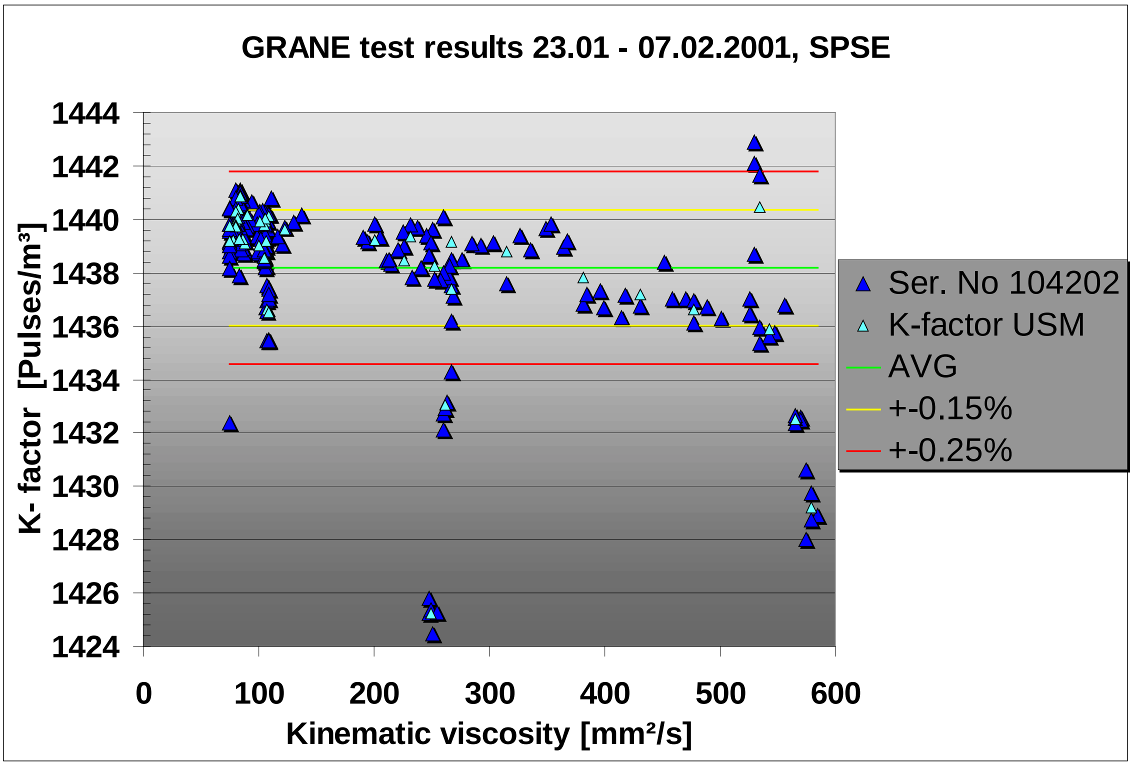

Figure 30. All meter factors from all 8 test series at SPSE.

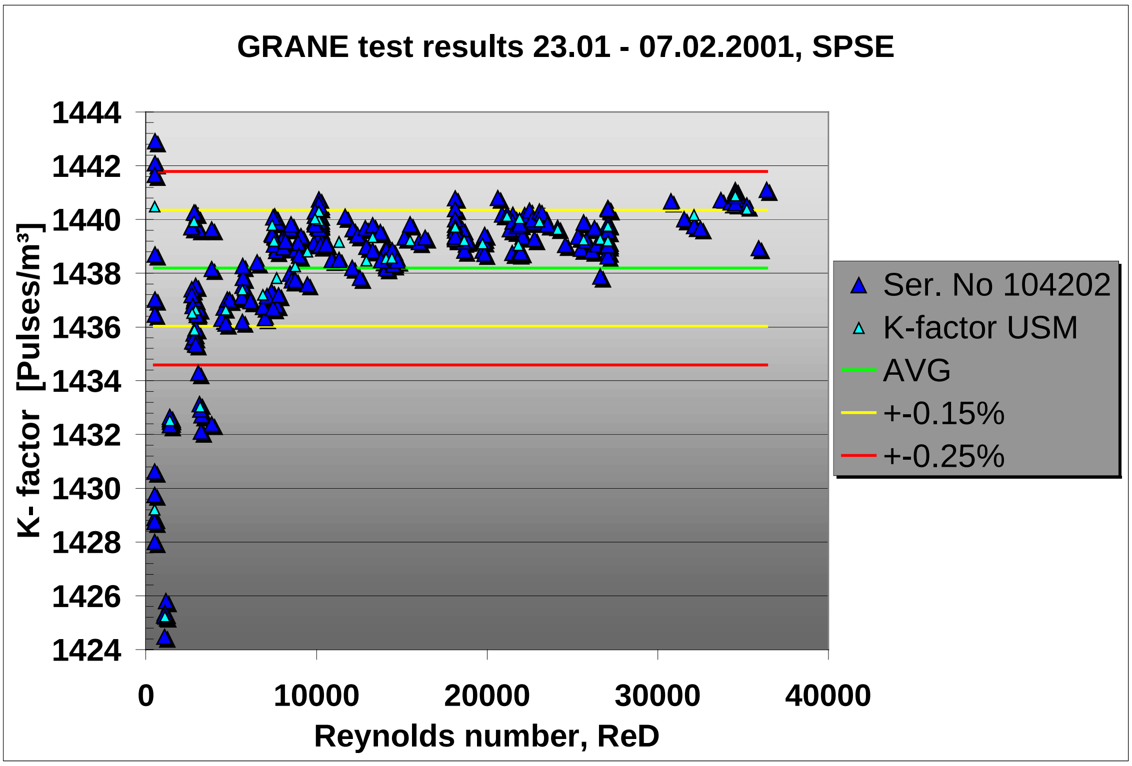

Figure 31. All meter factors from all 8 test series at SPSE.

Some meter factors below 1000 m^3/h have been removed in Figure 32:

a) When they are from the start of a test series starting with a cold prover and test loop.

b) When they are from after an abrupt change in flow rate where we could see the prover steel heating up the liquid going through.

This leaves 190 test results.

Now the meter factors for the ultrasonic meter were more constant since the questionable results all occurred at low flow rates and low Reynolds numbers.

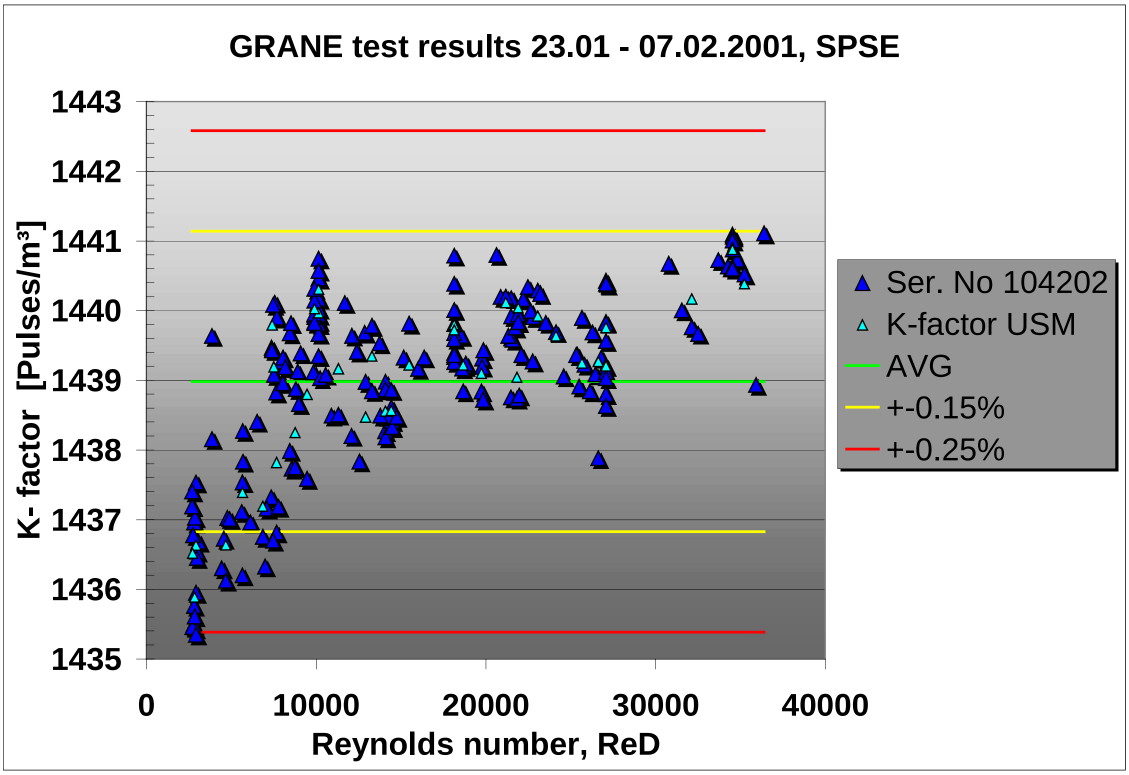

Figure 32. Questionable meter factors for flow rates below 1000 m^3/h removed from all 8 test series at SPSE.

There seems to be a trend in the meter factor both with flow rate and viscosity (and therefore with Reynolds number). For the same level of kinematic viscosity, the meter factor seems to increase with increasing flow rate while for constant flow rate the meter factor seems to drop as a function of increasing kinematic viscosity.

This is examined further in Figure 33 and 34 where the meter factors have been grouped together. In Figure 33 with respect to kinematic viscosity and in Figure 34 with respect to flow rate, for a selection of data best representing the operating conditions of the Grane export station.

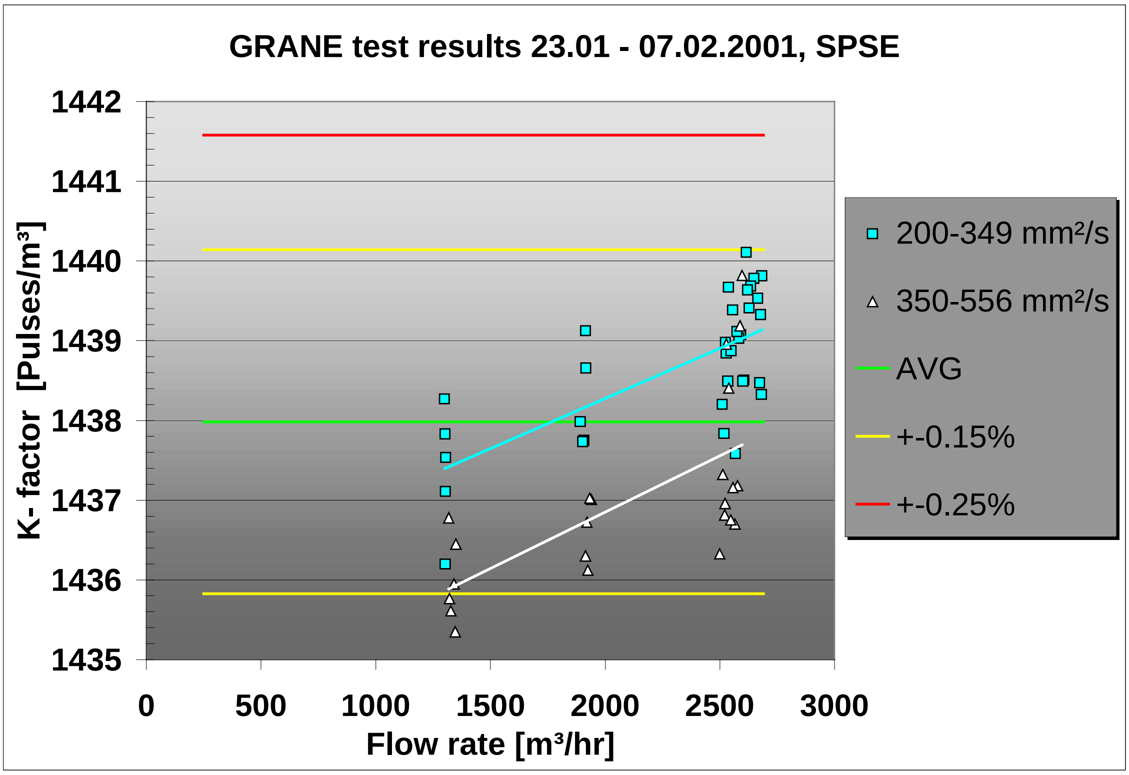

Figure 33. Questionable meter factors for flow rates below 1000 m^3/h removed from all 8 test series at SPSE. Selection of data.

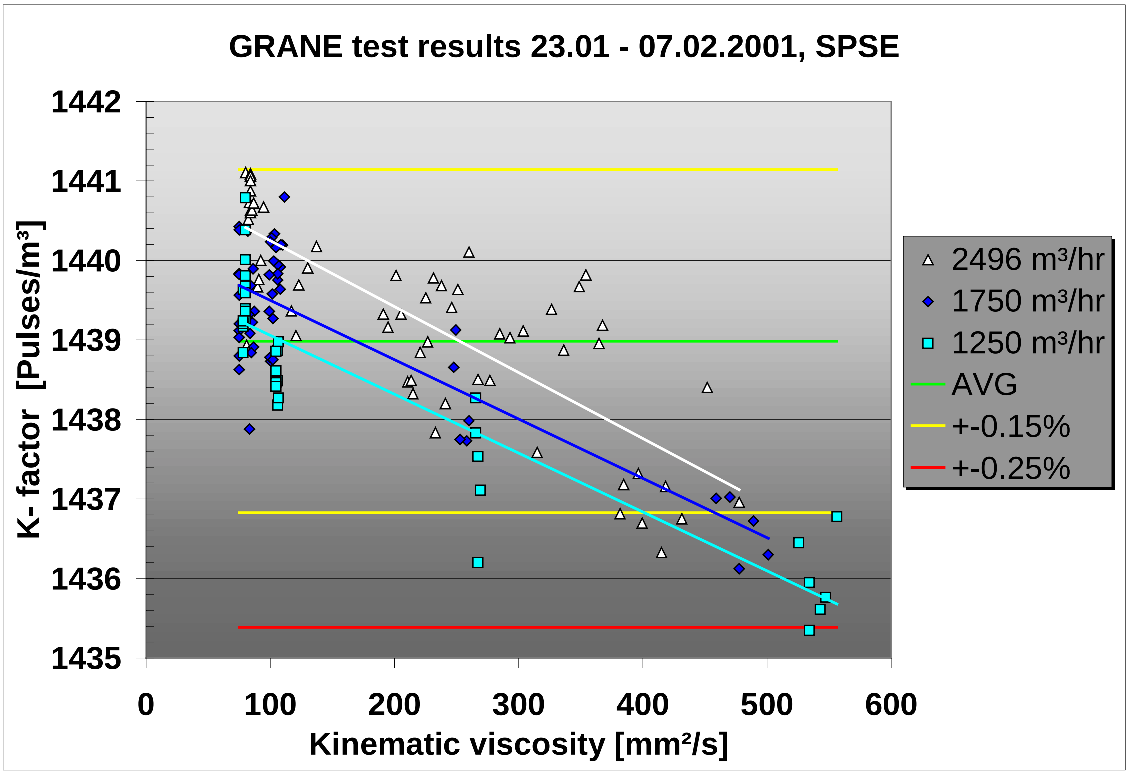

Figure 34. Questionable meter factors for flow rates below 1000 m^3/h removed from all 8 test series at SPSE. Selection of data.

From Figure 33 one can see that the meter factors for the ultrasonic meter were fairly linear and within ±0.15%, over a large flow range and a large variation in kinematic viscosity (change of more than 100 mm^2/s in kinematic viscosity).

The gradient of the curves indicate a need for reproving with changing flow rate and that the range of flow rate where the same meter factor is valid diminishes with increasing kinematic viscosity.

In Figure 32, the meter factor trend with Reynolds number could indicate that the Reynolds number compensation implemented in the KROHNE flow computer was not sufficient at low Reynolds numbers.

CONCLUSIONS

Using a statistical method to determine meter factors for the ultrasonic liquid flow meter clearly improves proving performance to give performance that are comparable to a turbine meter, for normal crude oil.

A metering system with an ultrasonic liquid flow meter and large pipe prover has good long-term reproducibility for normal crude oil.

The large variations in meter factors especially at low Reynolds numbers (ReD) indicates a deficiency of the Reynolds number compensation implemented in the KROHNE flow computer. The Reynolds number compensation should not be used in metering systems with prover.

The experience and proving results from the tests at the Sture fiscal metering export station no. 1 clearly demonstrates the feasibility of operating a 12" Krohne 5-path ultrasonic liquid flow meter on normal crude oil, within fiscal uncertainty requirements, using a large volume bi-directional prover and statistical evaluation of meter factors. The recommended statistical method to use is the uncertainty band at 95% confidence level for the estimator for the Mean meter factor (Equation 3).

The results from the tests at SPSE demonstrate the feasibility of operating a 12" Krohne 5-path ultrasonic liquid flow meter on heavy crude oil. Using a large volume bi-directional prover and statistical evaluation of meter factors, it is considered feasible to operate the ultrasonic liquid flow meter well within fiscal uncertainty requirements, on heavy crude oil.

ACKNOWLEDGEMENT

I would like to thank FMC Kongsberg Metering Systems and Krohne Altometer for providing data from their respective parts of the test system.

REFERENCES

[1] Folkestad Trond, "Proving a fiscal 5-path ultrasonic liquid meter with a small volume ball prover. Can it be done?" Proc. of the 17th North Sea Flow Measurement Workshop, 1999. 25.10.1999, Norway.

[2] Folkestad Trond, "Flow test - Oseberg Sør fiscal metering system for crude oil - Stord". Internal report Norsk Hydro E&P, 09.08.2000.