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EFFECTS OF FLOW CHARACTERISTICS DOWNSTREAM OF ELBOWS ON ORIFICE METER ACCURACY

Lecturer:

Mr. Kamal Botros
Nova Husky Research Corporation

EFFECTS OF FLOW CHARACTERISTICS DOWNSTREAM OF ELBOW/FLOW CONDITIONER ON ORIFICE METER

U. Karnik, W.M. Jungowski and K.K. Botros
NOVA HUSKY Research Corporation
2928 - 16th Street N.E.
Calgary, Alberta Canada
T2E 7K7

1.0 INTRODUCTION

Flow conditioners are used upstream of orifice meters to eliminate flow non-uniformities and swirl and thereby facilitate accurate metering within a shortest possible meter run. The tube bundle is the most commonly used flow conditioner in natural gas metering. The two important standards providing specifications on the design and locations of the tube bundles are the ANSI/API 2530 and the ISO 5167. An important specification is the straight length section between the piping element generating the disturbance and the flow conditioner (L_1), and that between the flow conditioner and the orifice plate (L_2). These specifications are quite different in the two standards which has led several experimenters and the gas industry to heighten research to study the effects of tube bundle location on orifice meter accuracy.

The available data produced to date, particularly those dealing with elbows generating the flow disturbance upstream, are numerous. Almost all of the published reports and papers attempt to specify a location of the tube bundle between the elbow and orifice meter which gives zero deviation in the orifice discharge coefficient (C_d). The term "cross-over point" is often used to define this optimum location; a shorter distance to the orifice causes a negative ΔC_d while a longer distance causes a positive one.

For this *cross-over* point, contradicting values of L_2/D started to appear (D is the pipe diameter). This was to be expected since the cross-over point is not a unique point for all installations. It should depend on the flow Reynolds number, total length of the meter run, orifice β–ratio, meter tube roughness, and instrumentation among other factors.

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For example, the EC program conducted at Gasunie and NEL for testing the performance of tube bundles in *good flow conditions* has revealed that the cross-over point lies between 10 D and 15 D [1,2]. A similar observation has been made by Brennan, et. al. [3] following experiments performed at NIST (Boulder). Extensive tests by McFaddin, et. al. [4] revealed that, for their meter run, a cross-over point at 17 D was obtained for all β-ratios and was independent of the location of the bundle w.r.t. the disturbance (two elbows in-plane separated by 12 D). Mean velocity profiles at 7 D and 27 D were also presented in [4] which show that although the mean profile at 27 D is nearly fully developed, this was not the optimum position and ΔC_d for the 0.67 and 0.73 orifice plates was around +0.5%. Unfortunately, the velocity profile at 17 D (the cross-over point) was not presented.

Sliding tube bundle experiments were conducted in the low pressure nitrogen loop (724 kPa, Re = 9 x 10^5) of the GRI Meter Research Facility at SwRI [5]. The cross-over point for a 0.75 orifice plate was ≈11 D for 45 D meter run and ≈15 D for 19 D meter run. Velocity profiles measured at different locations revealed that the flow is still far from fully developed in the 45 D meter tube length indicating that there are other factors contributing to the zero shift other than a fully developed velocity profile.

Experiments conducted on the 2" water facility at NIST in Gaithersburg [6] showed that with a tube bundle located at L_1 = 5.7 D from elbow outlet, a cross-over point was obtained at ≈12 D for three β-ratios (0.383, 0.5 and 0.75). Measurements of the streamwise and radial mean and turbulent velocity profiles upstream and downstream of the tube, obtained by LDV, showed that the tube bundle produces higher turbulence levels immediately downstream and that the levels reach fully developed (Laufer) values at 27.3 D from tube bundle outlet. Unfortunately, the mean and turbulent velocity profiles were not presented at the 12 D location which could possibly illuminate the contribution of the turbulence levels to the zero deviation of C_d.

In this paper an attempt is made not to produce another cross-over point for an elbow/tube bundle configuration, but to find the underlying mechanistic principles contributing to the optimum location of the tube bundle w.r.t. the orifice meter. Tests were conducted on NOVA's high pressure test facility at Didsbury, Alberta, Canada. The flow Reynolds number based on pipe diameter was ≈8 x 10^6. Two elbows in-plane separated by 10 D represented the disturbing element, and a 2.5 D long tube bundle (19 tubes) sliding along the pipe was used in the experiments. Mean velocity profiles were obtained by means of a Pitot-static tube traversing in two planes. Tests on a similar configuration were conducted in a low pressure air loop where profiles of the mean velocity and the Reynolds stresses were obtained by hot-wire anemometry.

In this paper, results from both the high pressure and low pressure facilities are presented and a preliminary conjecture on the effects of turbulence and shear stress distribution downstream of a tube bundle on the C_d shifts is proposed. An attempt is made to correlate the contribution of the mean velocity profile, turbulence level, and shear stress to the location of the cross-over point.

2.0 EXPERIMENTAL FACILITIES

High Pressure Facility

A schematic of NOVA's Gas Dynamic Test Facility at Didsbury, Alberta, Canada is shown in Figure 1. High pressure natural gas is diverted from the mainline into the test loop by means of a centrifugal compressor or in a free flow mode. The maximum operating pressure at the facility is 6450 kPa and the maximum Reynolds number in the test section of a 100 mm diameter was ≈ 8 x 10^8. The test section is shown in more detail in Figure 2. Two orifice fittings are installed in series, the one upstream being the reference meter. This reference orifice meter is preceded by 44 D straight meter run of internal roughness ≈5.0 µm Ra, and two reducers 200 x 150 mm and 150 x 100 mm with 16 D separation. Two elbows in-plane with 10 D separation are shown in Figure 2. Both in-line tube bundle or a sliding tube bundle were used upstream of the second (tested) orifice meter. The second orifice fitting is replaced with a traversing mechanism holding a standard Pitot-static tube (PST) when measuring the axial and transverse velocity profiles. High-accuracy transmitters were used in measuring the differential pressures across the flange-tapped orifices and also the static pressure to an accuracy of ±0.1% of span. As for the PST, the differential pressure transmitter connected to the stagnation and static holes is calibrated in the range of 1 to 12.5 kPa, while the static holes (for radial velocity component) differential transmitter was calibrated between - 1.5 to + 1.5 kPa. All velocity profiles were normalized by the instantaneous mean flow velocity obtained by the reference orifice meter upstream. Temperature accuracy is within ±0.2% of the span. A gas chromatograph is connected on line to give detailed gas composition of the gas during the course of the experiments.

Low Pressure Facility

The low pressure test facility consists of a 100 mm diameter test section, calibrated sonic nozzle and 30 kW blower. Air is driven through the test section in a suction mode as shown in Figure 3a. Experiments were conducted with a sonic nozzle securing mean velocity of approximately 14.7 m/s through the test section, resulting in a Reynolds number of ≈0.9 x 10^5. Mean and turbulent velocity profiles as well as shear stresses were obtained by x-wire miniature probe with a TSI anemometer (IFA 100). The x-wire was calibrated in a TSI calibrator. Figure 3a shows the test section for a fully developed turbulent flow measurements at ≈68 D downstream of a sprenkle plate following the inlet filter. This test section was used to evaluate the performance of the 19 tube flow conditioner in a good flow condition. Figure 3b shows the test section altered with an upstream elbow of radius 1.5 D and an in-line tube bundle. The x-wire was traversed across two perpendicular planes at 19 D from elbow outlet, for different location of the tube bundle. Figure 3c shows similar configuration with a sliding tube bundle and an orifice meter located at 19 D from the elbow outlet. The reference flow is measured by the calibrated sonic nozzle downstream. All pipes used in the low pressure experiments were clear PVC pipes with internal roughness around 0.25 μm (Ra). The elbow, however, is exactly the same steel elbow used in the high pressure facility.

3.0 RESULTS FROM HIGH PRESSURE FACILITY

At the high pressure test facility the Pitot-static tube was traversed in a vertical and horizontal plane. The measurements were taken at various distances from the second elbow: a) without any flow conditioner, b) 4 D downstream of the tube bundle outlet with the tube bundle at different positions from elbow outlet, c) with fixed position of the tube bundle inlet at 2 D from the elbow and PST at different locations downstream, and d) with fixed position of the PST at 19 D from the elbow and moved tube bundle.

The following observations were made:

re: a) the profiles acquired close to the second elbow outlet were typical for a single elbow configuration, they became flat at about 16 D and then more elongated at 27.6 D but still deviating from the reference profile which was measured upstream of the elbows in the straight pipe (Figure 4);

re: b) velocity profiles varied significantly with increasing distance between the elbow and tube bundle outlets until around 12.5 D and then the pattern was primarily determined by the distortion by the tube bundle itself (Figure 5);

re: c) the profiles at 6 D from the tube bundle outlet revealed strong distortions and at 27.6 D became rather uniform but more elongated than the reference profile (Figure 6);

re: d) with decrease in distance from 15 to 5 D between the elbow and tube bundle outlets, the profiles changed from an underdeveloped character to a more elongated one (Figure 7).

In order to correlate the velocity profiles to the cross-over point, the PST was replaced by an orifice plate and the flow rate was metered with various positions of the tube bundle as in case d). As Figure 8 shows, the cross-over occurred around L_2 = 8D for both orifice plates (β = 0.4 and 0.74). However, the corresponding vertical and horizontal profiles were underdeveloped compared to the reference profile. In order to characterize the reference profile, the distribution of the wall static pressure along the upstream pipe of the reference meter was measured. The reference profile was found previously when the reference meter was substituted with the pitot tube. Figure 9 shows a quasi-linear pressure drop along the pipe indicating that the flow is fully developed. Utilizing Darcy friction factor f = 0.0131 evaluated from the pressure drop and the approximate relation $n = 1/\sqrt{f}$ [14] between the exponent n characterizing the velocity profile and f, n = 8.74 was found. This relation, however, overestimates n by about 10%. On the other hand, the fit to the experimental reference profile (Figures 4 through 7) gave n = 7.83. Both results appear to agree well.

A few conclusions can be drawn from the study performed at the high pressure facility. A comparison of case a) with c) indicated that an enhancement of turbulence by the tube bundle significantly increased the rate of the velocity profile modification, even to the overdevelopment. Case b) showed that at a certain distance, distortion caused by the tube bundle dominates the effect caused by the elbows. This confirms earlier observations in [2,3,4] that the upstream distance L_1 has less effect than L_2 on metering error. However, placing the tube bundle close to the elbow outlet tends to freeze the incoming velocity profile and defeat the purpose of the tube bundle. Case d) and metering with the orifice plate revealed that the cross-over point can occur with different mean velocity profiles. This implies that some other factors contribute to the outcome of flow metering. The analysis of momentum equations pointed to the distribution of the Reynolds stresses and therefore gave an incentive to measure turbulence. Preparation for these measurements at the high pressure facility is currently underway.

In the meantime, in order to simplify experimental procedures and understand the flow characteristics, tests were conducted on the low pressure test facility. It is believed that these results could be scaled to the high pressure/high Re flows.

4.0 RESULTS FROM LOW PRESSURE FACILITY

4.1 Reference Profiles

Reference profiles were obtained, following a development length of approximately 68D, with the use of a miniature x-wire probe (see Figure 3a). The average velocity for this flow was around 14.7m/s resulting in a Reynolds number of $\approx 0.9\times10^5$. It can be seen from Figure 10 that the mean axial velocity profiles are nearly axi-symmetric and that the measurements are compatible with the power law

$$\frac{U}{U_{max}} = \left(\frac{y}{R}\right)^{1/n}.$$

A log-log plot of (y/R v/s U/Umax) revealed that the value of n in the above power law is ≈ 7.4. Measurements close to the wall and near the centerline were excluded for the regression. The "expected" value of n for a smooth pipe at $Re=0.9\times10^5$ is around 7.0. Thus, the present profile may be regarded to be slightly under-developed.

It has been shown, analytically [7] and experimentally [8,9], that for a fully developed flow the distribution of the turbulent shear stress (τ_t) across the pipe diameter is linear and its extrapolation to the wall would result in an estimation of the wall shear stress. Figure 11 shows our measurements of the turbulent shear stress $\overline{uv} = \tau_t/\rho$. The distribution is clearly linear. This indicates that, for all practical purposes, the flow is fully developed. The shear stress is zero at the center as expected and on extrapolating this distribution to the wall, the wall shear stress (τ_w/ρ) is estimated to be approximately $0.42 m^2/s^2$ resulting in a friction velocity (u_*) of 0.65m/s. Thus, if the measured wall shear stress is used to normalize the data, the shear stress distribution (Figure 12) is representative of a fully developed flow. Additionally, the distribution of the correlation coefficient ($\overline{uv}/u'v'$) is akin to that observed in a fully developed flow [8,9] where u' and v' are the rms values of the fluctuating axial and radial velocities. The correlation coefficient reaches an asymptotic value of approximately 0.43 near the wall. This value was measured as 0.4 and 0.5 by [9] and [8] respectively. The correlation coefficient is usually approximated to be around 0.45 for a boundary layer [10].

The axial and radial rms turbulent intensities, presented in Figure 13 are found to be comparable to Laufer's data [8]. The axial intensities appear to be slightly higher, however, a similar observation was made by Lawn [9], who measured intensities higher than those measured by Laufer [8] and those measured in the present experiments.

Thus, measurements at the reference location appear to indicate that, for all practical purposes the present flow is fully developed. Apart from providing details of the reference velocity field, these measurements have also served as a test of credibility for the data acquisition and post processing of the hot-wire anemometer signals.

4.2 Measurements Downstream of a Tube Bundle in Good Flow Conditions

Measurements downstream of a 19 tube tube bundle (circular pattern, d_i=18 mm, d_0=20 mm, 2.5D long) were obtained with the above reference profile as an input.

The mean axial velocity profiles at various locations downstream of the tube bundle are shown in Figure 14, normalized by the maximum measured velocity. Allowing for experimental inaccuracies, these profiles indicate that, after the initial decay of the jets/wakes generated by the tube bundle, the velocity profiles are nearly compatible with the reference profile (n=7.4) after 6 pipe diameters.

Profiles of the axial and radial rms turbulent velocities (normalized by the maximum velocity), at locations downstream of the tube bundle, are shown in Figures 15a and 15b, respectively. As expected, the turbulence intensities are maximum at the location closest to the tube bundle. These intensities decay at downstream locations to a level below that at the reference location and exhibit a growth further downstream. A similar behavior, on the centerline, has been observed by Morrow et. al. [17] in their sliding vane measurements. In their case, the tube bundle was placed downstream of a single elbow. The variation of the normal stresses on the centerline with downstream location, shown in Figure 16, indicates that the position of the minima is at 10 D from tube bundle outlet

This behavior of initial decay and subsequent growth of the normal stresses is consistent with the physics of the flow. Initially, the tube bundle generates high normal stresses (turbulence) due to the shear of the jets/wakes generated. As these jets/wakes coalesce, turbulence decays according to a power law in a manner similar to grid turbulence (Sreenivasan et al. [11], and Warhaft, [12]). This decay dominates the production of the pipe boundary layers until a balance is reached. Subsequently, turbulence grows and, in the case of a pipe flow, it should be expected to reach the fully developed magnitude asymptotically. This behavior of initial decay and subsequent growth in the presence of a uniform shear, has also been documented in the wind tunnel experiments of Tavoularis and Karnik [13]. However, in their case, due to the presence of a uniform shear, turbulence continues to grow downstream.

It may be worthwhile to note that the initial rate of decay of grid turbulence is dependent on the mesh size ($M = d_i$ in our case) of the grid and on the initial Reynolds number ($Re_M = UM/\upsilon$). Since decay of energy is mainly attributed to the draining of energy from the large eddies towards the smaller eddies via inertial interactions [14], a smaller mesh size would imply a quicker decay of energy. Also, in terms of the initial Reynolds number, a higher Reynolds number implies lower viscous dissipation due to either lower kinematic viscosity or a slower energy transfer due to larger scales (larger mesh size). This is evident from the measurements of Batchelor and Townsend [15] (Re_M upto 4.4×10^4) and those of Kistler and Vrebalovich [16]($Re_M = 2.4 \times 10^6$).

Measurements of the turbulent shear stress (Figure 17) reveal that the linear distribution of the incoming reference flow has been distorted. Initially, the shear stress changes sign, as expected, at locations of the jets/wakes. The shear stress is high at the locations of the maximum velocity gradients and the change of sign is at the location where the mean velocity gradient is zero. Further downstream, the shear stress begins to re-organize itself. The magnitude of the shear stress is low in the core of the flow due to a lower mean velocity gradient and increases towards the pipe walls. Further downstream, at about x/D=13, the shear stress appears to be re-aligning itself with the reference shear stress distribution (shown as solid line). Hence it is evident that although the mean velocity profile appears to be fully developed, the non-linear shear distribution indicates otherwise.

4.3 Measurements Downstream of a Tube Bundle with a Single 90^o Elbow

As mentioned earlier, these measurements were conducted to simulate the high pressure facility and understand the contribution of turbulence to metering error. The major differences in the two facilities are the working pressure, test fluid and the pipe Reynolds number. The present measurements were taken downstream of a tube bundle, described earlier, with the velocity profile from a single 90^0 elbow (r=1.5D) as in input.

Mean axial velocity profiles for the three different locations of the tube bundle with respect to the elbow in a 19D meter run are shown in Figure 18. The velocity profile at the location of the orifice plate appears to be dependent on the distance of the tube bundle from the elbow. For locations closest to the elbow (L_2=10 D), the reminence of the effect of the elbow is evident whereas at the location farthest from the elbow (L_2=4 D), the velocity profile downstream of the tube bundle is relatively flat indicating that the effects of the elbow are sufficiently diminished.

The above can also be concluded from the velocity profiles obtained at the high pressure facility. However, it appears that comparison of the velocity profiles in the two situations may not be possible due to differences in the Reynolds number. As mentioned earlier, the dissipation due to viscous action is less at higher Reynolds numbers and hence one could speculate that the effects of the elbow and tube bundle would diminish at downstream distances which are longer than those in the case of lower Reynolds numbers. This can be seen from the fact that at the high pressure facility (high Re), for L_2=4 D, the wakes/jets of the tube bundle are clearly detected (Figures 6 and 7), however, in the case of the low pressure facility for a similar configuration, there is no evidence of the presence of these wakes/jets.

As observed in the case of the tube bundle in good flow conditions and by Morrow et. al. [17], the axial and radial turbulence intensities in the present case are found to be lower than the reference values as seen in Figures 19 and 20. The shear stress (Figure 21) also exhibits a non-linear distribution similar to that seen in the case of a tube bundle in good flow conditions. It is worth mentioning at this point that the gradient of the shear stress away from the centerline appears to be greater than that for the reference flow.

In order to determine the cross over points of the C_d shift, the tube bundle pulling mechanism used in the high pressure facility was utilized for the present measurements. The orifice plate (β=0.44) was located at 19D from the elbow and the flow was metered by means of a calibrated sonic nozzle. In order to obtain a pressure drop across the orifice plate within the range recommended (10 to 40 kPa) the chosen sonic nozzle resulted in a Reynolds number of $\approx 1.4 \times 10^5$. The pressure taps for the orifice plate were located in the horizontal and vertical plane at r/R = -1.0. For each location of the tube bundle the % error in the flow rate and C_d was evaluated

Results of the comparative testing, shown in Figure 22., indicate that there exists a cross-over point at approximately 1.5D and another at around 6D. Also, the vertical pressure taps (in the plane of the elbow) consistently appear to read a lower pressure differential than the horizontal pressure taps indicating that the plane of location of the pressure taps is important when considering orifice metering accuracy.

5.0 ANALYSIS OF RESULTS

The first cross-over point at x/D=1.5 of Figure 22 is not surprising. At positions closer than 1.5D, the pressure has not fully recovered from the pressure drop due to the tube bundle, hence, the upstream pressure tap is subjected to lower pressure levels resulting in a positive shift in the discharge coefficient. As the tube bundle is retracted, at around 1.5D, pressure recovery takes place and levels of pressure are akin to the true pressure levels and a zero error (first cross over) occurs.

With further pulling of the tube bundle, the pressure has fully recovered from the tube bundle effects, and other parameters must be sought to explain the non-zero errors in the discharge coefficient. Previously, only the mean axial velocity profile has been used to explain this occurrence. It has been claimed that if the mean velocity profile is close to being fully developed, then a zero error would occur. However, deviations from this claim have been noticed. For example, measurements at the high pressure facility show that the mean horizontal velocity profile at the cross-over point is rather flat. We mention the horizontal profiles since the taps are on the horizontal plane. On the other hand, the profiles presented at 27D downstream of the tube bundle by NIST [4] indicate that the mean velocity profile is nearly fully developed and yet an error of +0.5% occurs in the discharge coefficient. Such contradictions have been stimulous to measure and document the turbulent stresses in the present work and if possible extend the correlation of the metering error to the turbulent structure of the flow.

Although more *"carefully planned and controlled"* experiments would be required to establish an exact relation between metering error and the turbulent structure, at this stage it suffices to show that there exists such a relationship and we propose what may possibly be viewed as conjectures based on the limited information in hand in the following.

Consider the mean axial momentum equation which can be written as [14]

$$\rho\frac{DU}{Dt}=-\frac{\partial P}{\partial x}+\mu\nabla^2 U-\rho\frac{\partial\overline{u^2}}{\partial x}-\frac{\rho}{r}\frac{\partial r\overline{uv}}{\partial r}-\frac{\rho}{r}\frac{\partial\overline{uw}}{\partial\theta}+F_x$$

where U,V and W are the mean velocities in the axial, radial and azimuthal directions and u,v and w are the corresponding fluctuating velocities.

For a steady, axisymmetric flow with negligible body forces the above equation can be simplified to

$$\frac{1}{2}\frac{\partial\left(\rho U^2\right)}{\partial x}=-\frac{\partial P}{\partial x}+\mu\frac{\partial}{\partial r}\left(\frac{\partial U}{\partial r}\right)+\frac{\mu}{r}\frac{\partial U}{\partial r}+\mu\frac{\partial}{\partial x}\left(\frac{\partial U}{\partial x}\right)-\rho\frac{\partial\overline{u^2}}{\partial x}-\frac{\rho}{r}\frac{\partial r\overline{uv}}{\partial r}$$

The above equation can then be re-written as

$$\frac{\partial P}{\partial x}=\left(\frac{\partial\tau_L}{\partial r}+\frac{\tau_L}{r}\right)+\left(\frac{\partial(-\rho\overline{uv})}{\partial r}+\frac{-\rho\overline{uv}}{r}\right)+\mu\frac{\partial}{\partial x}\left(\frac{\partial U}{\partial x}\right)-\frac{\partial\rho\overline{u^2}}{\partial x}-\frac{1}{2}\frac{\partial\left(\rho U^2\right)}{\partial x}$$

where the laminar shear stress is given by

$$\tau_L=\mu\frac{\partial U}{\partial r}$$

the quantity $-\rho\overline{uv}$ is the turbulent shear stress and $\overline{u^2}$ is the axial normal stress.

It is evident that the pressure field is not only coupled to the mean velocity, but also to the Reynolds stresses. Consider the following conjectures, based on the above equation, to explain the effects of the mean and turbulent velocities on the pressure difference across the orifice.

Having already explained the reasons for the first cross over point at 1.5D, consider the following explanation for the second cross-over point at 6D. Consider the profiles for the case (L_2 = 4 D), which is close to the second cross-over point. An examination of the above momentum equation as applied to the flow upstream of the orifice plate reveals that when the mean velocity profile approaching the orifice is flatter than the fully developed, the magnitude of the pressure gradient will be lower resulting in higher pressure levels at the upstream tap (hence higher Δp across the orifice). The same applies to the contribution of the turbulence level $\overline{u^2}$; lower values upstream of the orifice tend to increase Δp. On the other hand, if one extrapolates the shear stress measurements to the wall (Figure 21), then the resulting wall shear stress appears to be higher than the fully developed value. Also, the gradient of the shear stress is shown to be higher at the wall compared to that for a fully developed flow (Figure 21). Therefore, both a higher level of the shear stress and higher gradient at the wall would result in reducing Δp. This counteracting behavior could result in a cancellation effect resulting in a pressure level that produces a cross-over point.

For the intermediate location (L_2=8 D), the mean velocity profile approaching the orifice plate appears to be nearly fully developed. Once again, in applying the momentum equation the mean velocity inertial terms can be neglected. The decay of the normal Reynolds stresses tend to increase the pressure levels at the upstream tap, however, the gradient of the shear stress which is considerably greater than its fully developed counter part tends to reduce this pressure. The latter effects is more severe, resulting in a low differential pressure across the orifice plate and consequently a positive shift in the discharge coefficient.

In conclusion, as stated before, in the absence of more in-depth measurements, the above explanations may be viewed as conjectures, at best, however, they seem to adequately explain metering error which thus far could not be done solely on the basis of the mean velocity field. Finally, the present measurements and their interpretations most certainly illuminate the fact that there exists a definite relationship between orifice metering error and the turbulent velocity field.

6.0 FUTURE WORK

It is evident that there exists a need to conduct carefully planned and in-depth measurements to shed more light on the precise interaction between orifice metering errors and the mean and turbulent velocity field. Apart from the Reynolds stresses, also of interest are the measurements of the integral length scales and the Taylor (dissipation) microscale. These would provide information on the effect of initial scale size (due to tube bundle) on the decay of energy. Such experiments are being planned at the low pressure facility at NHRC. Also, this study is to be extended to the high pressure facility. Although equipment problems have been taken care of with regards to the functioning of the IFA 100 in natural gas application at high pressures, approval is currently being sought from the appropriate agencies to use this technique at such a hazardous location. Once this has been achieved, it will then be possible to document the mean and turbulent velocity flow field for low and high Reynolds numbers. This should go a long way towards shedding light on the interaction of orifice metering error and the velocity field.

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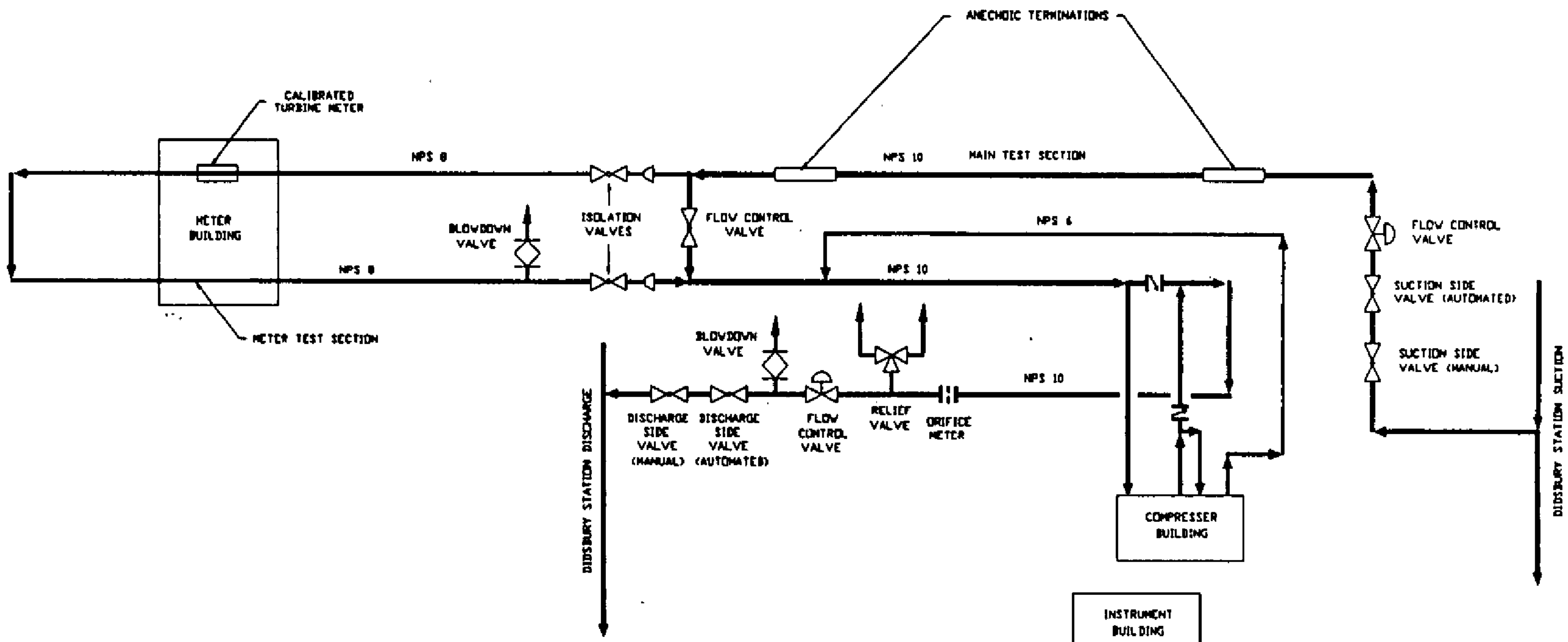


Fig. 1: NOVA's High Pressure Test Facility at Didsbury, Alberta, Canada

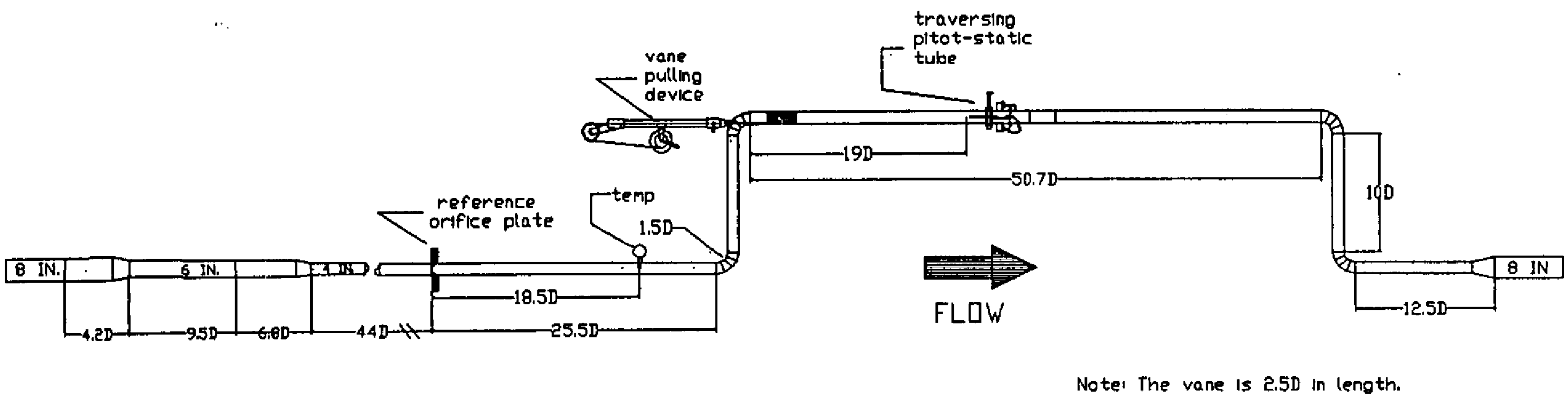


Fig. 2: Test Section Arrangement in the Meter Room of Fig. 1

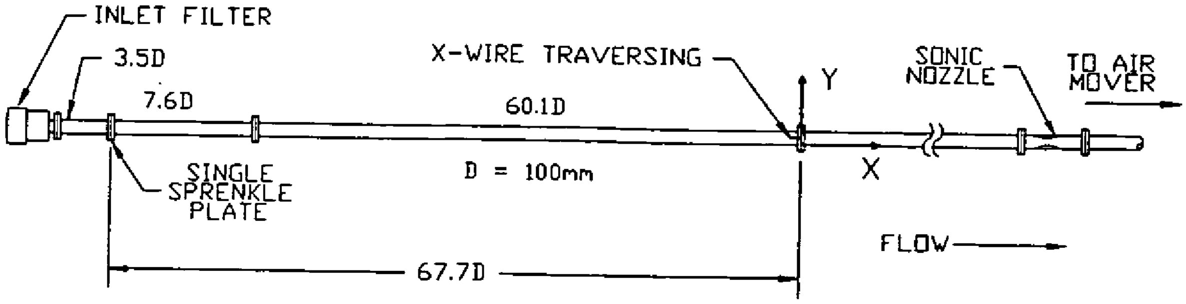
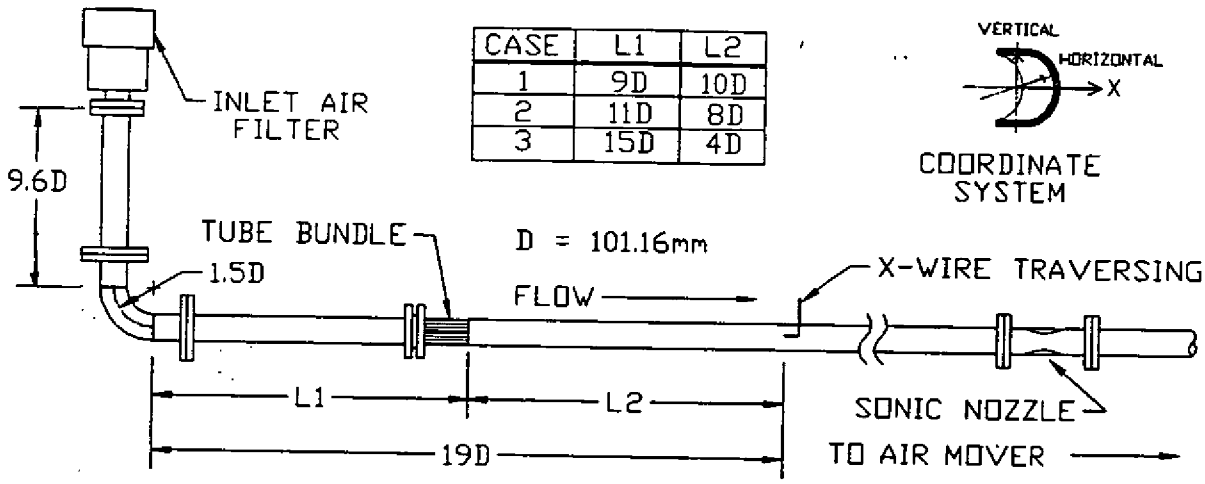


Fig. 3a: Low Pressure Test Facility - Good Flow Conditions



CASE	L1	L2
1	9D	10D
2	11D	8D
3	15D	4D

Fig. 3b: Low Pressure Test Facility - Elbow and In-line Tube Bundle

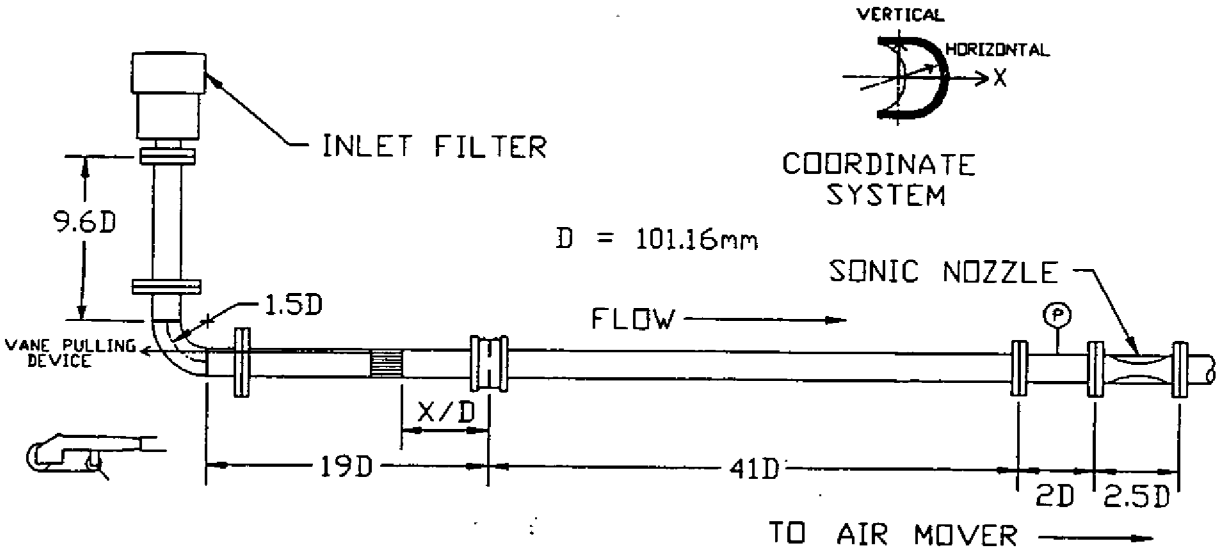


Fig. 3c: Low Pressure Test Facility - Elbow and Sliding Tube Bundle

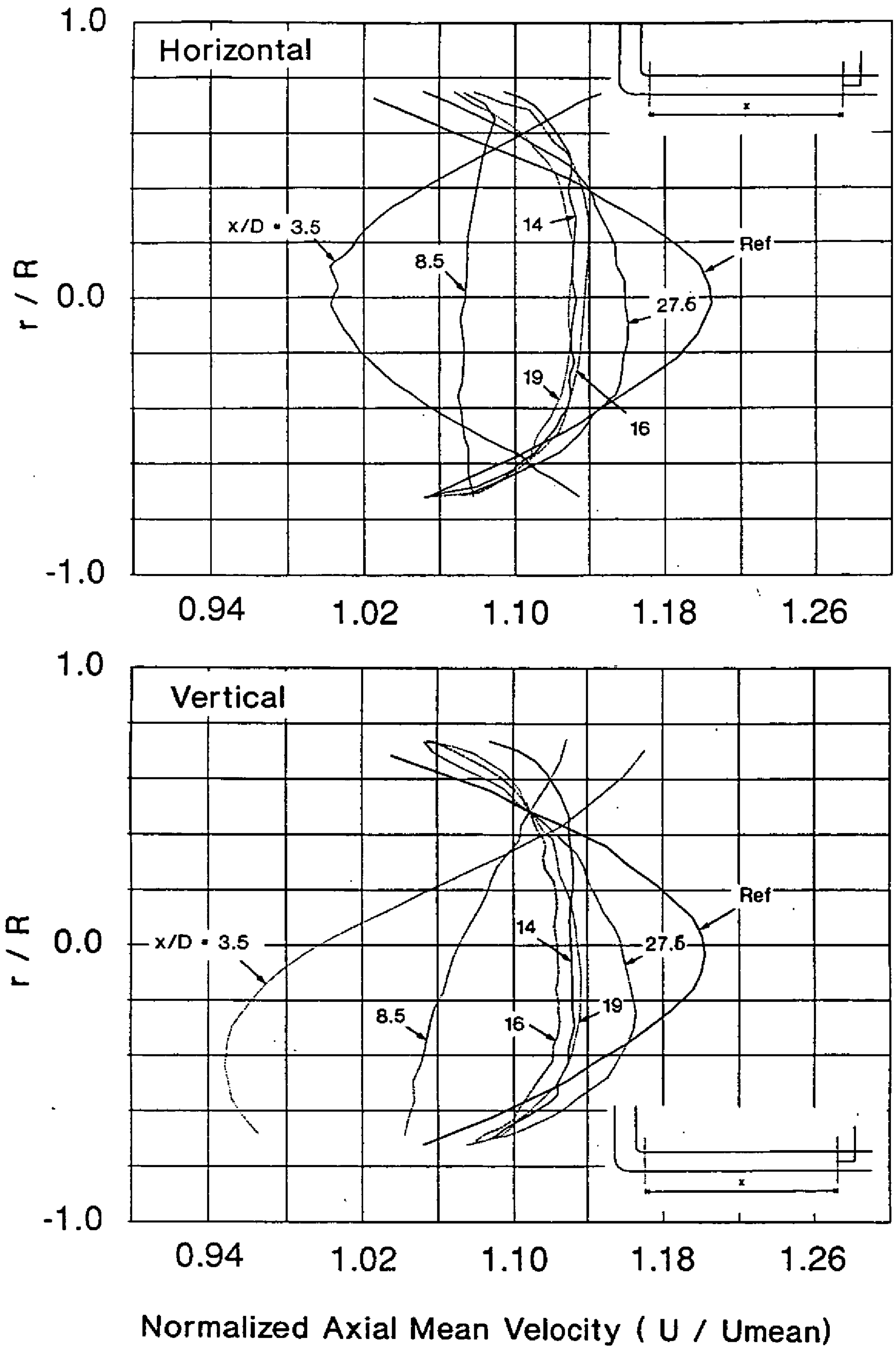


Fig. 4: Axial Velocity Profiles in the Horizontal and Vertical Planes Downstream of Two Elbows In-plane Without Flow Conditioner (Re = 8 x 10^6)

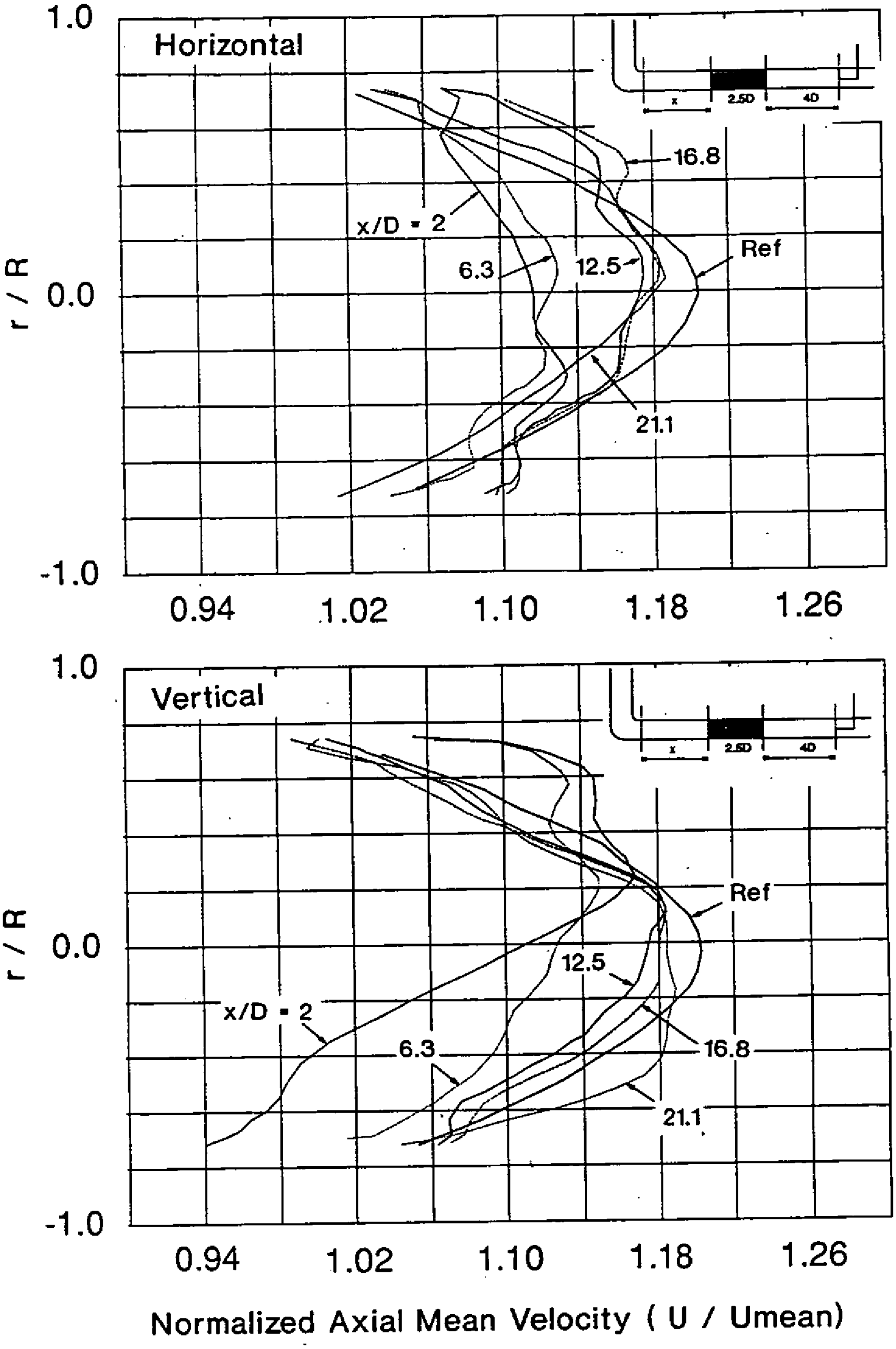


Fig. 5: Axial Velocity Profiles in the Horizontal and Vertical Planes Downstream of Two Elbows In-Plane with a Tube Bundle at Different Locations and PST at 4 D Downstream of Tube Bundle Outlet ($Re = 8 \times 10^6$)

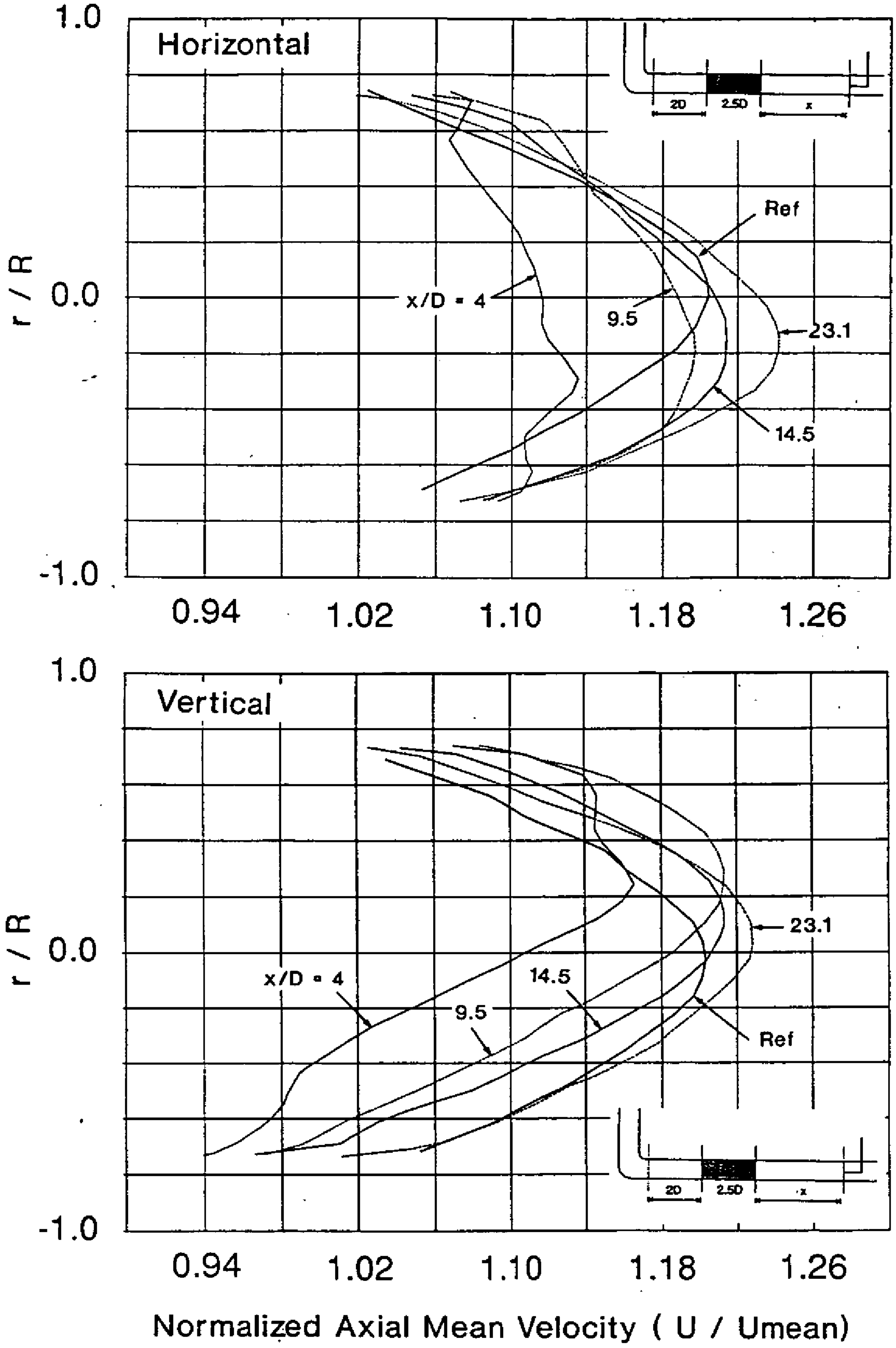


Fig. 6: Axial Velocity Profiles in the Horizontal and Vertical Planes Downstream of Two Elbows In-plane with a Tube Bundle at Fixed Location (2 D from Elbow Outlet) and PST at Different Locations Downstream (Re = 8 x 10^6)

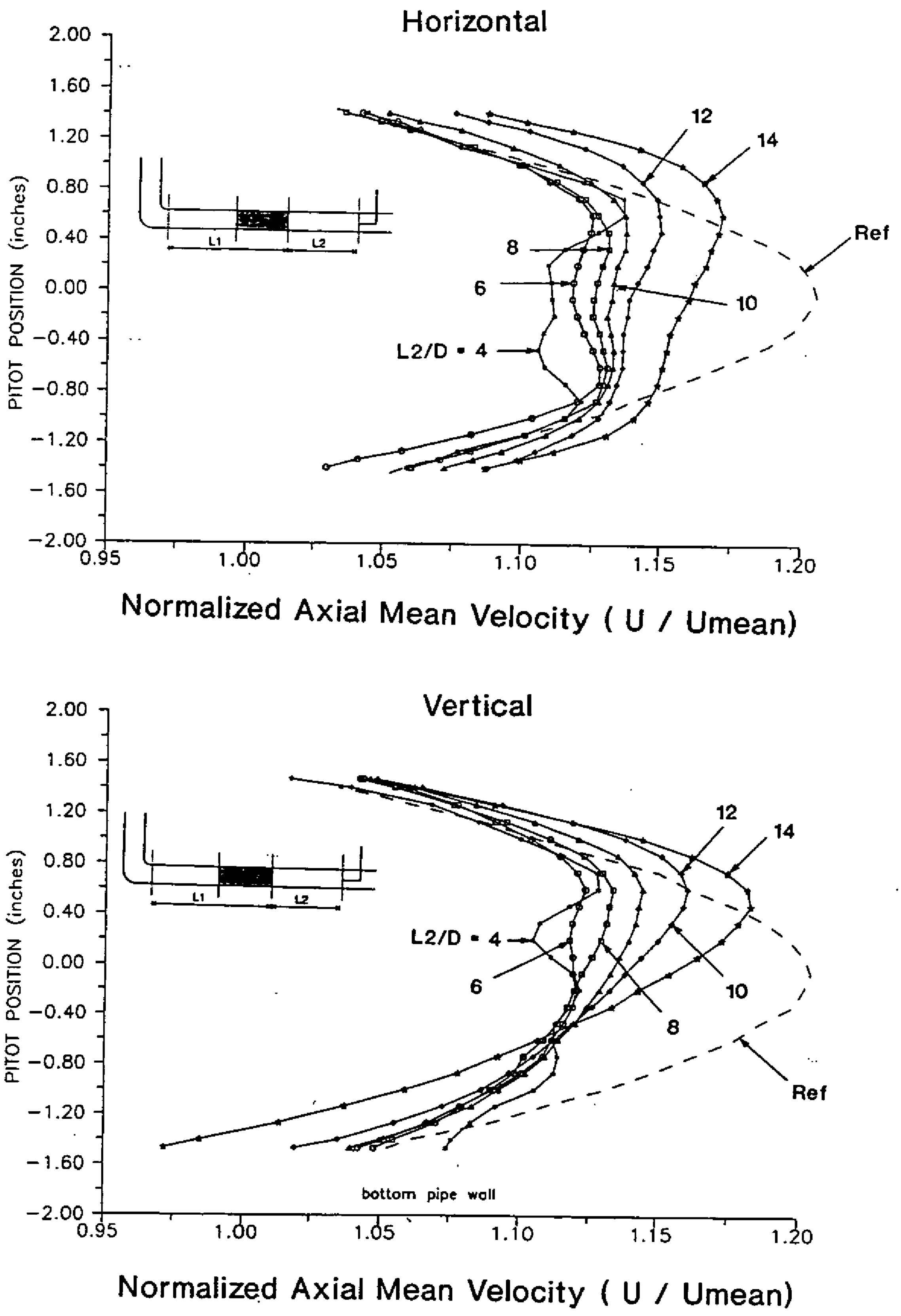


Fig. 7: Axial Velocity Profiles in the Horizontal and Vertical Planes Downstream of Two Elbows In-plane with a Sliding Vane and PST at 19 D from Elbow Outlet ($Re = 8 \times 10^6$)

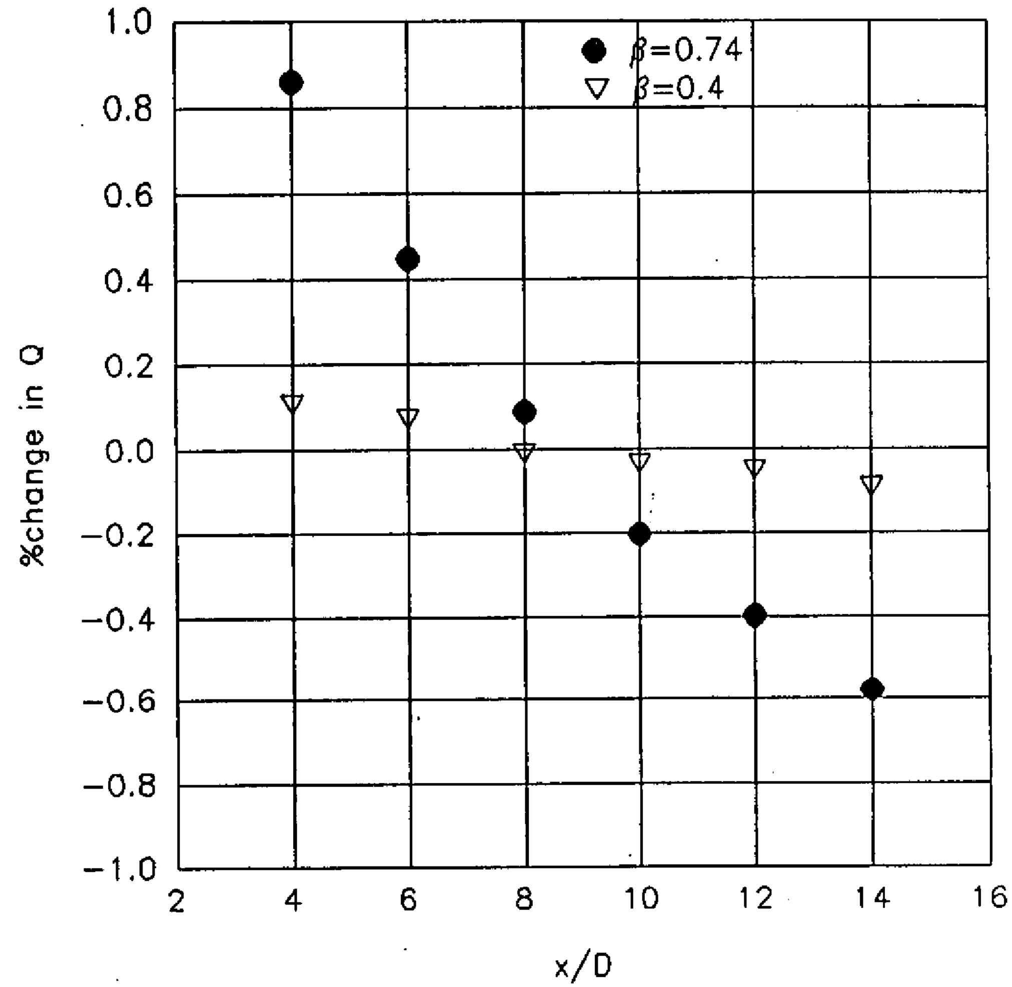


Fig. 8: **Results of Comparitive Tests with a Sliding Vane and 19 D Meter Run for Two β-ratios of 0.4 and 0.74 (Re = 8 x 10^6)**

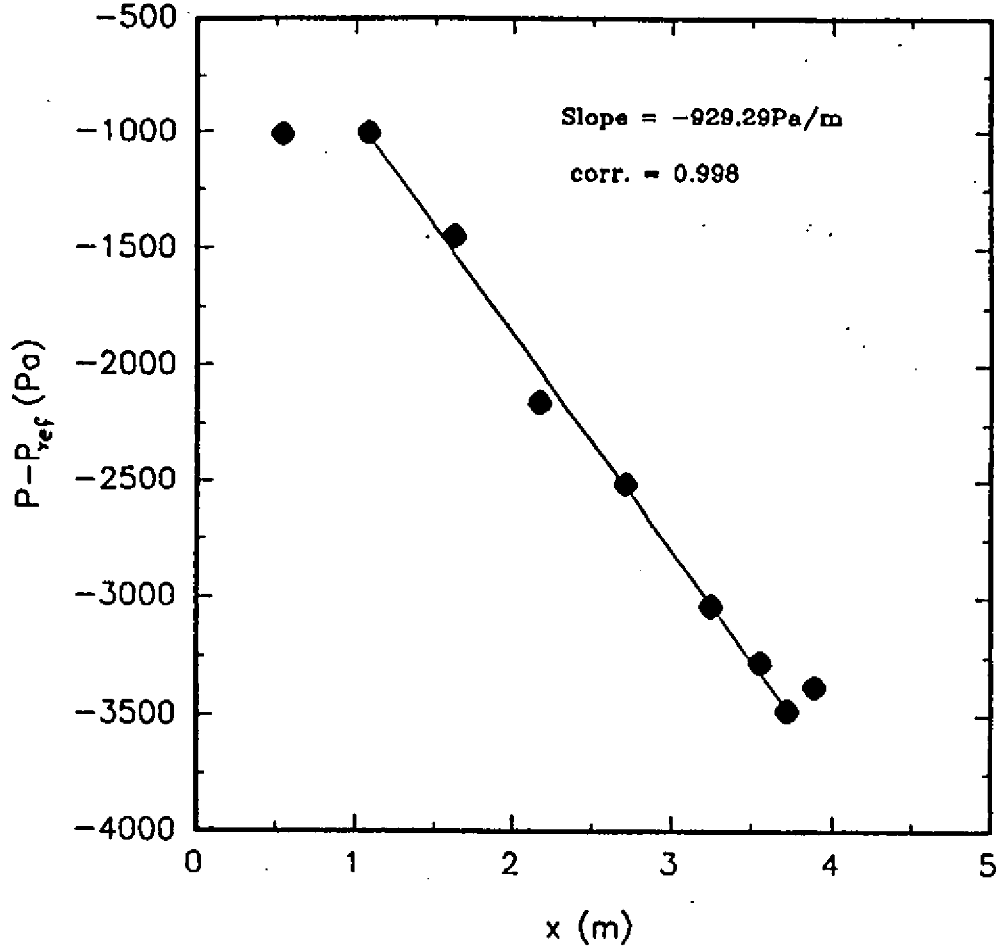


Fig. 9: Pressure Profile Along the 44 D Long Meter Run Upstream of the Reference Meter ($Re = 8 \times 10^6$)

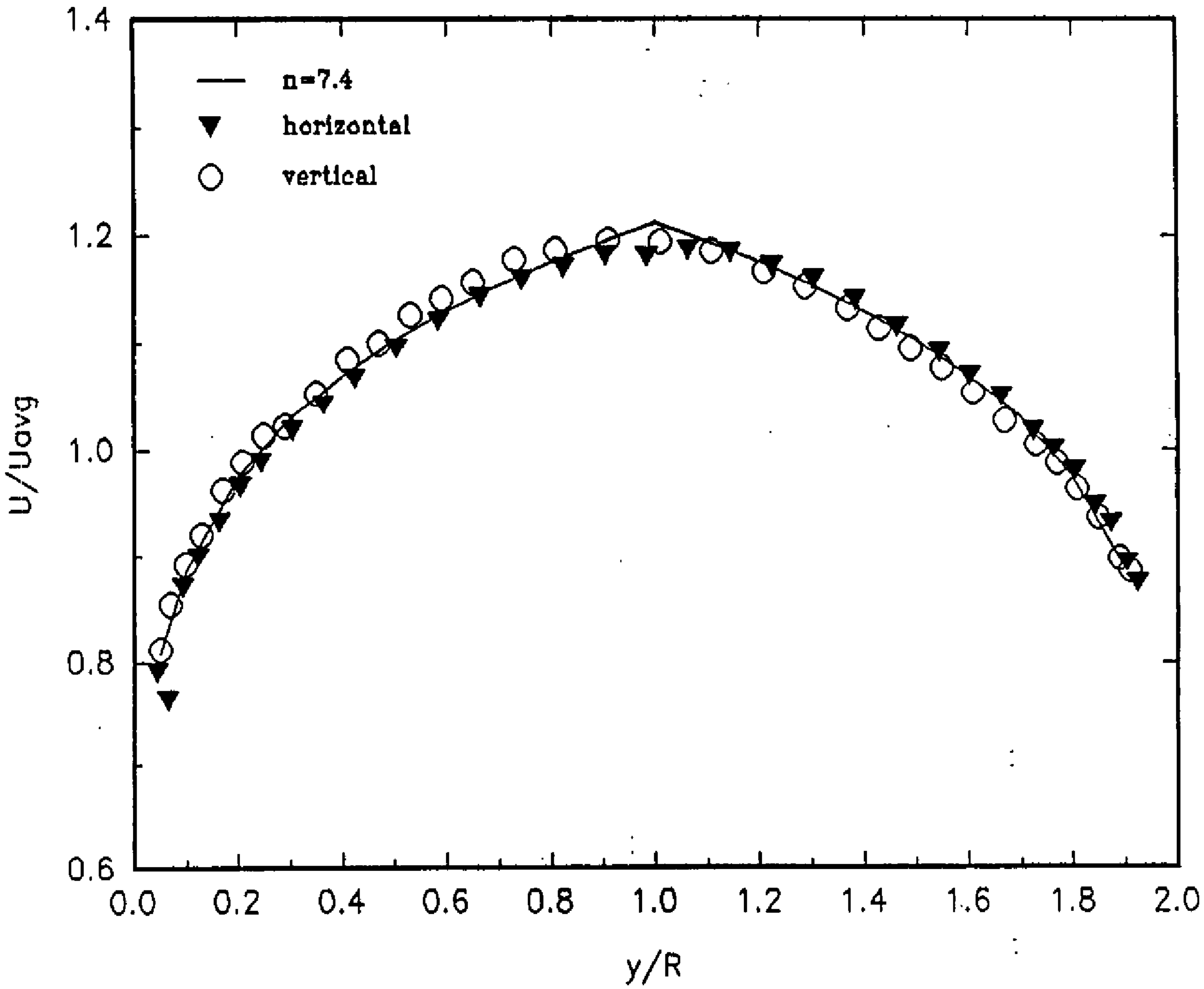


Fig. 10: Mean Axial Velocity Profiles in the Horizontal and Vertical Planes of a Fully Developed Flow on the Low Pressure Facility (Re = 0.9×10^5)

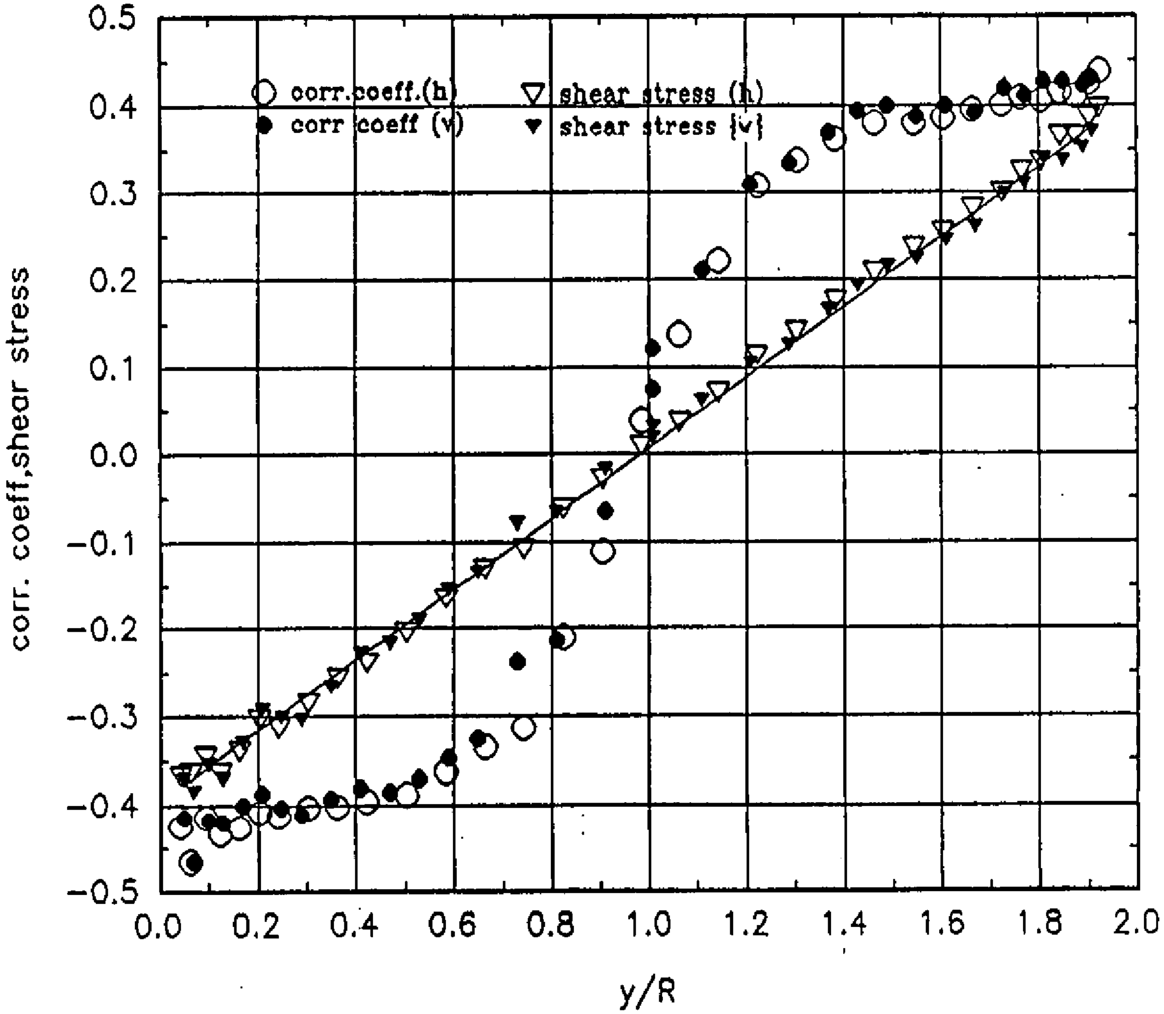


Fig. 11: Shear Stress and Correlation Coefficient for a Fully Developed Flow (Re = 0.9 x 10^5)

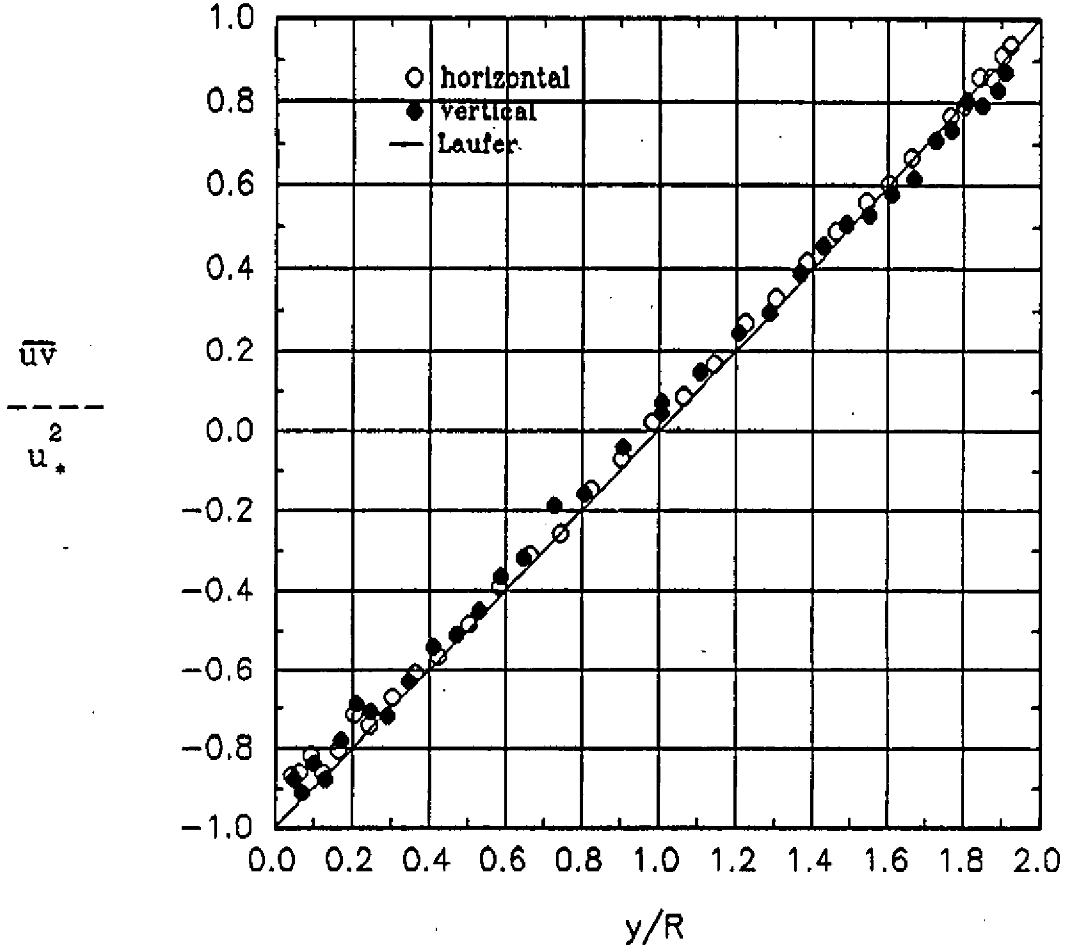


Fig. 12: Normalized Shear Stress with Frictional Velocity for a Fully developed Flow (Re = 0.9 x 10^5)

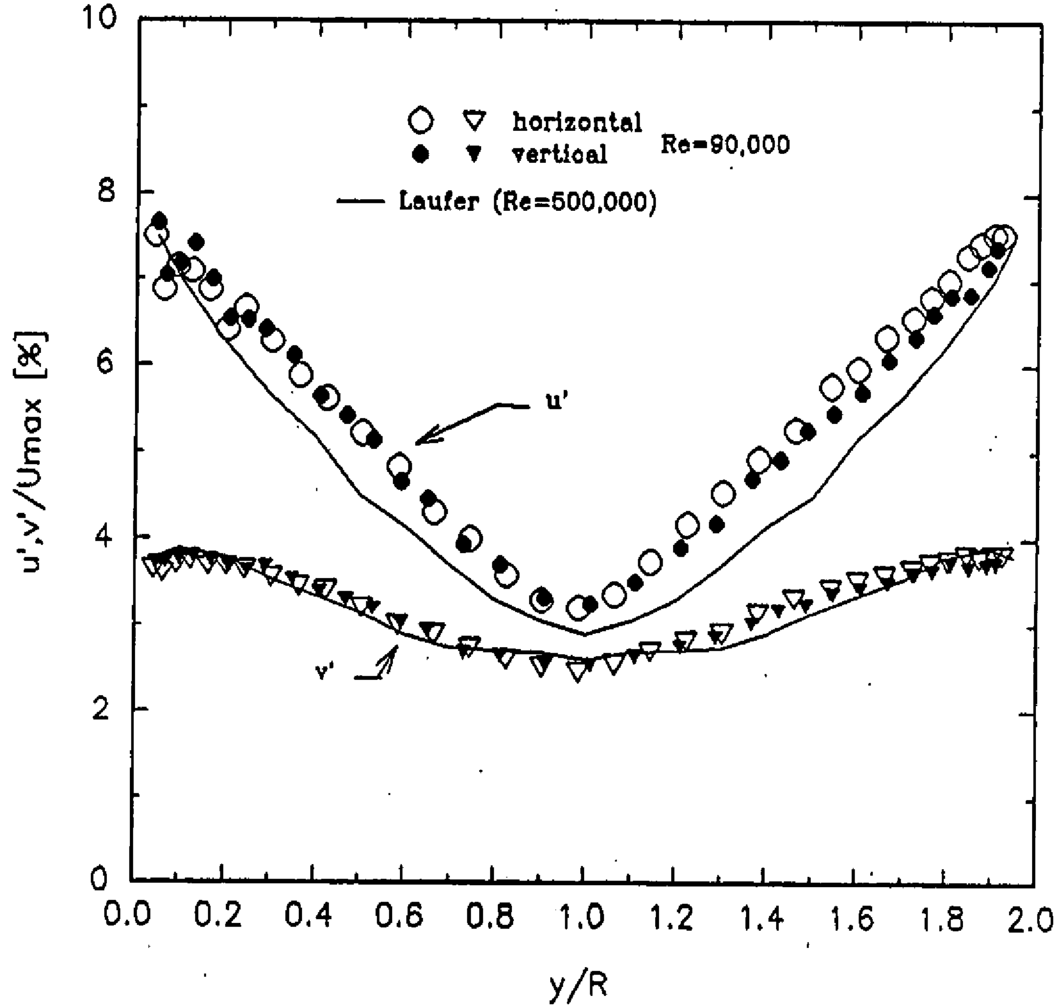


Fig. 13: Axial and Radial RMS Turbulent Intensities of a Fully Developed Flow (Re = 0.9×10^5)

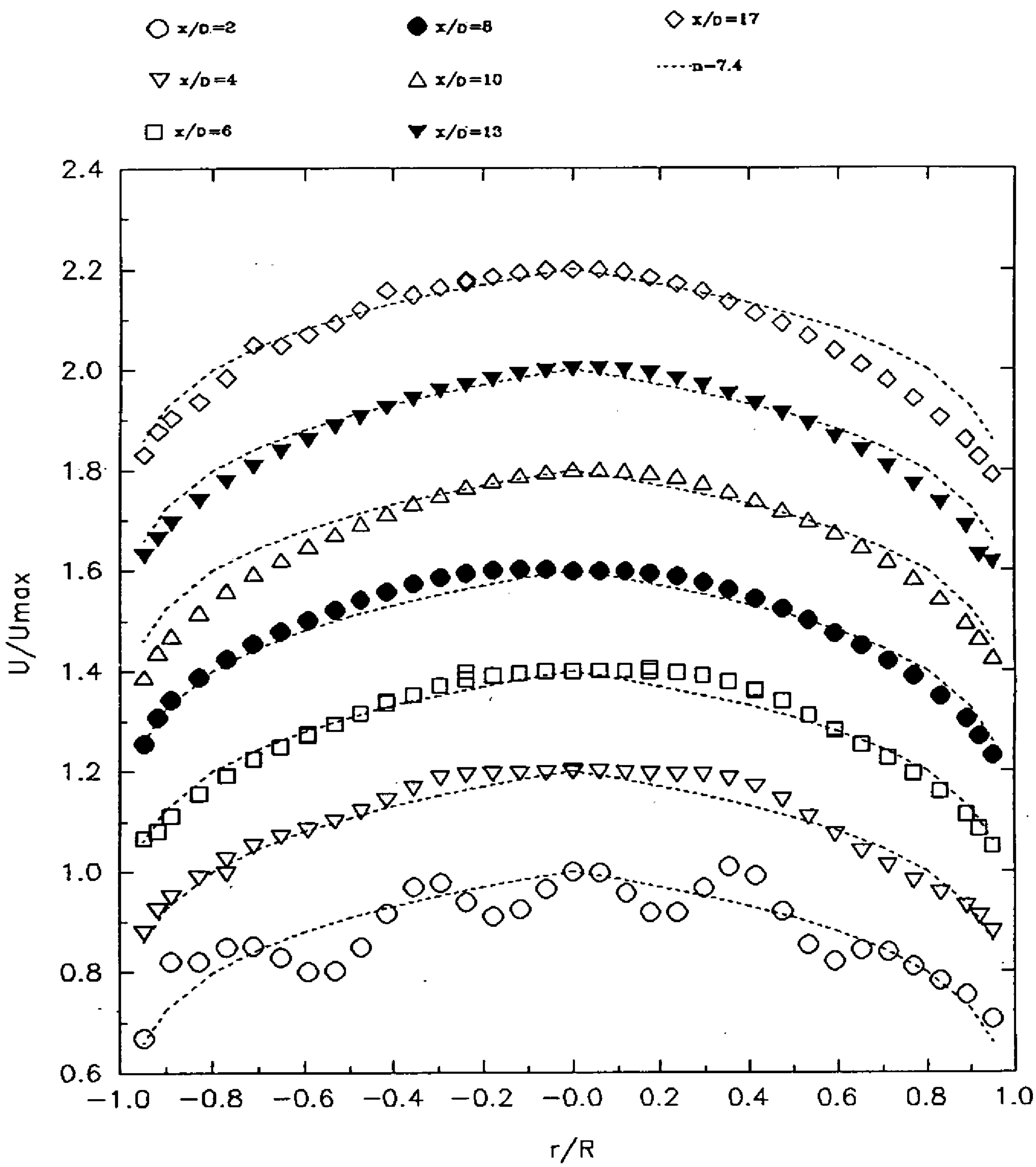
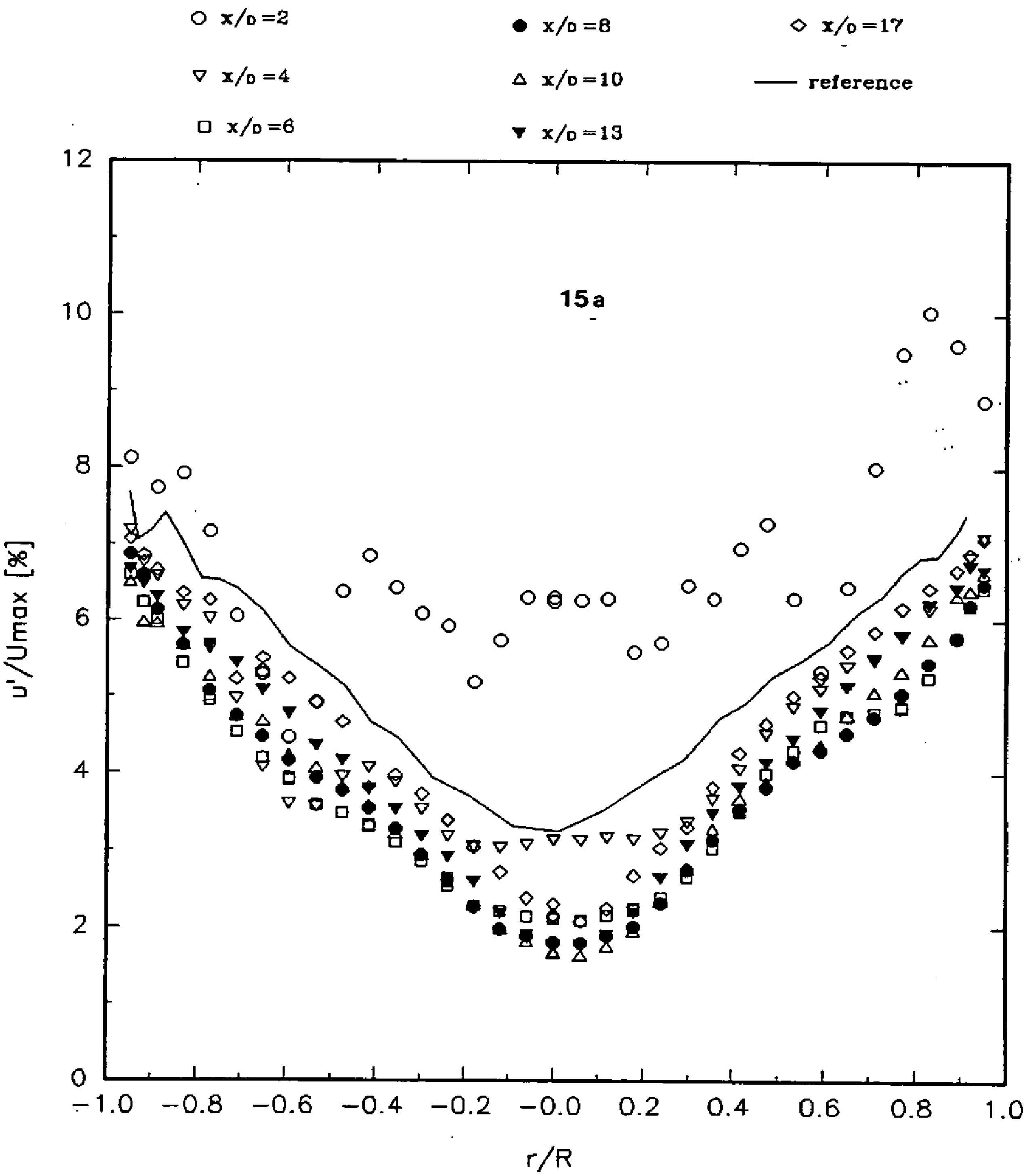


Fig. 14: Mean Axial Velocity Profiles Downstream of a Tube Bundle in Good Flow Conditions - (Re = 0.9 x 10^5) (Note: Each Profile following x/D = 2 has been offset successivly by 0.2 units for separation of profile)



x/D =2
x/D =8
x/D =17
x/D =4
x/D =10
reference
x/D =6
x/D =13
15a
u'/Umax [%]
r/R
0
2
4
6
8
10
12
-1.0
-0.8
-0.6
-0.4
-0.2
-0.0
0.2
0.4
0.6
0.8
1.0

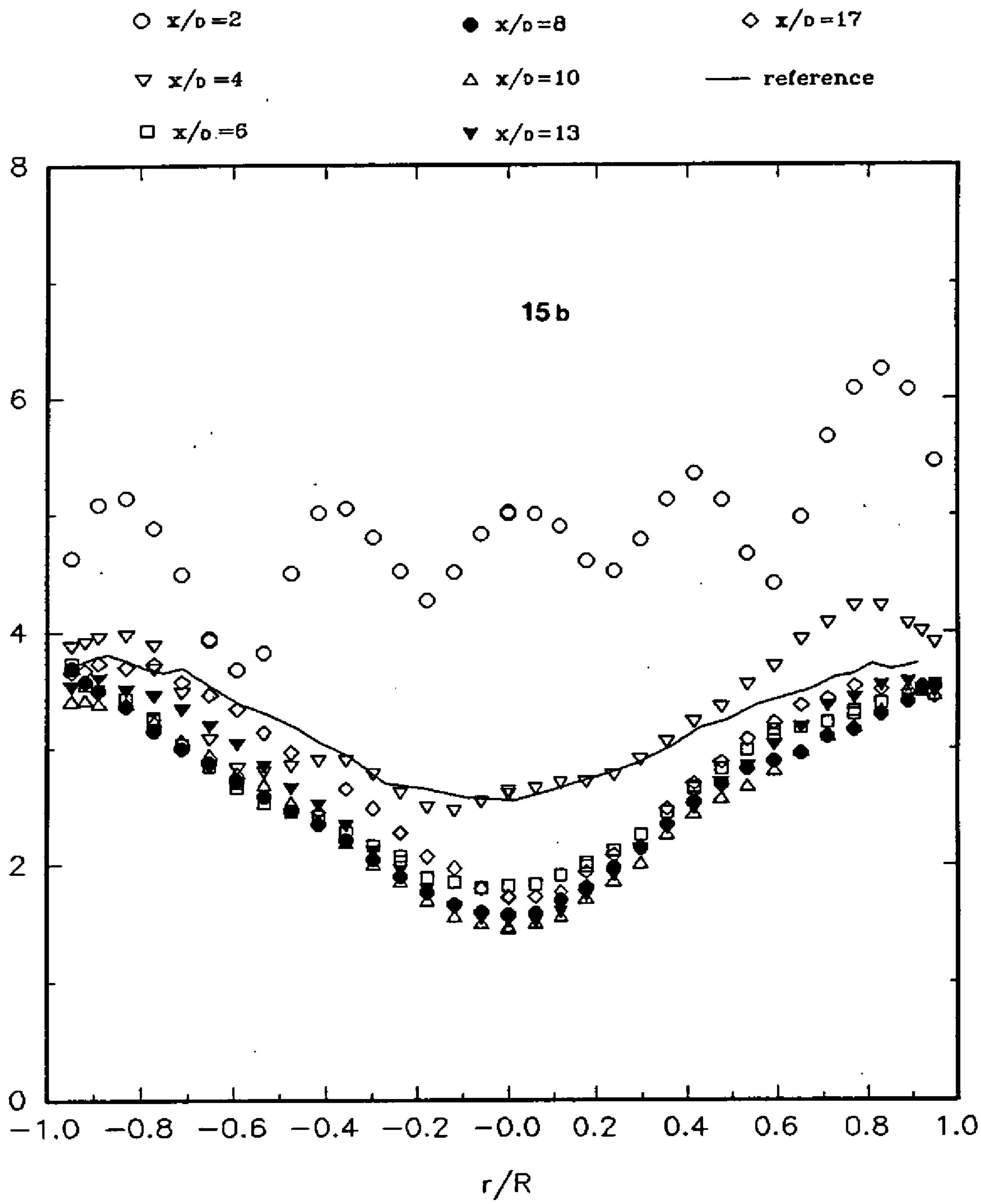


Fig. 15: Profiles of the Axial and Radial RMS Turbulent Velocities Normalized by U_{max}, Downstream of a Tube Bundle in Good Flow Conditions - ($Re = 0.9 \times 10^5$) (a - axial, b - radial)

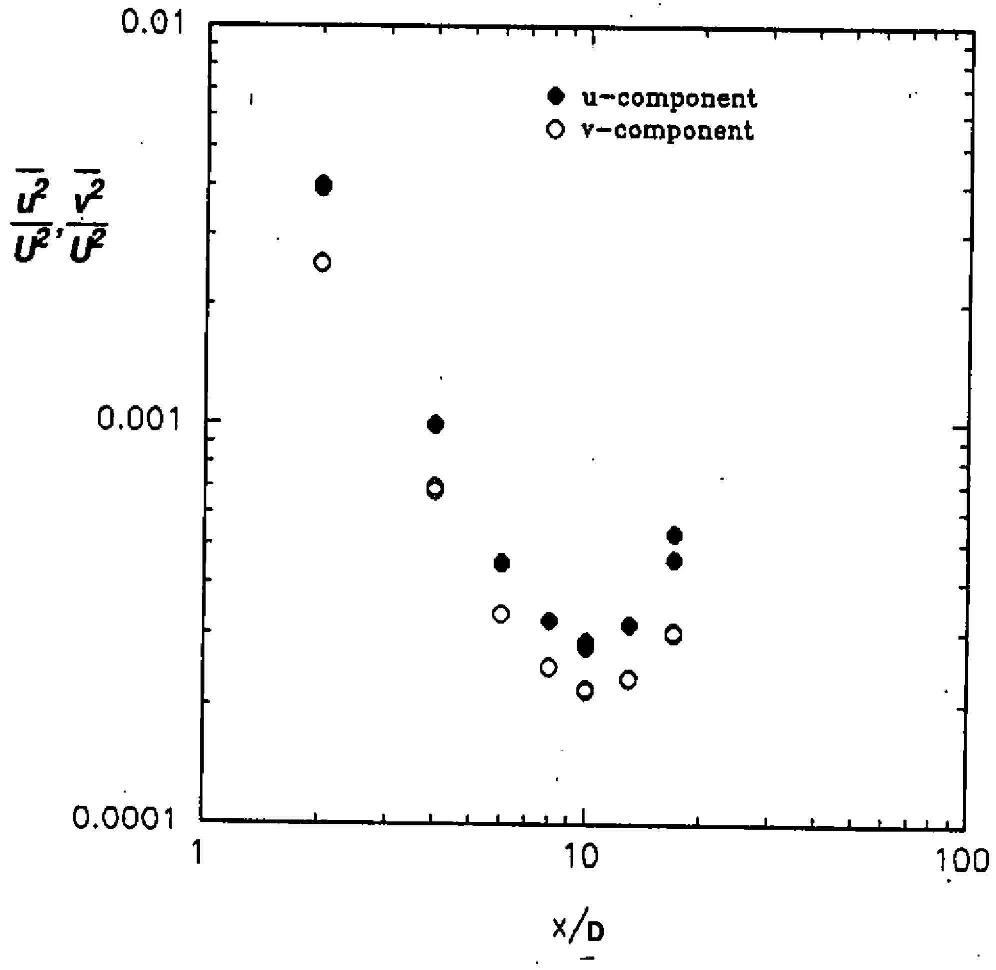


Fig. 16: Variation of the Normal Stresses on the Centerline Downstream of a Tube Bundle in Good Flow Conditions (Re = 0.9×10^5)

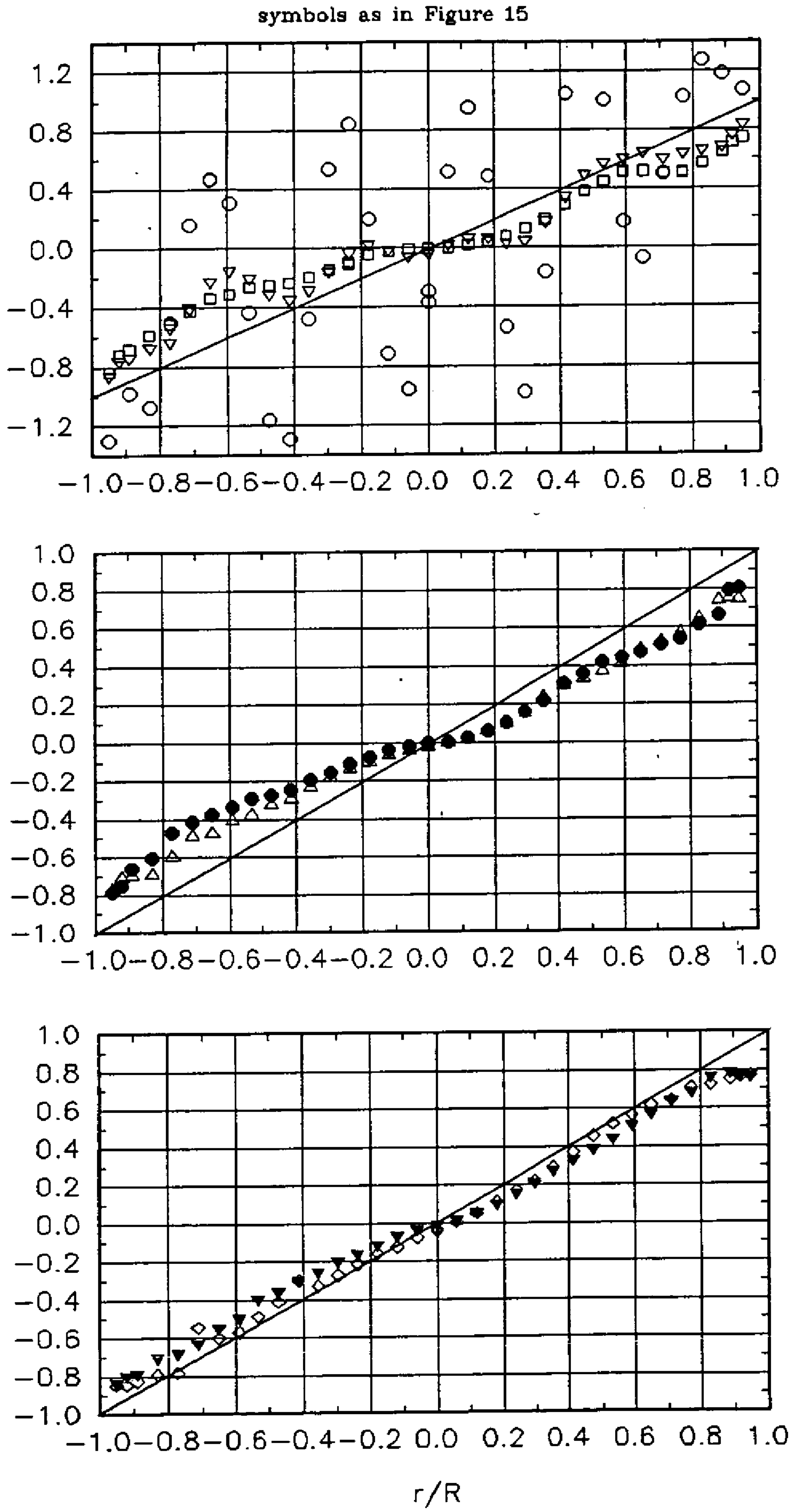
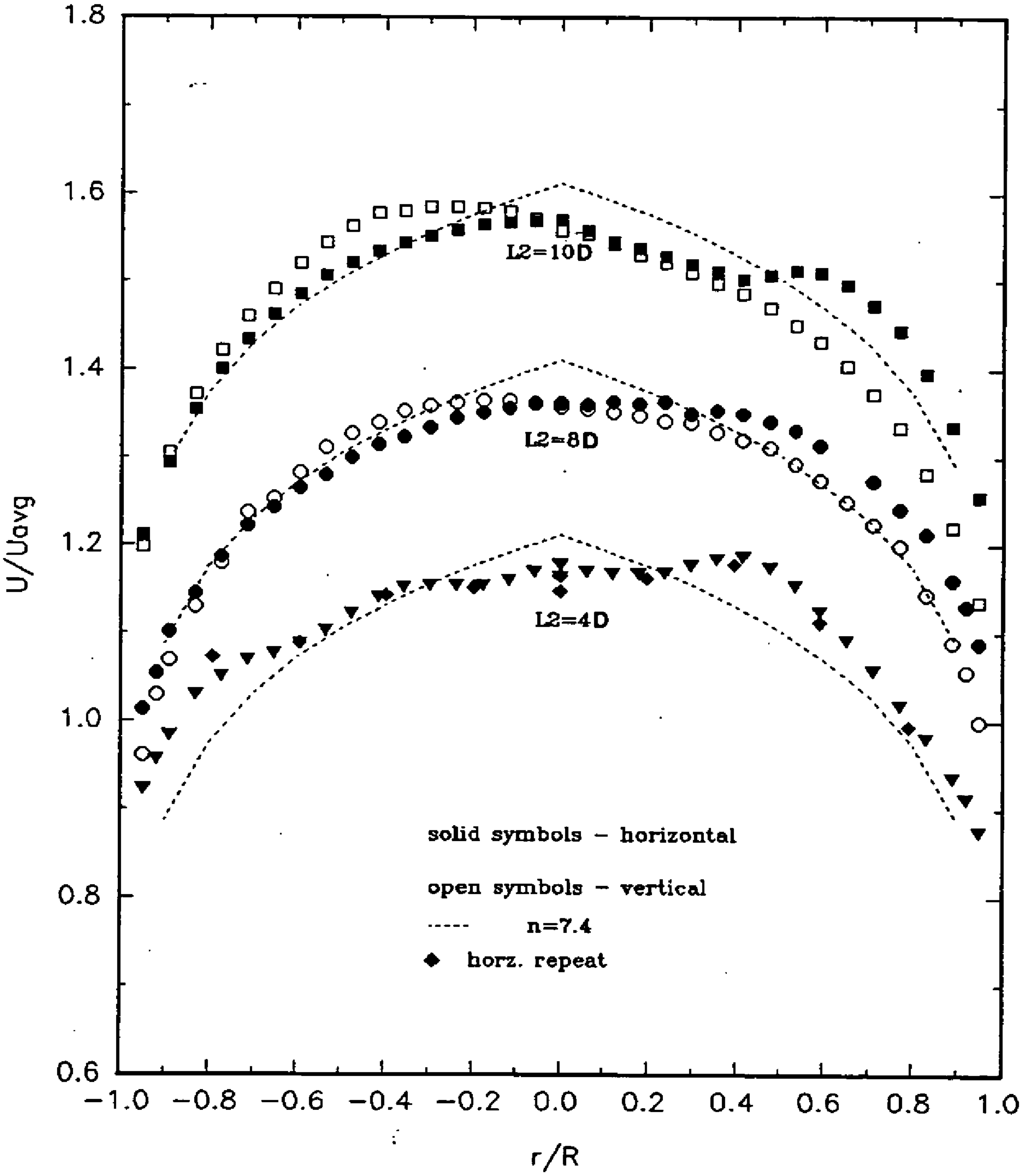


Fig. 17: Distribution of the Normalized Turbulent Shear Stress $\left(\overline{uv}/u_*^2\right)$ Downstream of a Tube Bundle in Good Flow Conditions (Re = 0.9 x 10^5)



Note: Each data set following L2=4 has been offset by 0.2 units

Fig. 18: Mean Axial Velocity Profiles for Three Different Locations of a Tube Bundle Placed in 19 D Meter Run Downstream of a 90° Elbow - Re = 0.9 x 10^5

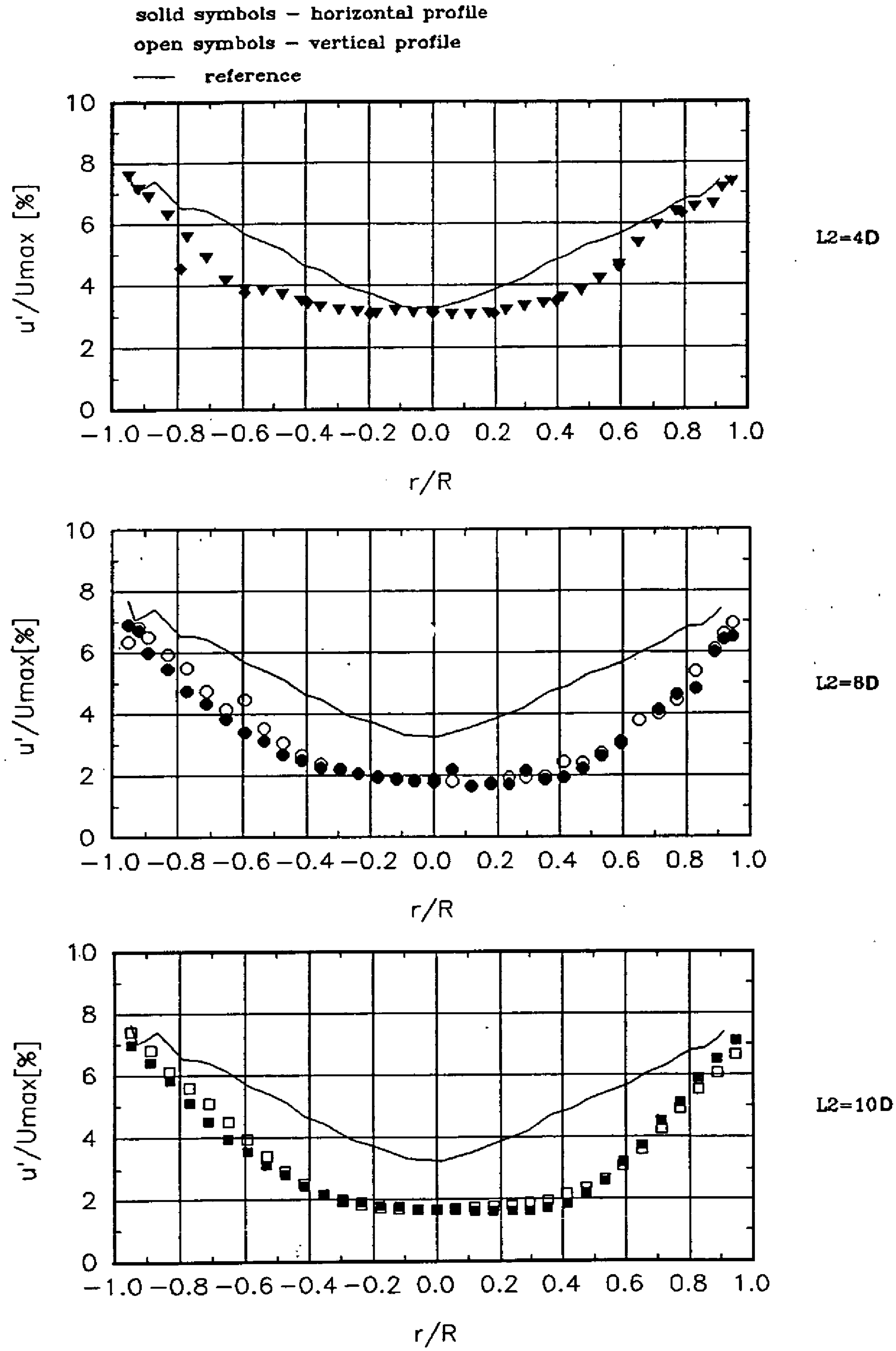


Fig. 19: Axial Turbulent Intensity (RMS) Downstream of a Tube Bundle Placed in 19 D Meter Run Downstream of a 90° Elbow (Re = 0.9 x 10^5)

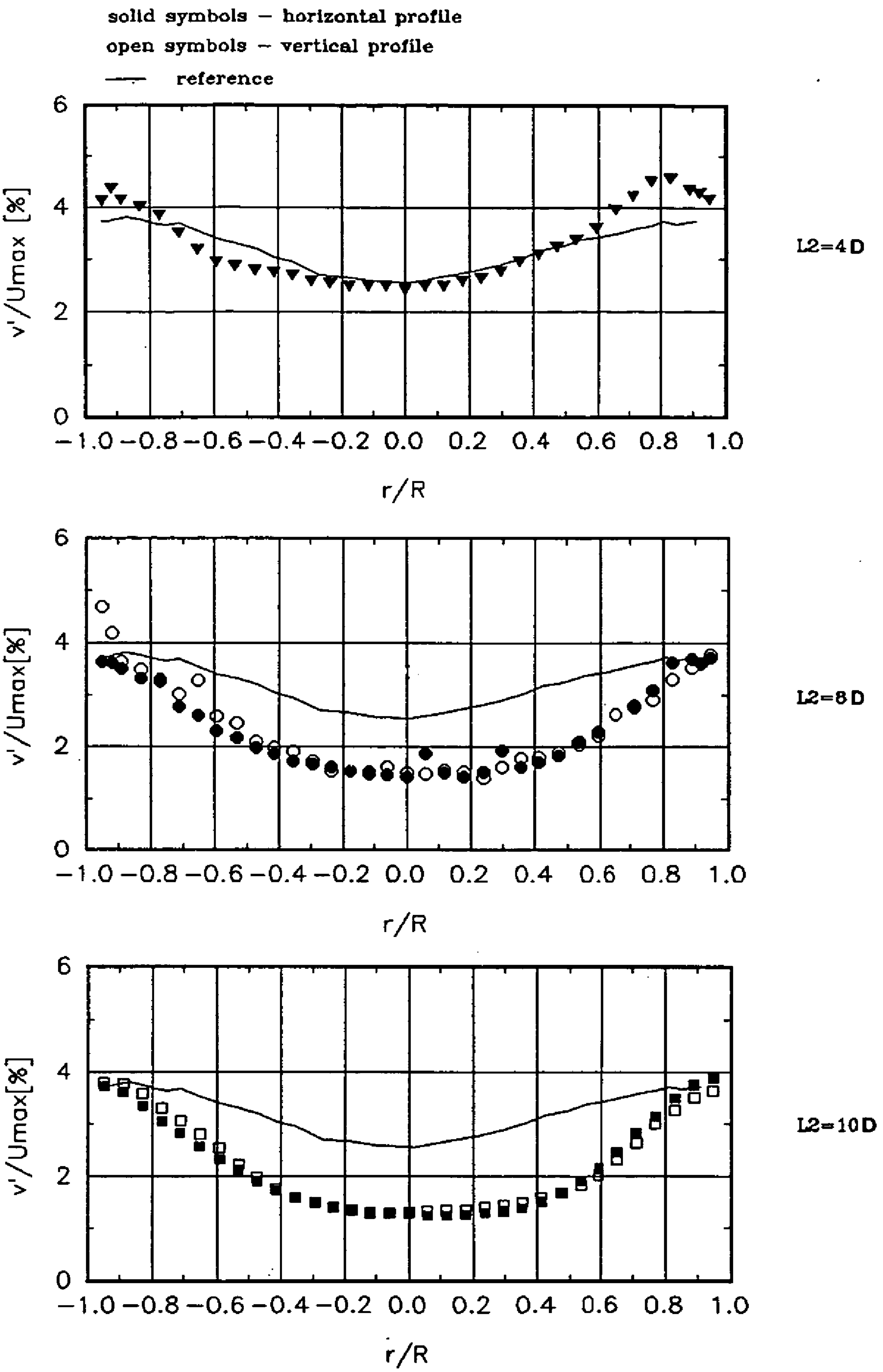


Fig. 20: Radial Turbulent Intensity (RMS) Downstream of a Tube Bundle Placed in 19 D Meter Run Downstream of a 90° Elbow (Re = 0.9×10^5)

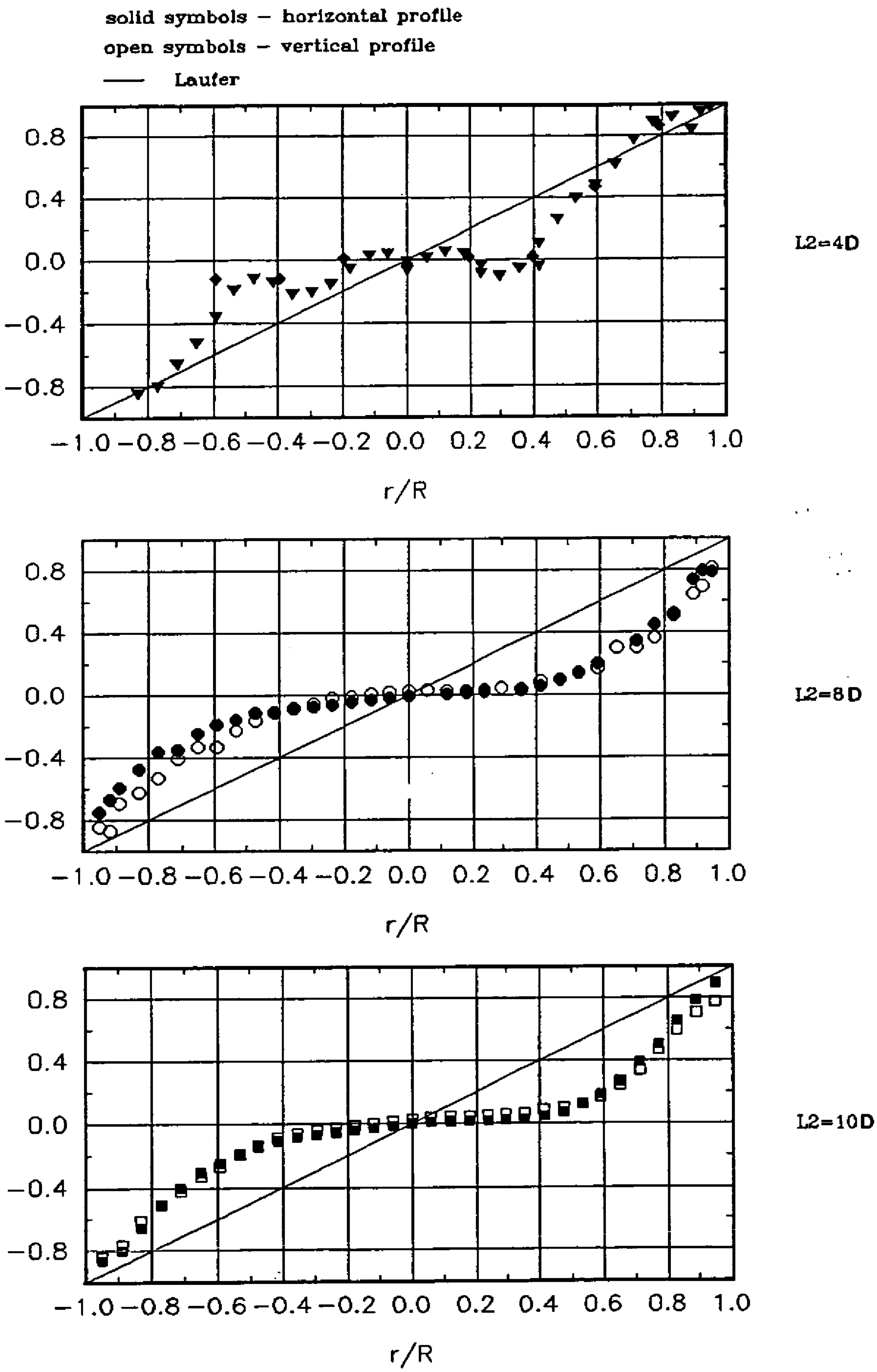


Fig. 21: Distribution of the Normalized Turbulent Shear Stress $\left(uv/u_*^2\right)$ Downstream of a Tube Bundle in 19 D Meter Run Downstream of a 90° Elbow (Re = 0.9 x 10^5)

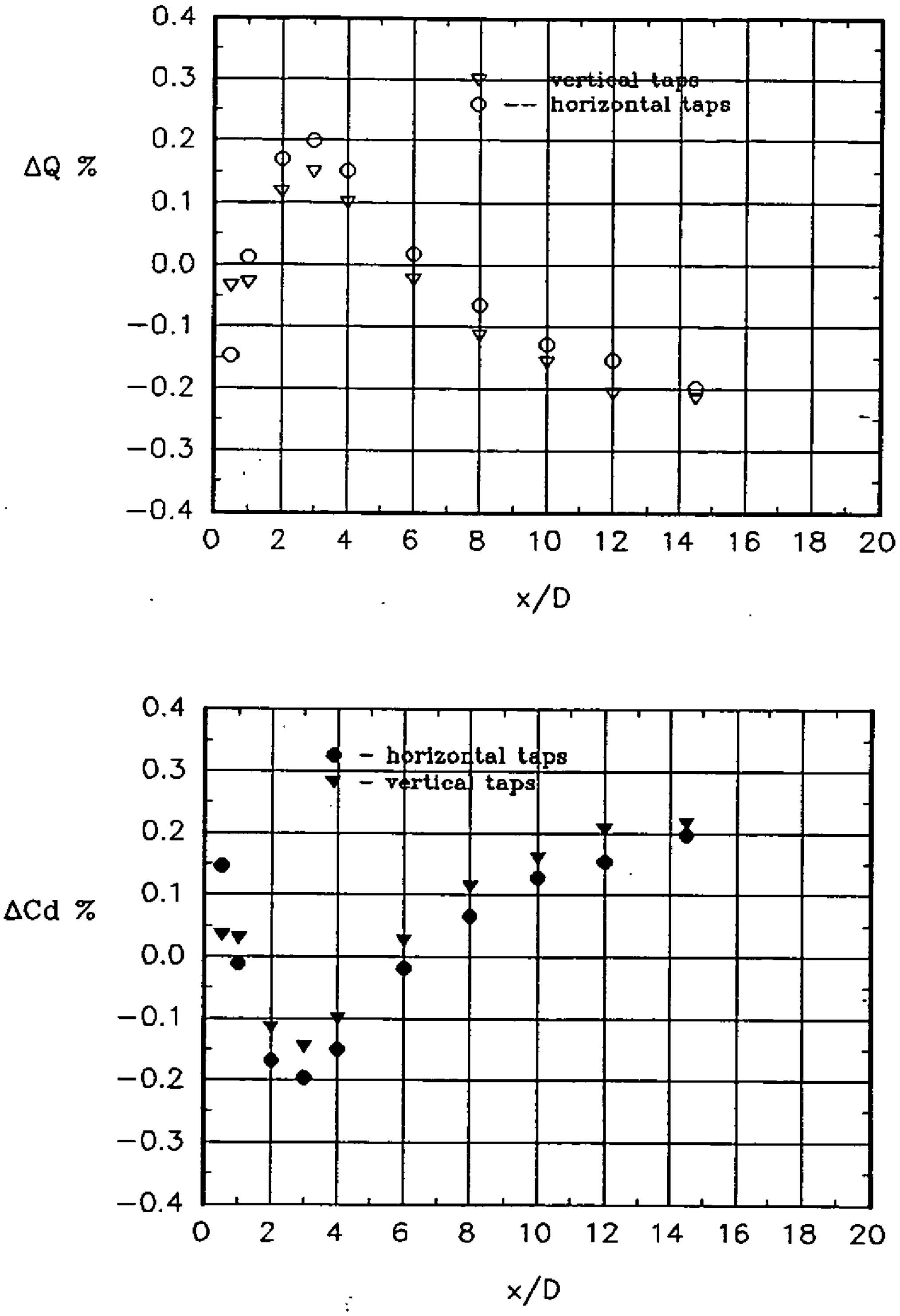


Fig. 22: Results of a Comparative Tests with a Pulling Vane in a 19 D Meter Run Downstream of a 90° Elbow ($Re = 1.4 \times 10^5$)

Norwegian
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NORTH SEA FLOW MEASUREMENT WORKSHOP

OCTOBER 22. - 24. 1991
SOLSTRAND FJORD HOTEL, BERGEN - NORWAY

TRACEABILITY IN MEASUREMENT OF NATURAL GAS QUALITY

Lecturer:

Mrs. Marianne Tambo
DANTEST

9 th North Sea Flow Measurement Workshop
Bergen, 22-24 of October 1991

Traceability in Measurement of Natural Gas Quality

Marianne Tambo
The Gas Density Laboratory
The Metrology Division
Dantest, The Force Institutes
Denmark

Summary

Flow measurement of natural gas combined with quality determination of the gas (e.g. the calorific value) provides the usual units in which accounts are settled. The concept of traceability in flow measurement is well defined but in the determination of the quality of gas the term traceability has up to now been bypassed because of technical difficulties. During the last two years a lot of work has been done internationally to reach a possible method of obtaining traceable determination of the quality of natural gas. The status of the work done within ISO and WECC will be given and the possible impact on the natural gas industry will be reflected on.

Traceability in measurement of natural gas quality

Index

1.0 Introduction.

The definition of traceability of a measurement is given in ref. (4) and is repeated below:

Traceability: The property of a result of a measurement whereby it can be related to appropriate measurement standards, generally international standards, through an unbroken chain of comparisons.

Why should this apply to natural gas quality and how can it apply? To answer these questions a quick look into the state of art of obtaining information on the gas quality will be given.

Gas quality is usually specified by the calorific value of the gas. This parameter is defined in ISO 6976 (ref. 3) and can be measured by using for example calorimeters or gas chromatographs. In the last years on-line gas chromatographs have totally dominated the scene in determining the calorific value.

The gas chromatograph determines the molar composition of the gas and by using the calculation procedures described in ISO 6976 the calorific value can be calculated.

Therefore in the following the concept of traceability in measurement of natural gas quality will deal with the traceability of the determination of the calorific value through gas chromatographic analysis.

2.0 Traceability of the determination of the calorific value of natural gas.

A gas chromatographic analysis system comprises a gas chromatograph but equally important reference gas mixtures to calibrate the gas chromatograph. In table 1 is listed a number of parameters that are necessary to take into account in order to achieve an accurate determination of the molar composition of the gas sample.

Table 1 Parameters in the analysis of gas
1. Performance evaluation of the chromatograph (Linearity, stability, repeatability etc.).
2. Procedures of analysis.
3. Correct calibration procedures(e.g. recalibration intervals)
4. Operator training.
5. Correct reference gas mixtures for the gas to be analysed, both in compositions and in numbers.

Let us assume that laboratory A and laboratory B analyse the same gas and, although they have fulfilled the demands in table 1 optimally, are getting major deviations on f.ex. the nitrogen content or another very common error contributor: The ethane content. The laboratories go into very costly research and come up with one factor that deviates: The manufacturer of the reference gas mixtures. Laboratory A uses another manufacturer of gas than laboratory B.

The answer to the first question: "Why traceability in the measurement of natural gas quality" is illustrated by this example: If both manufacturers could claim traceability of their reference gas mixtures, deviations as laboratory A and B found, would not be encountered.

In table 2 are listed some of the reasons why traceability is necessary and the importance is no less when laboratory A and laboratory B represent two countries at a major sales junction.

Table 2 Why traceability

1.	Avoid costly investigations of the analytical systems.
2.	Avoid disputes with costly lawsuits.
3.	Ensure reliability of measurement results.
4.	To create confidence in measurement results.

Unfortunately not all deviations are detected as easily as in the case of laboratories A and B and this is one of the reasons why the next question: "How to apply traceability", is only on the verge of being solved.

The rest of this paper will be devoted to how to obtain traceability in the determination of the calorific value of natural gas and thereby the traceability of the analysis of gas by gas chromatography.

3.0 Working towards traceability in the analysis of natural gas.

Looking again at table 1: The different parameters that are necessary for obtaining an accurate analysis of gas, it can be said that within ISO TC 193 SC1[1] there is being done a lot of work to cope with the first three of the parameters, ref. (5) and ref. (6). The training of the operator is then mainly a point of she/he regularly operating the chromatograph following the accepted standards.

[1] ISO TC 193 SC1: International Standards Organization: Technical committee 193 on Natural Gas; Subcommittee 1 on Natural Gas Analysis.

Therefore the remaining problem of obtaining traceability in gas analysis is the traceability of the reference gas mixtures applied to calibrate or check the analysis equipment.

3.1 Reference gas mixture.

A reference gas mixture is a mixture of pure gases that often closely resembles the natural gas to be measured upon. The mixture is usually prepared using gravimetrical techniques which still is the most accurate method of preparing gas mixtures.

ISO Standard 6142 (ref. 7) gives guidelines in the preparation of these reference gas mixtures. But the standard is too general a standard to achieve reproduceability between different laboratories. Fortunately actions are being taken now to revise this standard also in the forum of ISO TC 193 SC1.

The uncertainty of the composition of the reference gas mixture is of great importance as the uncertainty of the determination of the molar composition of the gas sample is directly proportional to the uncertainty of the reference gas mixtures.

In table 3 is seen some of the major parameters in preparing reference gas mixtures that can contribute to the uncertainty of the mixture. As can be seen several parameters contribute to the uncertainty of the reference gas mixture besides the weighing procedure.

Table 3 Some major parameters in gas mixing	
1.	Impurities of the gases used in the mixing.
2.	Lack of knowledge of impurities.
3.	Lack of cleanlines of the gas cylinders, and the mixing system(e.g. valves,tubing)
4.	Insuffcent filling/weighing procedures.

After having mixed the gas the question of checking the gas mixtures arises and the methods of checking or analysing the reference gas mixture are often less accurate than the methods of preparing the gas mixture (gas chromatography versus gravimetrical techniques).

Following up on the preparation of the reference gas mixture parameters that are often forgotten are the stability of the mixture and the influence of the different pressures of the gas as the reference gas mixture is being used.

3.2 Traceability of reference gas mixtures.

The interest in traceability in analysis of gas in general and thereby in reference gas mixtures is reflected by the number of European and International groups that are working towards obtaining traceable determinations. In table 4 some of the groups are mentioned.

Table 4

Organization	Working Groups
1. WECC[2]	Reference Materials.
2. ISO TC 193 SC1	Traceability in natural gas analysis.
3. ISO-REMCO[3]	Reference Materials.
4. EURACHEM[4]	No 5: Calibration in Chemistry.

All the groups mentioned have as one of their work items promised to obtain a close liason with other relevant working groups to avoid double work. And in fact at least one person: Deputy Manager mr. Anton Alink of the VSL of NMi[5], is a member of all four working groups. FORCE-Dantest has a close contact through NMi to the work and is a member of the first 2 working groups. FORCE-Dantest is representing the Danish Institute for Fundamental Metrology in the WECC working group. All of these working groups are no more than 2 years old.

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[2] WECC: Western European Calibration Cooperation

[3] ISO-REMCO: Council Commitee on Reference Materials

[4] EURACHEM: European Analytical Chemistry in General

[5] VSL of NMi: The Van Swinden Laboratorium of The Netherlands Measurements Institute, Holland

In the following will be given a short description of the scopes of the two first mentioned working groups and a status of the work in the groups up to now.

3.2.1 WECC:

As a working group for a cooperation of calibration services the main scope of this working group is to develop guidelines (protocols) that the calibration services of each country can use to accredit laboratories. In this case the laboratories are gas manufacturers who manufacture reference gas mixtures.

The initial protocols are at this state being set up by members of NMi, BNM, NPL and SFM[6]. In Europe there exists three manufacturers of gas that are already accredited following national protocols and for reference gas mixtures that are relevant for the measurement of exhaust gases. They are situated in Switzerland. In England and Holland several gas manufacturers have shown an interest in accreditation.

Another important purpose is to establish a close cooperation between the different countries in establishing reference gas mixtures with the level of primary gas standards. These can be produced by the National Standards Laboratory or by equivalent laboratories i.e. laboratories which are authorized by each government. One of the major aspects of this is the necessary intercomparisons between these laboratories and exchange of information. Laboratories that at this stage manufacture primary gas standards are NMi, NPL and NIST[7].

The major result of this work is to obtain the possibility that traceability of a reference gas mixture can be obtained through comparison to primary gas standards.

3.2.2 ISO TC 193 SC1 Advisory group: Traceability.

The main aim of this group is to aid the working groups of the SC1 in obtaining the description of traceable methods in their standards. The advisory group therefore set up a scope in which primarily general guidelines should be made by the group which the other working groups should apply to their standards.

---

[6] NMi: Netherlands Measurements Institute, Holland
BNM: Bureau National de Metrologie, France
NPL: National Physical Laboratory, UK
SFM: The Swiss Federal Office of Metrology, Switzerland

[7] NIST: National Institute of Standards and Technology, USA

Secondarily the advisory group would then review each draft standard for the correctness of the application of the guidelines. The guidelines were given out as a 1 st. draft in June 91 and were also submitted to ISO-REMCO (Ref. 1).

Although the guidelines are far from finished they give an idea in what direction the advisory group is aiming namely again that traceability of a reference gas mixture can be obtained through comparison to primary gas standards.

The guidelines are meant for ISO standardization groups who have to implement traceability in their standards but the guidelines can be used in many other connections although not at the level of the natural gas analytical equipment.

3.3 Summarizing

- The traceability in measurement of natural gas quality corresponds in this paper to the traceability in analysis of natural gas using gas chromatography.
- One of the major problems in obtaining traceability in the analysis of natural gas using gas chromatography is the lack of traceability of the reference gas mixtures used to calibrate or check the gas chromatographs.
- Several International and European working groups are working on solving the problems for nearly all levels in the traceability chain of reference gas mixtures. And the major idea is that traceability of a reference gas mixture can be obtained through comparison to primary gas standards.

4.0 Conclusions

Each level in the traceability chain of reference gas mixtures is being worked on except possibly the level of the natural gas analytical equipment. The major idea being that traceability of a reference gas mixture can be obtained through comparison to primary gas standards.

The Norwegian Petroleum Directorate has asked FORCE-Dantest to produce guidelines for traceability in measurement of natural gas quality, (ref. 2) that could be used at the level of the analytical equipment. A first draft of the guidelines has been completed and comments to these guidelines and how to implement them are very welcome.

To help the work being done it is now necessary for us, the users, to begin possibly not yet demanding that, but at least enquiring whether our gas manufacturers follow this work as closly as possible.

One thing is to establish guidelines another is to put them to use, here is where all of us can be of help. Even at this early stage the awareness of the necessity and possibility of traceability will help the cause.

The possibility of obtaining traceable reference gas mixtures following the concepts described in this paper is not possible at this stage except from a few National Standards Laboratories of which the larger are NIST, NMi and NPL.

But in 5 years time we will hopefully be looking back and saying: Traceability in measurement of natural gas quality - No problem!

5.0 Postscript

One of the major problems in the methods for checking reference gas mixtures is that the accuracy level of the methods are often many times less than the preparation methods of the gas mixtures. At the Gas Density Laboratory at FORCE-Dantest we have a method for checking reference gas mixtures. It will not check the mole fraction of each constituent but will check the overall uncertainty and thereby detect any major error sources. The uncertainty of this method is very close to the uncertainty of the preparation method. The method is based on the determination of the mole mass of gas and a project partially funded by the National Council of Metrology in Denmark has been performed to prove the efficiency of this method, ref. (8).

6.0 Reference list

1) ISO TC 193 SC1. Advisory Group Traceability: General Features of traceability in the analysis of gas.

2) FORCE-Dantest: Guidelines for traceability in measurement of natural gas quality, 1990-04-26

3) ISO 6976: Natural Gas - calculation of Calorific Values, Density, Relative Density and Wobbe Index from Composition.

4) BIPM/IEC/ISO/OIML/IFCC/IUPAC:
International vocabulary of basic and general terms in metrology (VIM). Draft revision 1989.

5) ISO/DIS 10723:
Natural gas-analysis of natural gas and natural gas substitutes - performance evaluation.
(DIS: Draft International standard)

6) ISO 6974 - Natural Gas - Determination of hydrogen, inert gases and hydrocarbons up to C8 - Gas chromatographic method.

This document is now being revised by ISO/TC 193 SC1 WG8: Natural gas - The determination of natural gas composition for the calculation of calorific value, density and wobbe-index with calculable uncertainty. Gaschromatographic method.(Working Group Draft)

7) ISO 6142 Gas Analysis - Preparation of calibration gas mixtures - Weighing Method.

8) The FORCE Institutes: Determining the Mole Mass of Gas-Verification of a method that can be used in quality control of reference gas mixtures.

Norwegian
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NORTH SEA FLOW MEASUREMENT WORKSHOP

OCTOBER 22. - 24. 1991
SOLSTRAND FJORD HOTEL, BERGEN - NORWAY

TESTING OF CORIOLIS METERS FOR METERING OF OIL CONDENSATE AND GAS

Lecturers:

Mr. Jens Grendstad, Kongsberg Offshore A/S
Mr. Jostein Eide, FIMAS
Mr. Per Salvesen, AUTEK A/S

Kongsberg Offshore a.s
North Sea Flow Measurement Workshop 1991

Title

TESTING OF CORIOLIS METERS FOR METERING OF OIL, CONDENSATE AND GAS

0	07.10.91	J.Grendstad	[signature]	[signature]	[signature]	
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TABLE OF CONTENT

1 INTRODUCTION

The tests described in this paper are the results of a joint venture development project to investigate and qualify the abilities of Coriolis mass flowmeters for fiscal measurement of gas and liquid.

The companies responsible for the project was:

- Autek Instrument a.s (Micro Motion representative)
- Fimas (Schlumberger representative)
- Kongsberg Offshore a.s (Project responsible, Mechanical engineering and Control System Design)
- Elf Aquitane Norge a.s
- The Norwegian Petroleum Directorate
- Phillips Petroleum Company Norway a.s (PPCON)
- Saga Petroleum a.s
- Statoil. (Den Norske Stats Oljeselskap a.s)

The project was established the 30. August 1990 and finalized on the 9. Mai 1991.

The main objectives of the project to design and test the performance of a metering station based on coriolis mass flowmeters suitable for high pressure gas application. The testing was done at the K-lab natural gas test loop.

The metering station (testrig) was designed specifically for the test and standard coriolis mass flowmeters were selected to meet the maximum test pressure of 100 Bar.

In addition Statoil provided the group with the opportunity to check the performance of the coriolis mass flowmeters in a liquid application at Kårstø NGL plant using the N-butane liquid loading facilities.

This paper has been prepared by Kongsberg Offshore a.s, Autek Instrument a.s and Fimas.

2 ABBREVIATIONS

NGL - Natural Gas Liquids
KOS - Kongsberg Offshore a.s
MM - Micro Motion Master Meter
MM1 - Micro Motion Meter 1
MM2 - Micro Motion Meter 2
NPD - The Norwegian Petroleum Directorate

3 TESTRIG DESIGN

To make the tests as realistic as possible the project decided to design a purpose made testrig. The testrig was designed to test 3 mass flowmeters, model DH300-S manufactured by Micro Motion and 1 mass flowmeter, model 7860B manufactured by Schlumberger.

The arrangement of the testrig is shown in Figure 1. Four photos that illustrate the final testrig design is included as appendices.

One of the main installation requirements for coriolis mass flowmeters are to minimize pipe stress on the sensor process connections, both axial and lateral. This was reflected in the rig design by the positioning of the Micro Motion Master Meter (MM) and the Micro Motion Meter no. 1 (MM1) in the upper positions.

The rig was designed so that each coriolis mass flowmeter could be run either separately or in series with the Master Meter. Each metering line was equipped with two downstream shutoff valves with a bleed port in between. This to ensure actual zero flow when adjusting the transmitters zero set point.

At the inlet of the testrig an extra pipe construction where made consisting of four off 90 degree bends. This pipe section could be connected to the inlet manifold by manually operating the appropriate shut off valves. The purpose of this pipe section was to test if the upstream pipe configuration influenced the mass flowmeters accuracy.

The Micro Motion Master Meter and the Schlumberger mass flowmeter was monitored for pressure drop across the flowmeters by differential pressure transmitter. In addition the rig itself was monitored for pressure drop by means of one pressure transmitter on the inlet manifold and one on the outlet manifold.

The testrig was designed according to Statoils specifications for equipment to be installed K-lab.

Size of testrig: Length = 5.9 m
Height = 2.1 m
Width = 2.5 m

Weight of testrig = approx. 2.5 tonnes

4 CORIOLIS MASS FLOWMETER SPECIFICATIONS

The manufacturers specifications given for the coriolis mass flowmeters are available only for liquid and thereby relevant only for the liquid test on N-butane. The specifications could only be used as an indication of what to expect when using the mass flowmeters in Natural Gas since no testing on these meters had been performed on natural gas before.

Micro Motion Model D300 Mass Flow and Density Sensor

Maximum Flowrate	: 200 tonnes/hour
Nominal Pipe bore	: 80 mm
Mass Accuracy	: ±0.20% of rate ± zero stability
Mass Repeatability	: ± 0.05
Mass zero stability	: ± 0.11 tonnes/hour
Max Operating pressure	: 276 Bar
Temperature range	: - 240 to +204 degree Celsius

Schlumberger Massmaster 150

Maximum Flowrate	: 150 tonnes/hour
Nominal Pipe bore	: 50 mm
Mass Accuracy	: ±0.25% of rate ± zero stability
Mass Repeatability	: ± 0.05
Mass zero stability	: ± 0.03 tonnes/hour
Max Operating pressure	: 150 Bar
Temperature range	: - 50 to +110 degree Celsius

5 CONTROL SYSTEM DESIGN

A special Control System was made by Kongsberg Offshore a.s (KOS) to sample the data from the mass flowmeters and from the instruments on the test rig.

The Control System consisted of the following main parts:

- One Computer Cabinet containing:
    - One Massmaster Flowcomputer type 7960 (Schlumberger)
    - Three RFT 9712 Mass Flow Transmitters (Micro Motion)
    - One Process Machine (Kongsberg Offshore)
- Free Standing Items
    - One VDU (Interfacing the Process Machine)
    - One PC with VDU (Data Storage)
    - One printer.

The Process Machine interfaced the instrumentation on the testrig, the Schlumberger flowcomputer and the Micro Motion Mass Flow Transmitters. For each Test run the Process Machine sampled all process data and stored them in separate files. These files could be transferred to the PC for further treatment and presentation on VDU or as printed.

See Figure 2.

6 TEST ON LIQUID

This test was performed at the Kårstø NGL plant using the N-butane Liquid loading facilities.

6.1 Aim of the Test

The aim of the test was to verify the performance of the coriolis mass flowmeters on liquid. In addition the test were to verify the functionality of the testrig, the coriolis mass flowmeters and the control system before the gas test.

The metering accuracy aimed for where ± 0.5 %.

6.1.1 Reference Conditions

6.1.1.1 Test Fluid

The test fluid was N-butane. Samples of the liquid was collected and analysed before and after the test period. The results showed that the composition could be considered as constant during the test. The tests was performed at the following conditions:

Pressure : approx. 10 Bar
Temperature : 3-5 degree Centigrade

6.1.1.2 Reference Flowmeter

The reference flowmeter for this test was a 3" Brooks turbine meter calibrated using a compact prover

The linearity of the turbine meter within the flowrange 10:1 was ± 0.15 %

6.1.1.3 Reference Density

The calculation of the liquid density was performed using the API COSTALD method. For N-butane this method will give an accuracy of ± 0.3 % or better.

6.1.2 Description of the Tests

Figure 3 is giving a representation of the practical test arrangement.

Liquid N-butane is pumped through the test setup using the pumps on the N-butane tank.

The flow rate through the test arrangement was limited by the pressure drops in the recirculation line, testrig and the calibration skid.

These operational limitations made it possible to carry out tests at only three different relatively low flowrates:

Mass flow : approx. 15, 30 and 40 tonnes/h

6.1.3 Test Procedure

Prior to the start of the test the 3" Brooks turbine reference meter was calibrated at the three different actual flowrates:

15 tonnes/h
30 tonnes/h
40 tonnes/h

An accurate meter factor was thereby established as an reference. The density of the liquid was known from the Costald calculations.

The tests were performed as follows:

1) The flow was manually started and data for the reference meter and the coriolis mass flowmeter on test was noted.

2) Pulses from the reference meter and the mass flow meter was read continously by the appropriate flowcomputers for 2 hours.

3) The flow was stopped manually and data for the reference meter and the mass flowmeter on test was noted.

4) The reference mass flow was calculated multiplying the number of pulses collected from the Brooks reference meter, dividing by the meter factor from the Brooks reference for the actual rate and multiplying by the density calculated by the Costald routine. The Brooks meter factor is the average meter factor as determined by the Con-tech´s Turbine meter calibration computer.

Two testruns were performed. The first was run with MM1 in series with [illegible] second test was run with the Schlumberger mass flow meter in seri[illegible]

6.1.4 Test Results

The results for MM1 and the Schlumberger mass flowmeter are presented in Figure 4 and Figure 5. The figures show the coriolis mass flowmeters deviation from the reference plotted for the three test flow rates.

It should be noted that the meter factor for both the Micro Motion meter and the Schlumberger meter used during the test was determined from the water calibration of the coriolis mass flowmeters.

Further the equipment used in this test are high pressure versions of the mass flowmeters.

6.1.4.1 Schlumberger

The Schlumberger mass flowmeter made a close to perfect linear relationship but were off the correct result with approximately +1%. The reason for this can be explained by a to early zero set point setting. Adjusting the straight line to an assumed correct zero set point gives a metering accuracy well within the specification of the mass flowmeter.

See Figure 4.

6.1.4.2 Micro Motion

The accuracies obtained for the Micro Motion mass flowmeter were well within the specified accuracy of the mass flowmeter. Results are only plotted for the "MM1".

During the test it became evident that the Micro Motion "Master Meter" showed abnormal behaviour. In order to confirm this, the "Master Meter" and the "MM1" was interchanged. New tests where carried out and the error with the "Master Meter" was confirmed. Stress caused by distortion between flanges are the most likely reason for the high deviation from the reference meter.

Finally the "MM2" connected in parallel with the "Master Meter" showed instability, and was subsequently disconnected". A possible reason for the instability was crosstalk.

7 TEST ON NATURAL GAS

This test was performed at K-lab using the natural gas test loop.

7.1 Aim of the test

The aim of the test was to calibrate the mass meters against the reference bank of sonic nozzles at K-lab. In addition repeatability, reproducibility and cross talk should be checked.

The accuracy aimed for was ± 1% within a operational range to be defined through the tests. This reflecting the requirements for fiscal measurment of gas from NPD.

7.2 Reference Conditions

7.2.1 Test Fluid

The test fluid was natural gas with the following composition.

C1 = 84.94
C2 = 12.10
C3 = 0.71
IC4 = 0.03
NC4 = 0.05
IC5 = 0.00
NC5 = 0.00
C6+ = 0.00

N2 = 0.93
CO2 = 1.24
H2O = 0.00
H2S = 0.00

7.2.2 Reference Flowmeter

The reference flowmeter were K-labs bank of sonic nozzles which where calibrated over the range of 20 to 100 bars absolute.

The flow computation through the nozzle bank was performed by a specially designed Scientific Data Acquisition System.

K-lab makes a statement of uncertainty using the sonic nozzles of 0.3% of the mass flowrate.

7.2.3 Reference Density

The reference density in the nozzle bank was calculated using the AGA8 equation of state.

7.3 Description of the Tests

Figure 6 is giving a representation of the practical test arrangement.

A centrifugal compressor circulates the gas around the loop. Three air coolers cool down the gas coming from the loop compressors before the gas enters the 6" test section where the testrig was installed, and finally the gas passes through the sonic nozzle section.

The tests performed can be divided in three main groups:

1) Preliminary Test:

   - Crosstalk
   - Repeatability

2) Main calibration Tests:

   - Micro Motion 1 (MM1)
   - Micro Motion Master Meter
   - Schlumberger

3) Additional Tests:

   - Effect of twisted bend
   - Reproducibility test
   - Clamp test
   - Schlumberger installed directly in line
   - Effect of zero adjustment

See Table 1 for a complete Test Matrix.

7.4 Test Procedure

The following procedure was used to obtain a test point.

1) The number of nozzle lines necessary to achieve the required flow through the test loop were opened.

2) The loop was flared or filled with gas until the pressure was as close as possible to the requested test pressure.

3) The pressure control set point was adjusted so that the test pressure was correct upstream the nozzles.

4) The cooling system was adjusted so the gas had the correct temperature upstream the nozzles.

5) If neseccary the flow were adjusted by opening or closing more nozzles.

6) Then the system was left alone until the pressure and temperature had stabilised.

7) Then, at the same time the flow on the SDAS and the Kongsberg Offshore a.s (KOS) data acquisition system where integrated for a period of three minutes. This was repeated until 5 test points where obtained.

7.5 Test Results

7.5.1 Preliminary Tests

The test started with a check of the repeatability of the different mass flowmeters and continued with cross talk tests. Cross talk tests where done by turning the power on and off the mass flowmeters which where not in operation.

The preliminary tests where performed at 37 degree Celsius, 70 bara and a flowrate of 30.6 tonnes/h.

Micro Motion

Three tests were done to check crosstalk effects and repeatability on the MM.

The results are given below:

Test no	Mean Dev. from Sonic Nozzles MM	Repeatability MM	Flow through Meter	Power on	Power off
1	- 0.14	± 0.95	MM	MM,	MM1&MM2
2	1.05	± 0.94	MM	MM&MM2	MM1
3	0.46	± 0.90	MM	MM&MM1	MM2

Two test were done to check crosstalk effects and repeatability on the MM2. The results are given below:

Test no	Mean Dev. from Sonic Nozzles MM2	Repeatability MM2	Flow through Meter	Power on	Power off
1	- 1.01	± 0.57	MM2	MM2	MM1&MM
2	- 3.46	± 0.26	MM2	MM2&MM	MM1

From these tests it was difficult to determine whether the deviation from the sonic nozzles were caused by crosstalk or was a result of the poor repeatability.

The only "clear" indication of a possible crosstalk effect was on the MM2 which had an clear increase in the mean deviation from the sonic nozzles. The decision was made to disconnect the MM2 and to continue testing on MM1 and the Master Meter.

In addition to these tests, the massflow displayed by the Micro Motion mass flow transmitter was observed, while the power on the MM2 and MM1 where turned on and off. The same were checked and with loose clamps and tight clamps on meter flanges. No clear change in massflow could be observed.

Schlumberger

A repeatability test was performed on the Sclumberger massmeter at 70 bar a and 37 degree Celsius at a flowrate of 2.9 kg. The repeatability of this meter was ± 0.05 %.

This is within the Schlumberger mass flowmeter specification for liquid, however here obtained using gas.

7.5.2 Main Calibration Tests

7.5.2.1 Micro Motion Meter 1

The results obtained calibrating the MM1 against the sonic nozzles are summarised in Figure 7 and Table 2.

As can be seen from the results of the Micro Motion Meter 1, the meter functioned well within the aim of the test (accurcay of ± 1% of rate) for the following conditions:

Pressure (bar)	Temp (deg C)	Flowrate (tonnes/h)
70	37	5.3 - 28.1
100	50	20.0 - 59.3
100	37	55.0 - 60.8

An additional observation is that all results are above the zero line and following the same trend as the specified accuracy curve for the meter. This could mean that the zero is not correct set on the meter. Moving the results to an assumed correct zero would bring the results within the meters specified accuracy for liquid which is given in Table 2.

7.5.2.2 Master Meter

The results obtained calibrating the Micro Motion Master Meter against the sonic Nozzles are summarised in Figure 8 and 9 and Table 3 and 4.

Worth noticing is that this is the meter which was installed with a certain amount of stress on the process connections.

The results obtained at 70 bar are not within aim of the test but the results are following the same trend as the specified accuracy curve of the meter. The deviation from the correct result are increasing with decreasing flowrate.

The results within the aim of the test (± 1% of rate) obtained at 100 bars are summarised below:

Pressure (bar)	Temp (deg C)	Flowrate (tonnes/h)
100	37	7.8 - 23.1
100	50	22.4 - 40.5

The results which were within the aim of the test were obtained when the MM was connected in series with the MM1. When connecting the Schlumberger meter in series with the MM the values obtained from the Meter tended to shift to an higher uncertainty but still following the specified trend of the accuracy curve. To find the reason to this trend more tests will have to be performed.

7.5.2.3 Schlumberger Mass meter

The results obtained when calibrating the Sclumberger meter against the sonic nozzles are summarised in Figure 10 and Table 5.

The results obtained within the aim of the test (accuracy of ±1% of rate) are summarised below.

Pressure (bar)	Temp (deg C)	Flowrate (tonnes/h)
70	37	7.8 - 15.6
70	50	2.5 - 15.1
100	50	11.2 - 29.4
100	37	4.0 - 30.3
20	40	2.1 - 4.2
55	37	2.1 - 5.5

The results obtained from the Schlumberger meter are as for the Micro Motion meters. following the same trend as the specified accuracy curves of the Meter. The maximum flowrate obtained through the Schlumberger meter is lower than the corresponding maximum value of the Micro Motion meter. This is due to the different diameter of the Meters.

7.5.3 Additional Tests

Effect of twisted bend

The idea was to see if the accuracy of the meters changed if the twisted bend upstream the inlet manifold was connected or not.

Several tests where run but no influence on the accuracy could be observed.

Reproducibility test

Several tests where run confirming that the results where reproducible.

Clamp test

This test was run for Micro Motion meters only.

The aim of this test was to see the influence of a "bad" installation. First a test where run with the clamps tight. Then the clamps where loosened and a new test where run.

This procedure introduced a shift in the metering accuracy of approximately 2%. This confirming the importance of installing the meters according the manufacturers requirements.

Effect of zero adjustment

After the clamp test the clamps were tightened and the meters zero point were adjusted. The accuracy of MM1 after this procedure was + 0.5 % of the correct result when running at 70 bara, 50 degree Celsius and a flowrate of 27 tonnes/hour. This underlining the importance of adjusting the zero set point of the Micro Motion meters whenever changes has been made.

Schlumberger meter Installed directly in the line

The Schlumberger meter was installed directly in the test loop to quantify the effect of the Test rig when it comes to limitations in the flowrate.

In the testrig the Schlumberger meter could measure 20.52 tonnes/hour before the measurment error became to large. Installed directly in the loop the maximum flowrate was increased to 25.92 tonnes/hour (26% increase).

It is worth notizing that the change in location from the testrig to the test loop was done without resetting the zero. The metering accurcay of the meter was not influenced by the change in process and installation conditions.

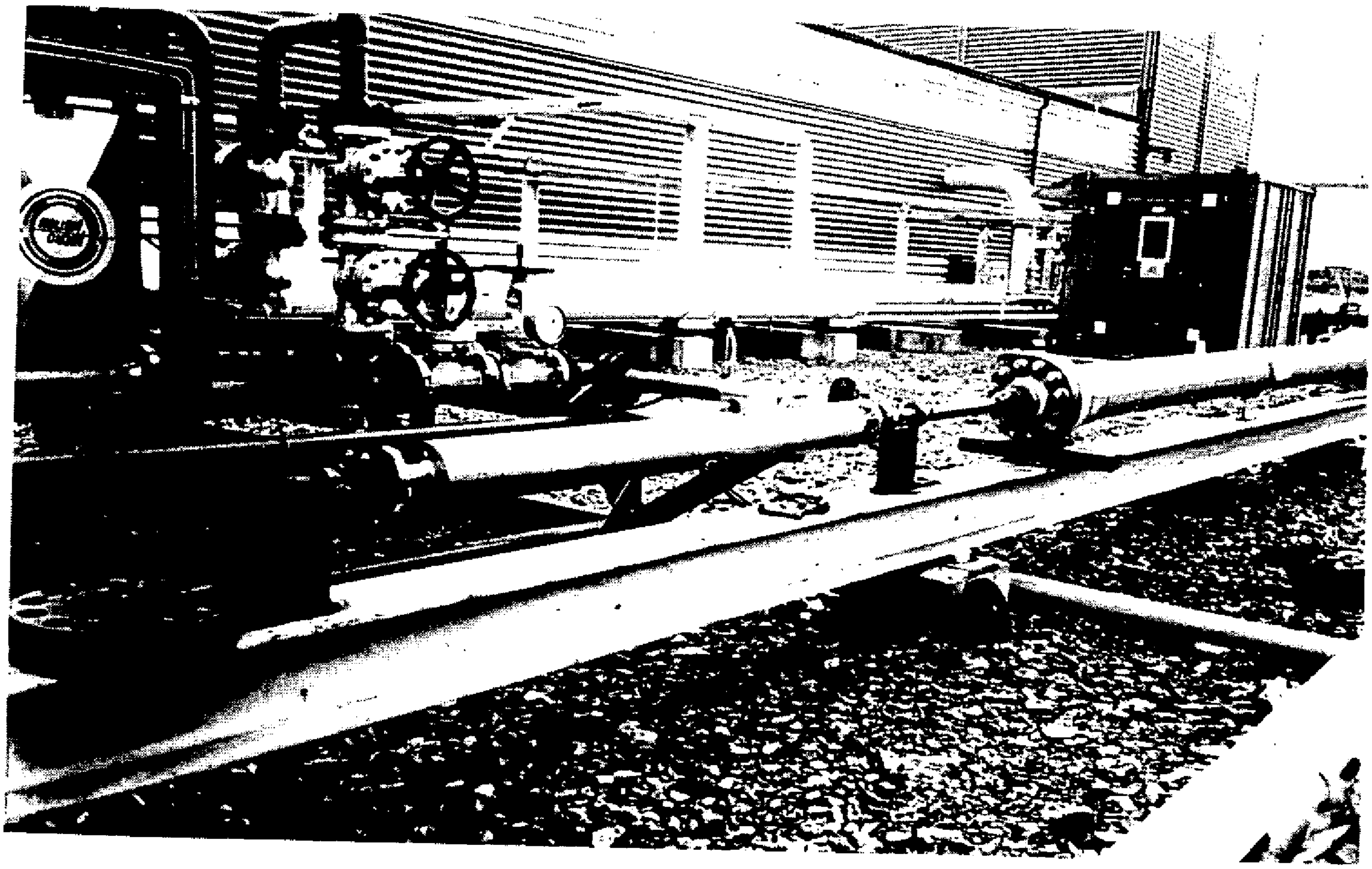
This indicating that more consideration must be put into minimizing the pressure drop when designing Coriolis Metering Skids.

8 LESSONS LEARNED

- The importance of a correct zero point setting whenever a change in temperature or pressure has occured for Micro Motion mass flowmeters
- The importance of correct installation of the coriolis mass flow meters.
- Calibration of the coriolis meters should if possible be performed on the fluid which they are to be used.
- Selection of the coriolis mass flowmeters must carefully consider the process conditions which they are to meet

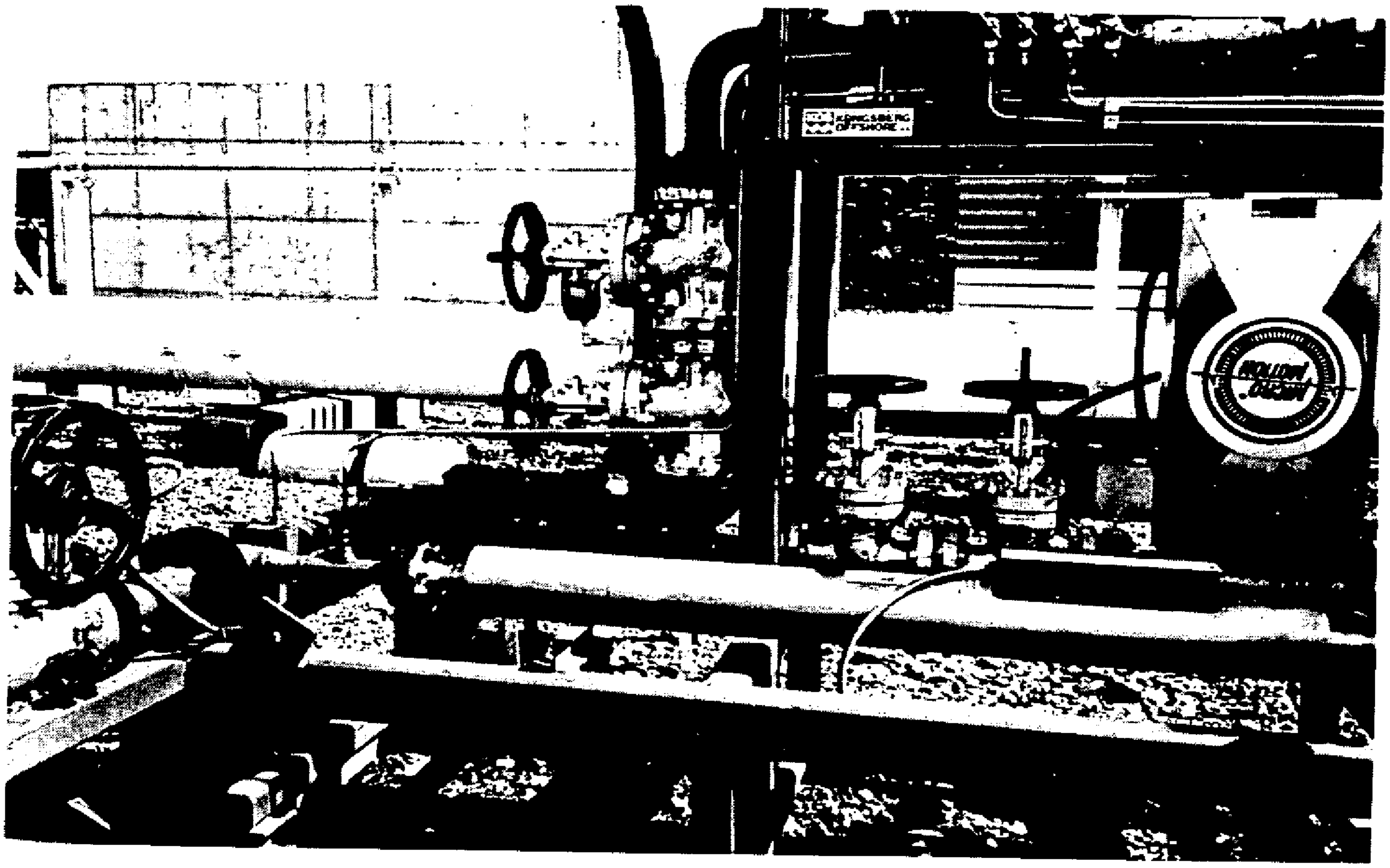
APPENDIX A

PHOTOS



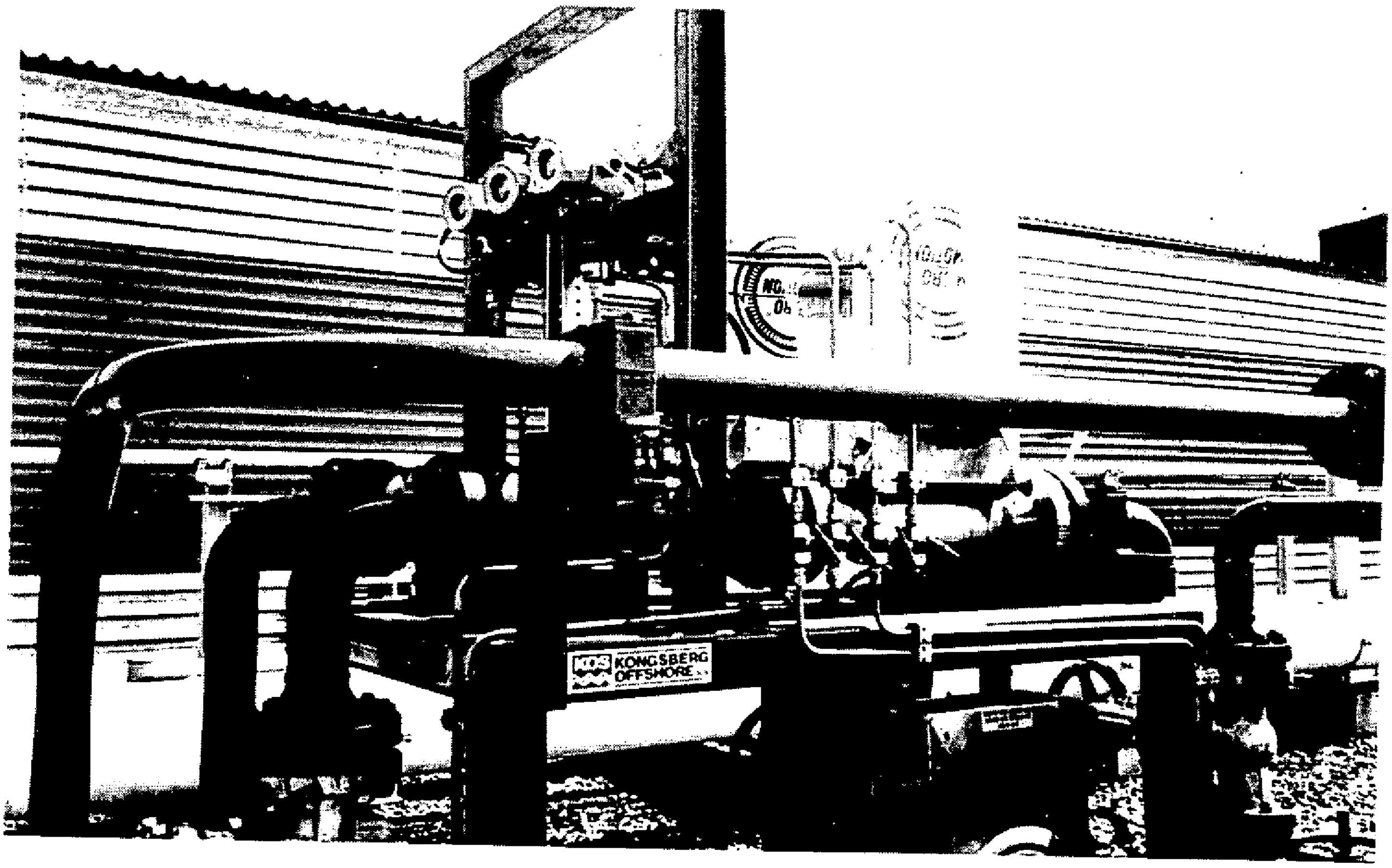
DETAILS OF THE SCHLUMBERGER MASS FLOW METER
INSTALLED DIRECTLY IN THE TESTLOOP

PHOTO 4



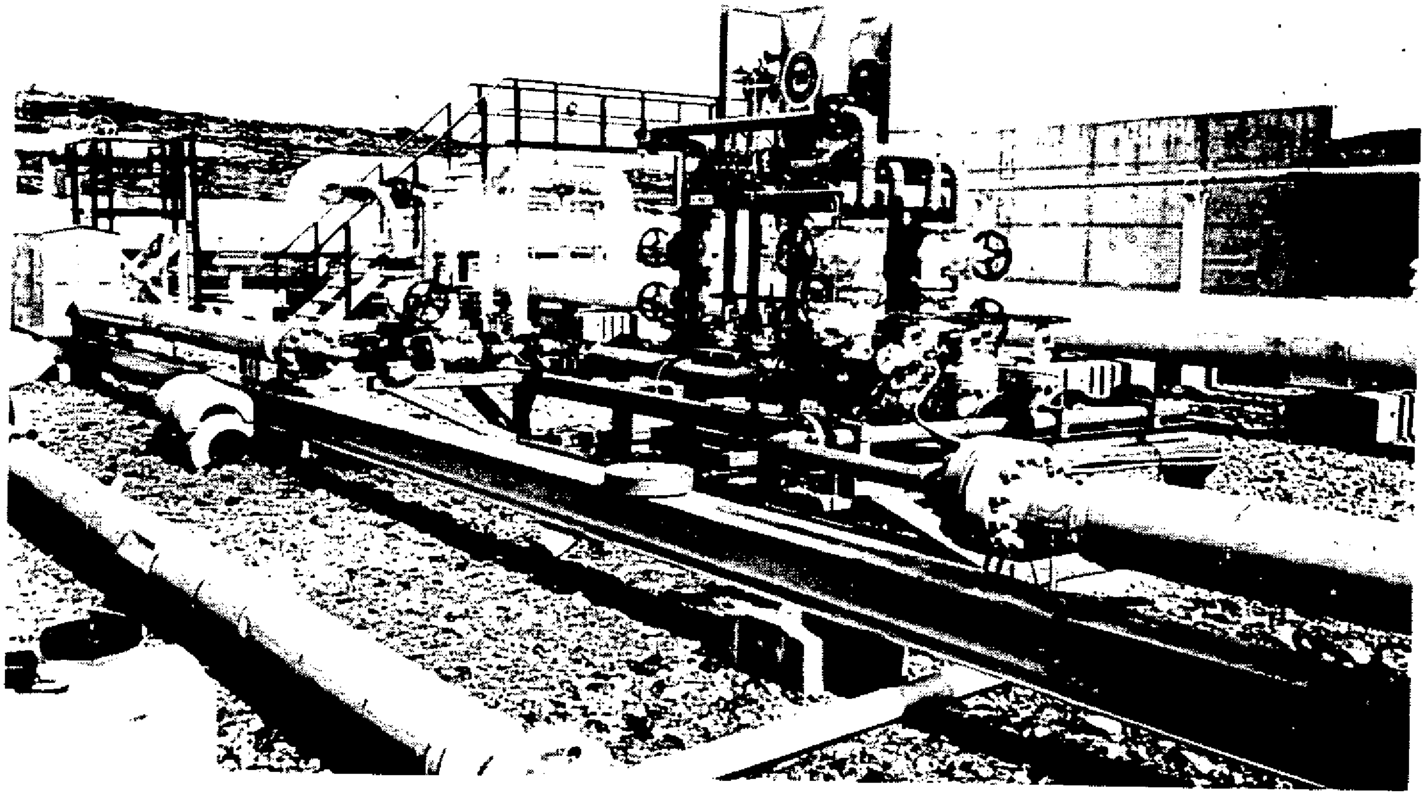
DETAILS OF THE SCHLUMBERGER MASS FLOW METER
INSTALLED IN THE TESTRIG

PHOTO 3



DETAILS OF THE MICRO MOTION MASS FLOW METER
INSTALLED IN THE TESTRIG

PHOTO 2



TESTRIG INSTALLED IN THE NATURAL GAS TEST LOOP
AT K-LAB

PHOTO 1

APPENDIX B

FIGURES

TESTRIG LAYOUT

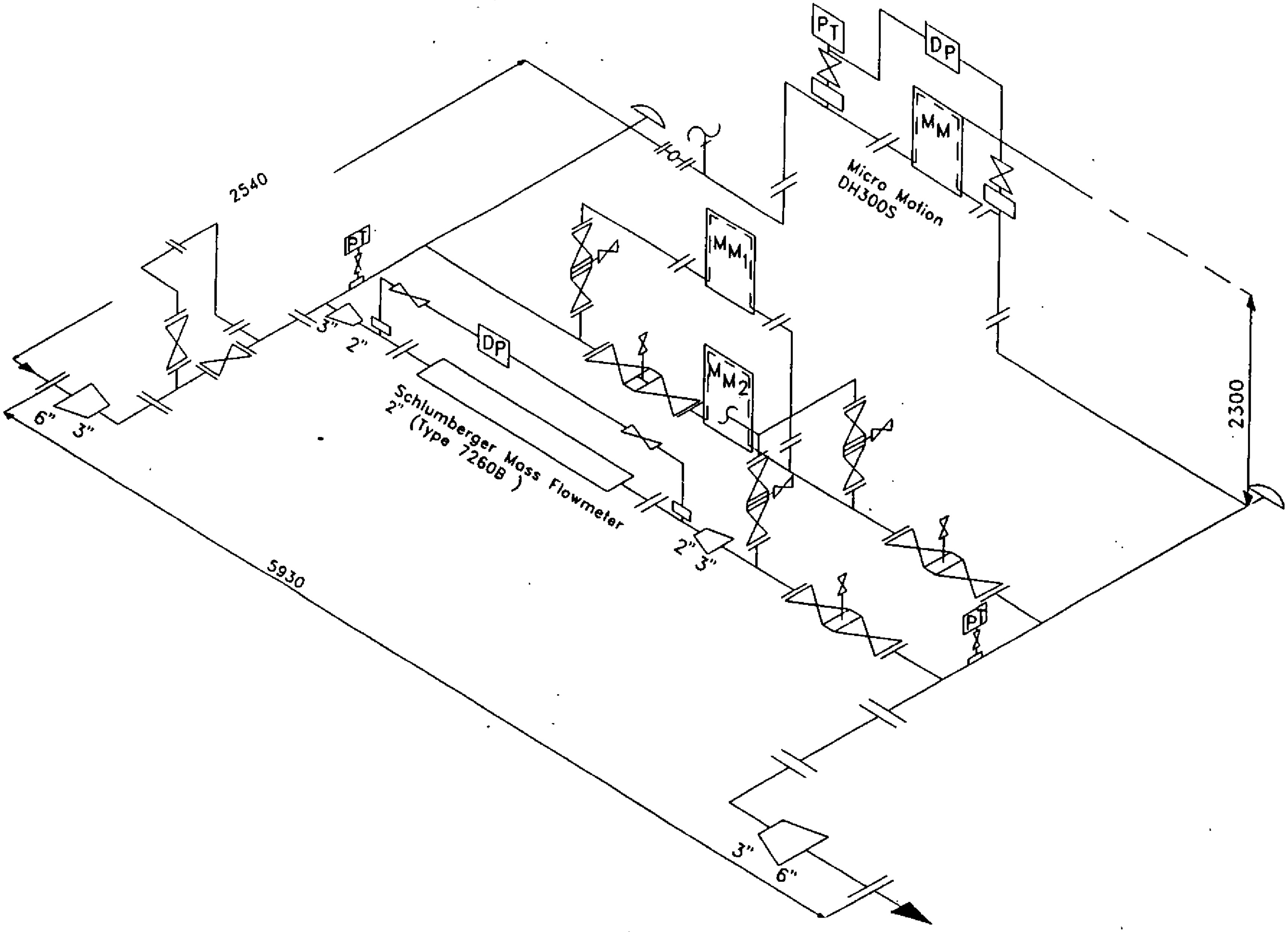


FIGURE 1

CORIOLIS TEST CONTROL SYSTEM

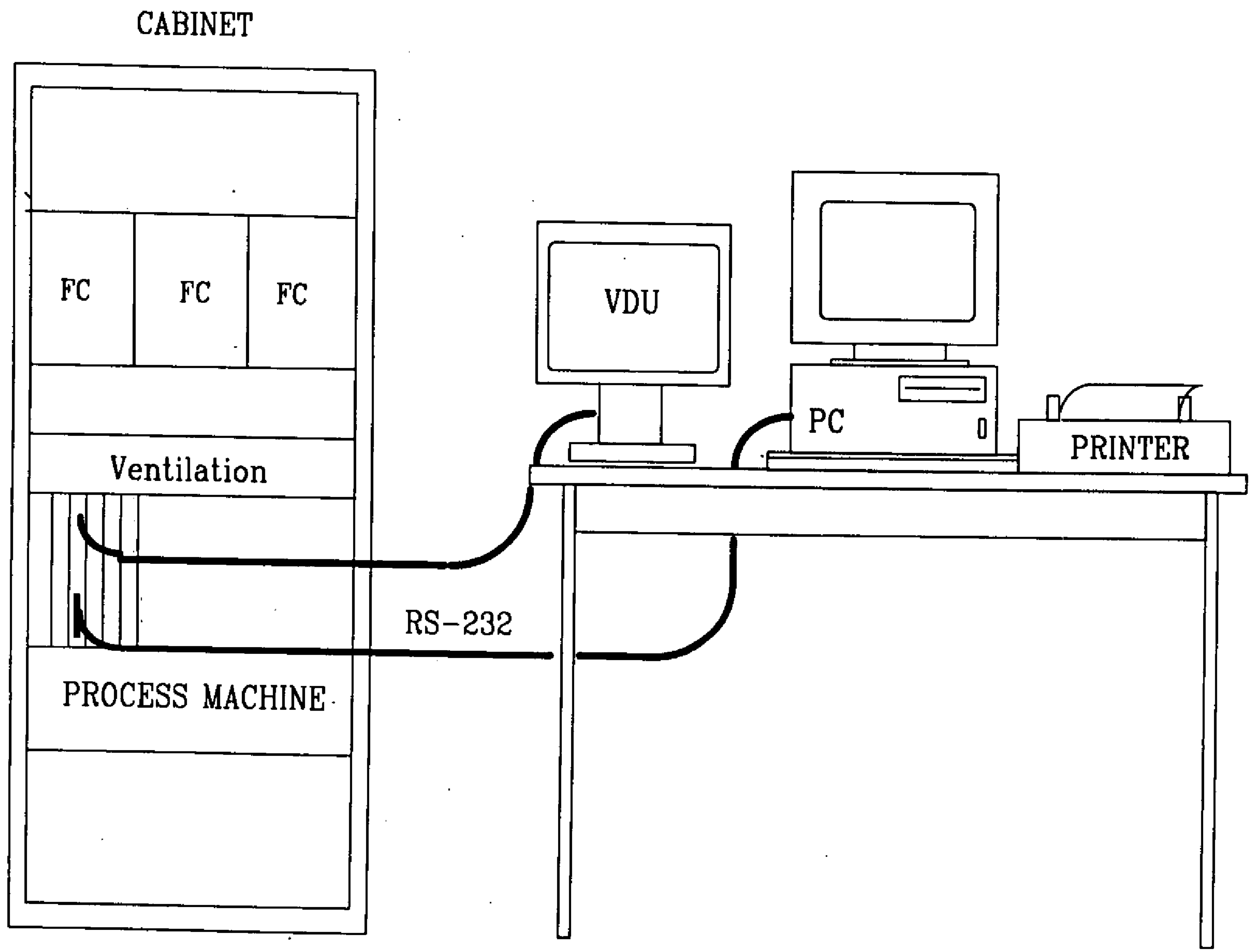


FIGURE 2

ARRANGEMENT FOR TESTING MASS FLOWMETERS IN LIQUID

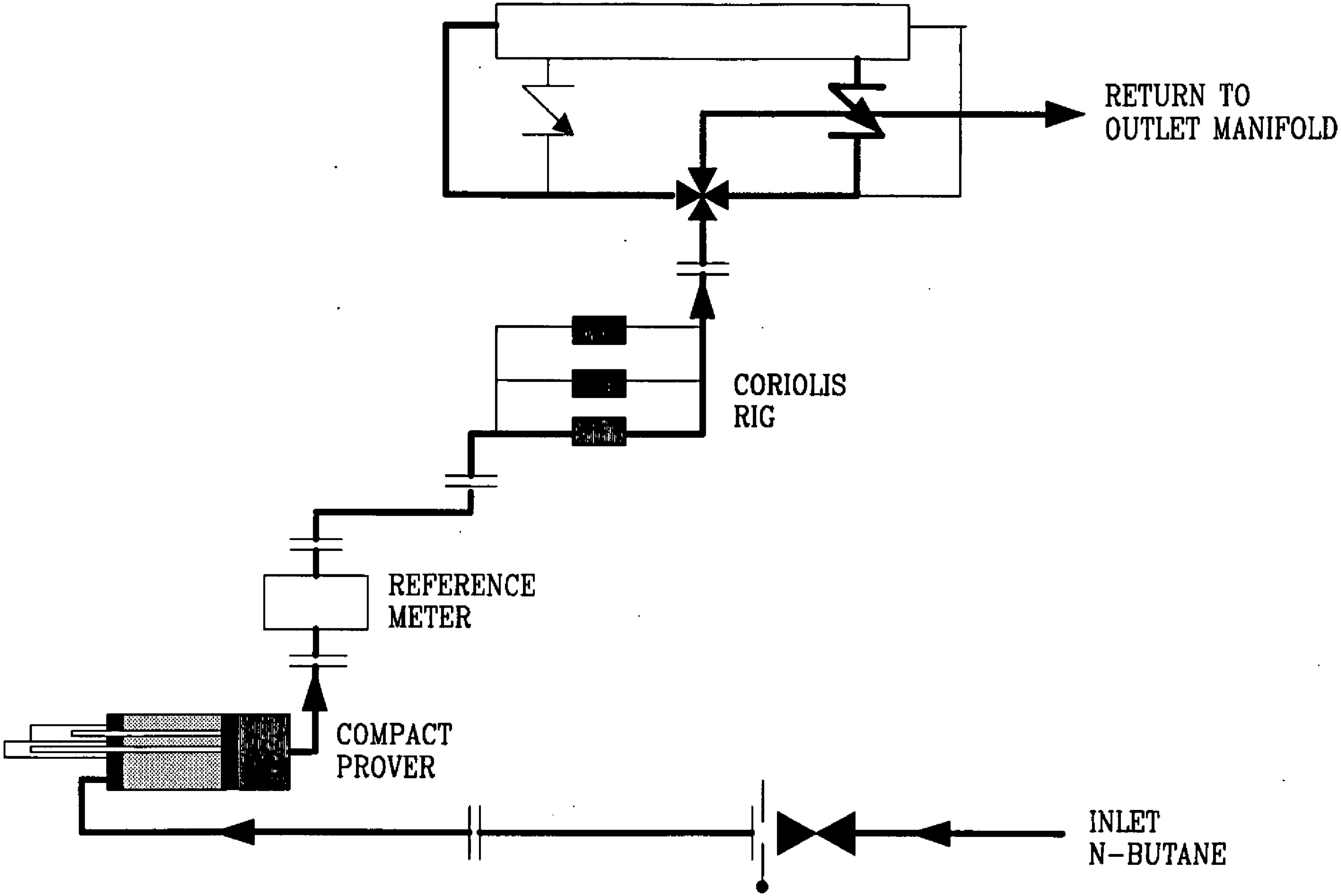


FIGURE 3

GRAPH SHOWING DEVIATION IN PERCENT BETWEEN
REFERENCE METER AND SCHLUMBERGER MASS FLOWMETER

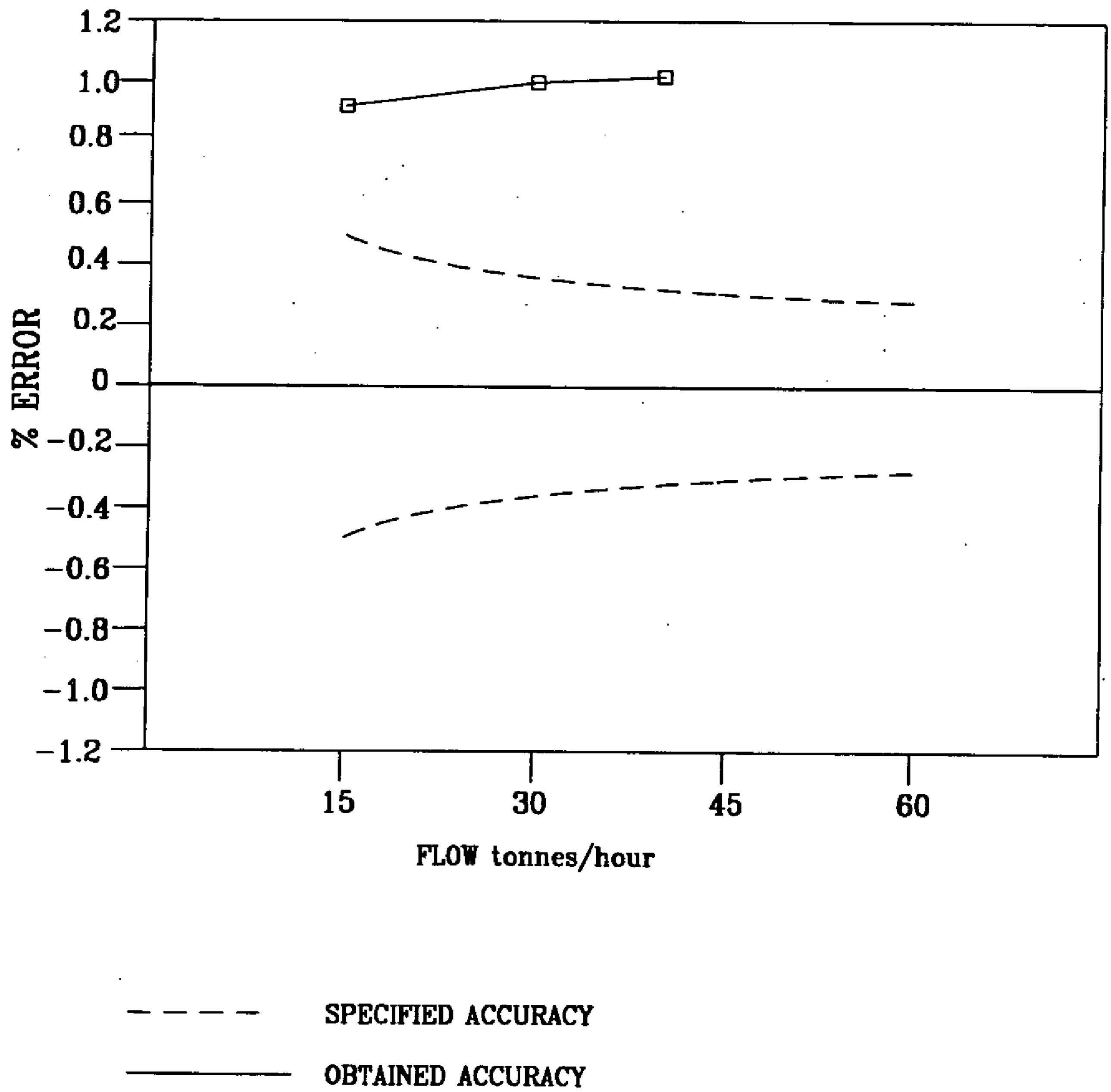


FIGURE 4

GRAPH SHOWING DEVIATION IN PERCENT BETWEEN REFERENCE METER AND MICRO MOTION MASS FLOWMETER

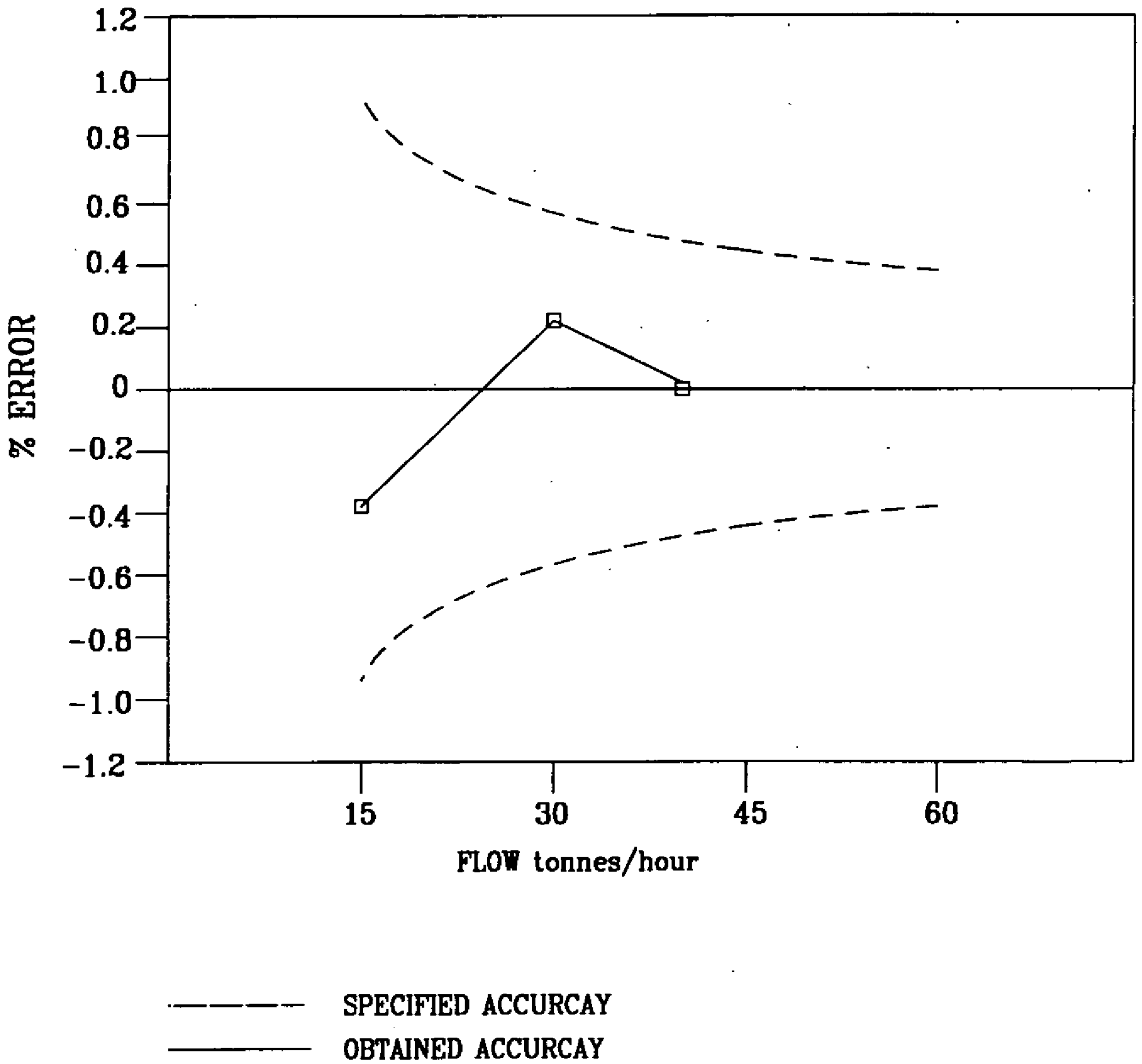


FIGURE 5

SCHEMATIC LAYOUT OF THE K-LAB TEST LOOP

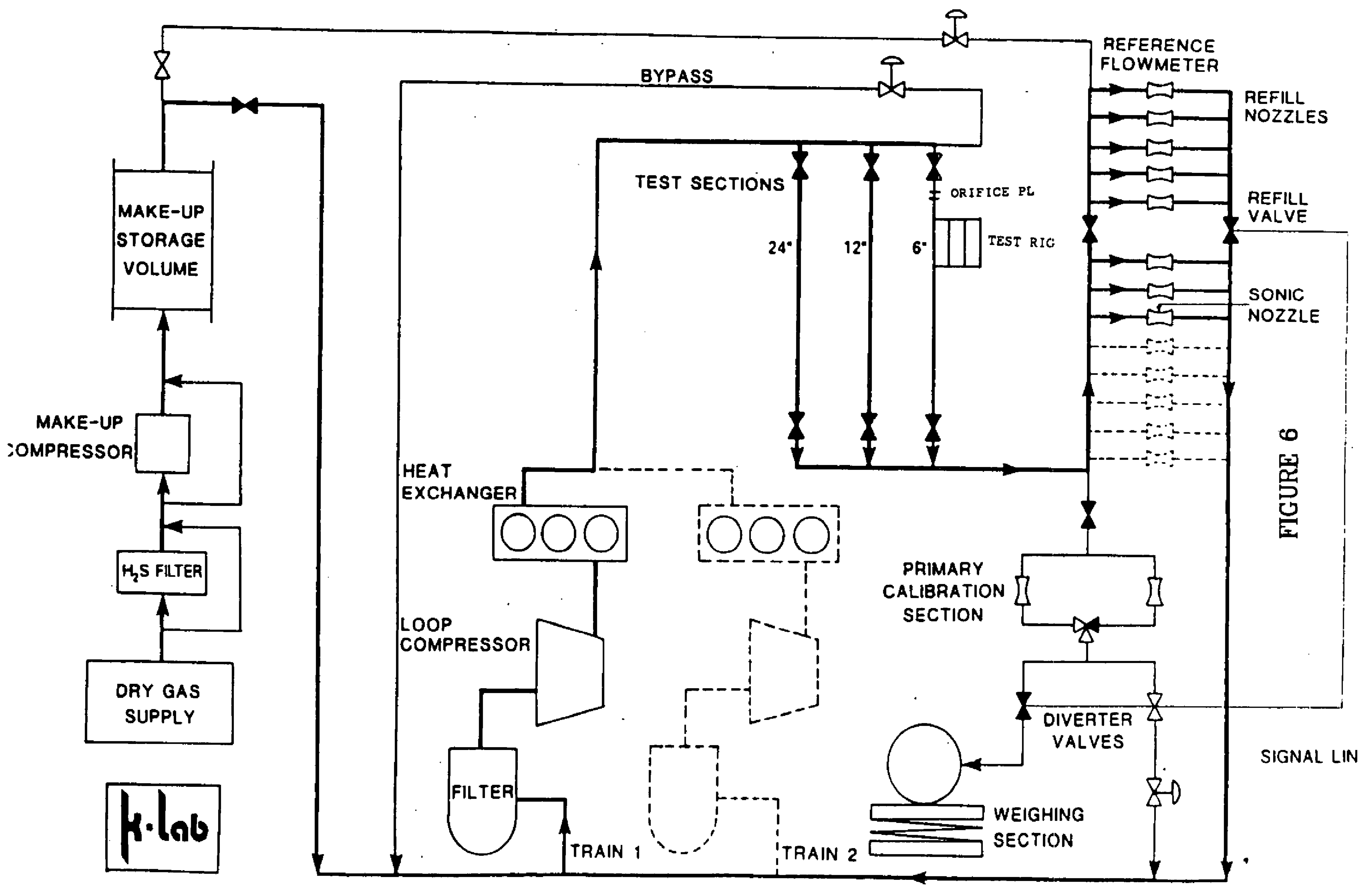
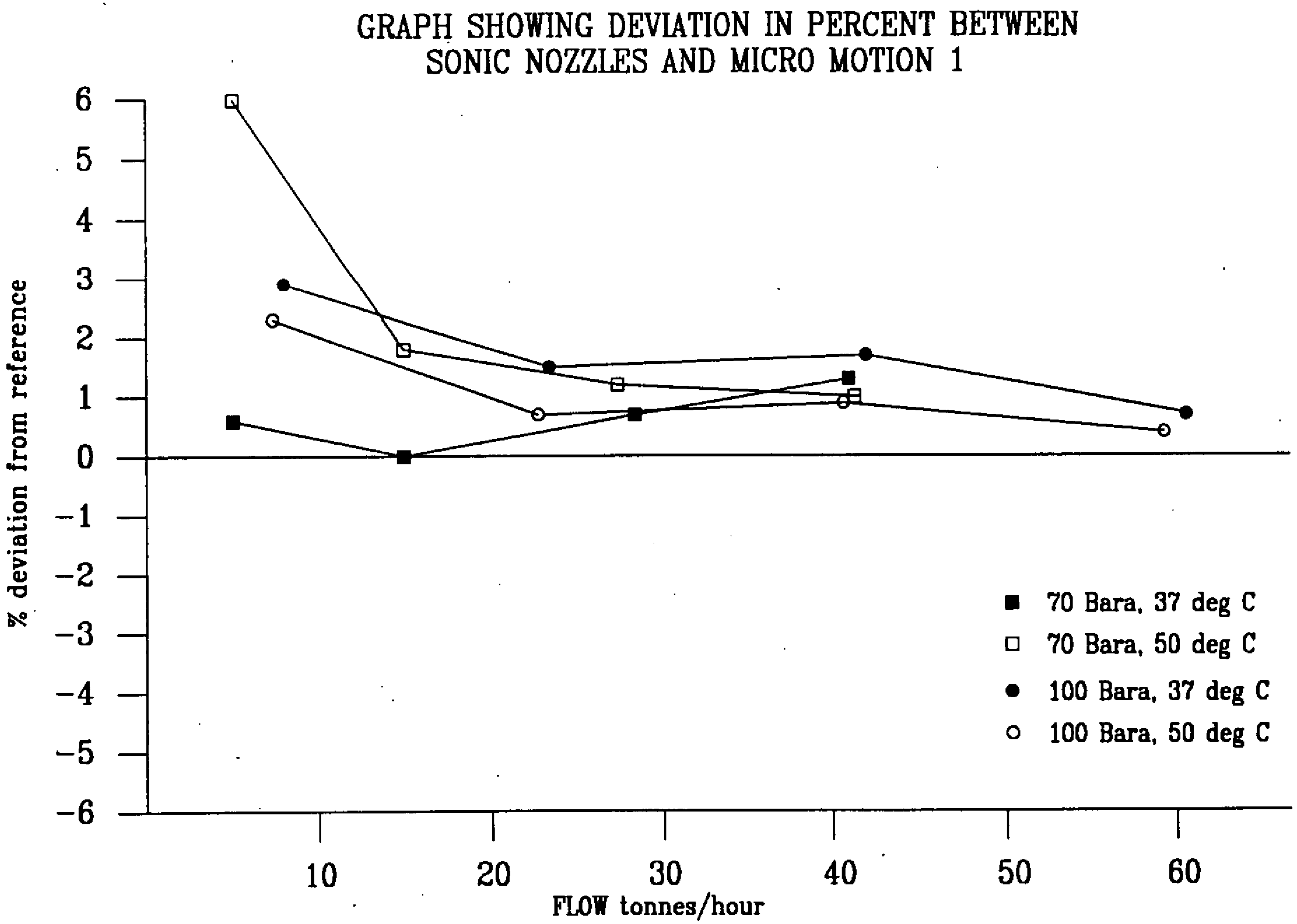
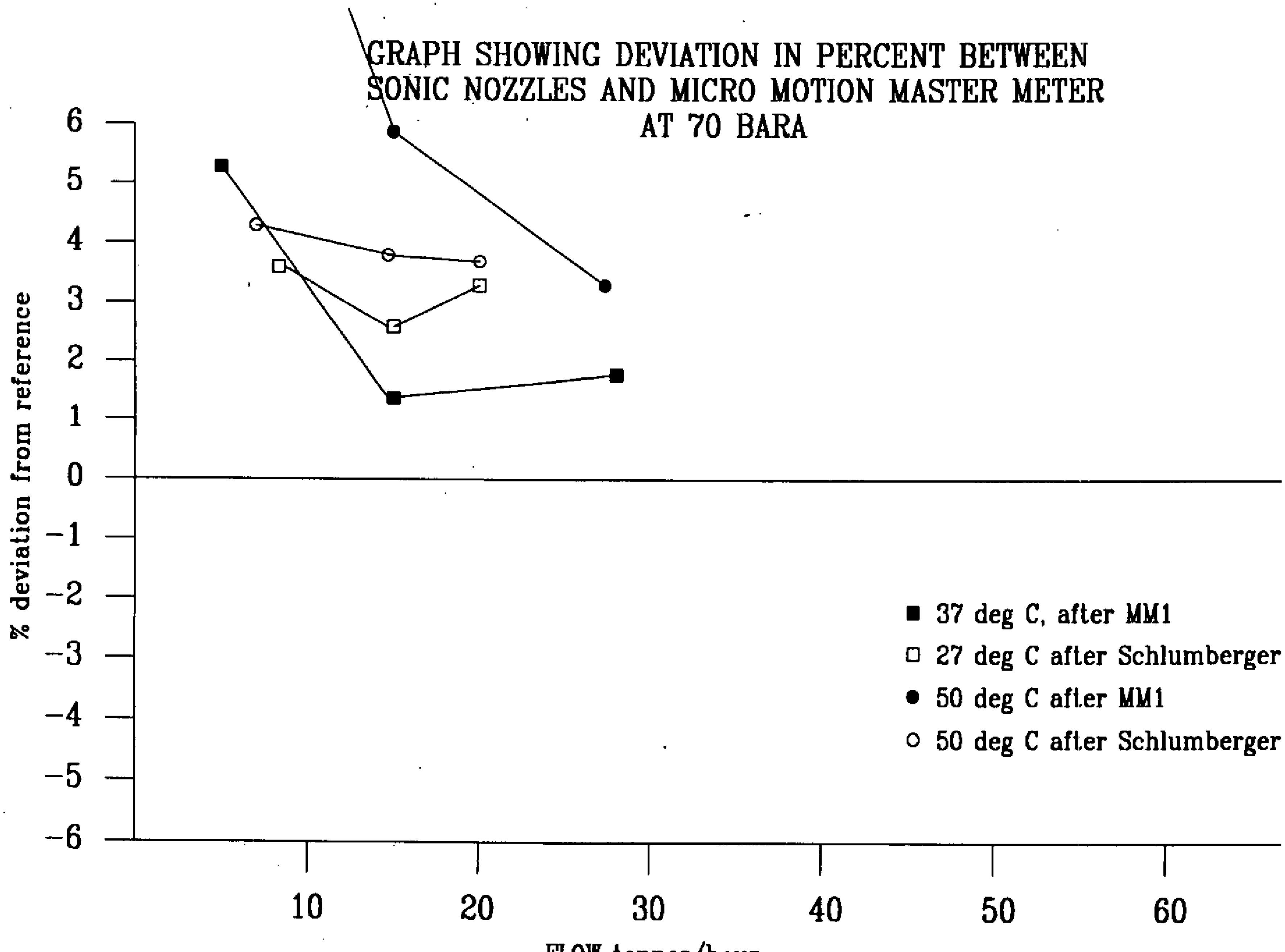


FIGURE 6



GRAPH SHOWING DEVIATION IN PERCENT BETWEEN
SONIC NOZZLES AND MICRO MOTION 1
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
% deviation from reference
10
20
30
40
50
60
FLOW tonnes/hour
70 Bara, 37 deg C
70 Bara, 50 deg C
100 Bara, 37 deg C
100 Bara, 50 deg C

FIGURE 7



GRAPH SHOWING DEVIATION IN PERCENT BETWEEN
SONIC NOZZLES AND MICRO MOTION MASTER METER
AT 70 BARA
% deviation from reference
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
10
20
30
40
50
60
FLOW tonnes/hour
37 deg C, after MM1
27 deg C after Schlumberger
50 deg C after MM1
50 deg C after Schlumberger

FIGURE 8

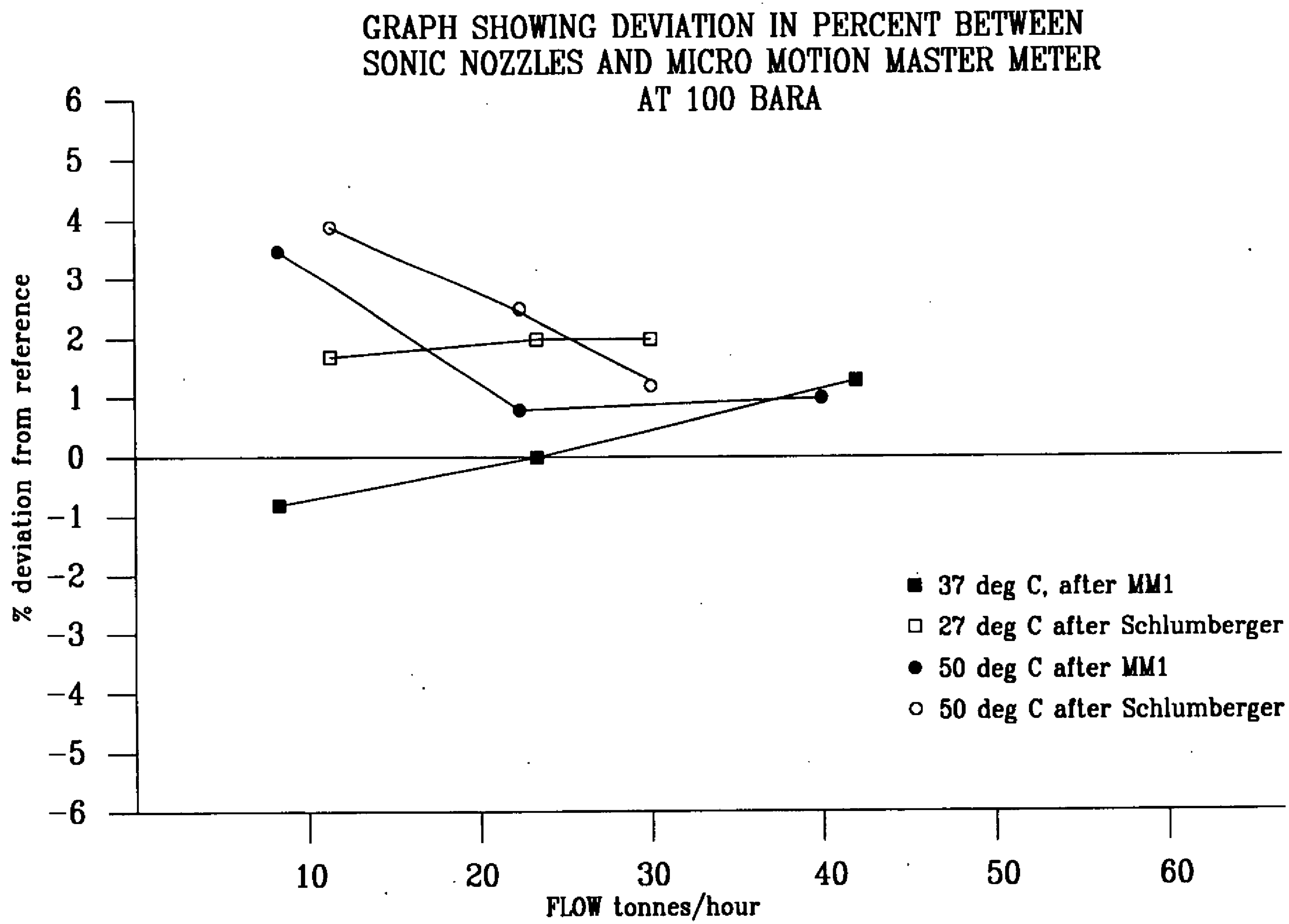

GRAPH SHOWING DEVIATION IN PERCENT BETWEEN
SONIC NOZZLES AND MICRO MOTION MASTER METER
AT 100 BARA
% deviation from reference
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
10
20
30
40
50
60
FLOW tonnes/hour
37 deg C, after MM1
27 deg C after Schlumberger
50 deg C after MM1
50 deg C after Schlumberger

FIGURE 9

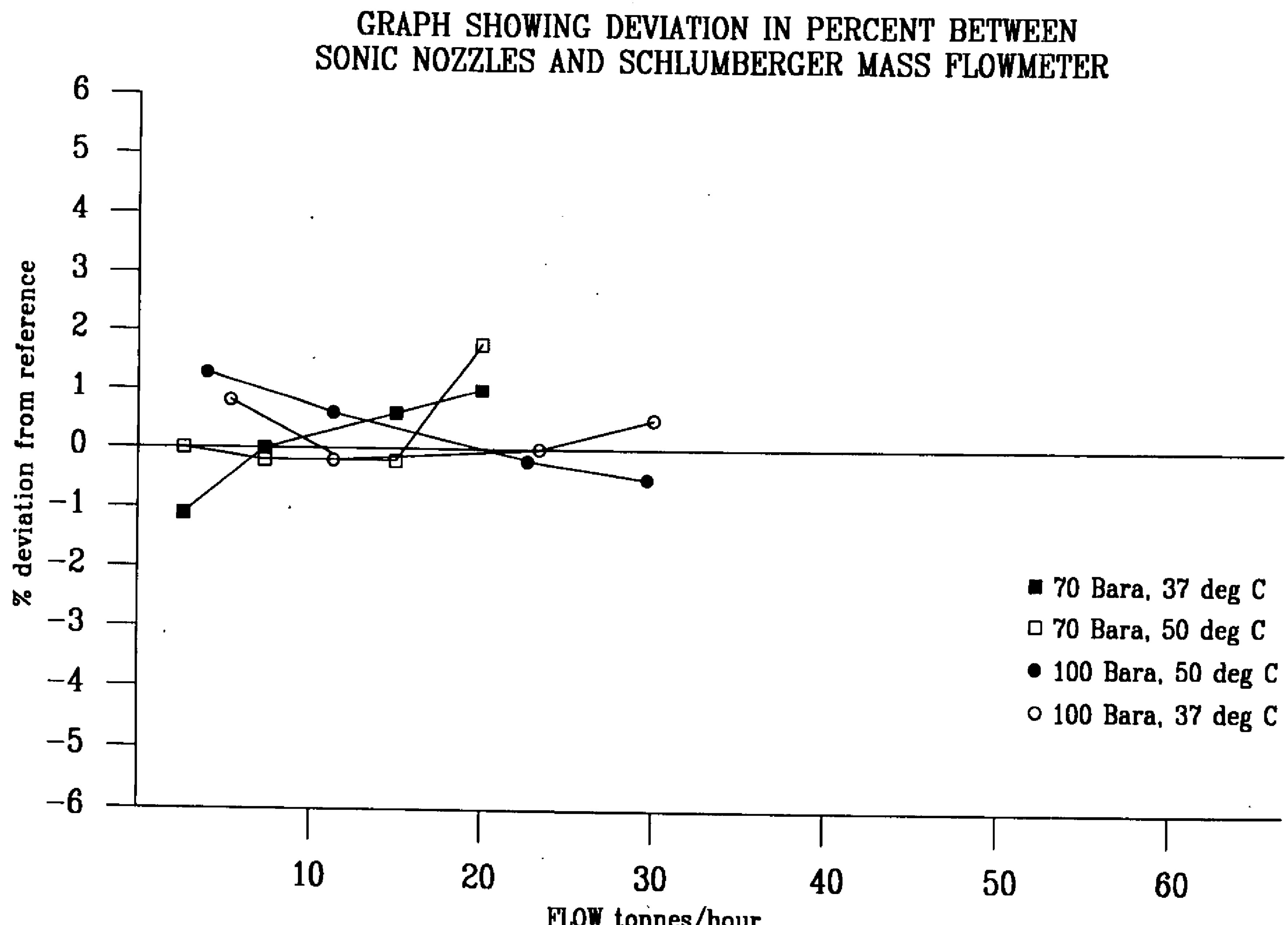

GRAPH SHOWING DEVIATION IN PERCENT BETWEEN
SONIC NOZZLES AND SCHLUMBERGER MASS FLOWMETER
% deviation from reference
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
10
20
30
40
50
60
FLOW tonnes/hour
70 Bara, 37 deg C
70 Bara, 50 deg C
100 Bara, 50 deg C
100 Bara, 37 deg C

FIGURE 10

APPENDIX C

TABLES

TABLE 1

TEST MATRIX

TEST NO	SENSOR	PRESS (BAR)	TEMP. (C)	FLOWRATE (TONN/H)			
0-146	ALL	70	37	31.0			PRELIMINARY TESTS
146-150	MM1	70	37	41.0			
151-165	MM1+MASTER	70	37		28.1	15.5	5.3
166-185	SCH +MASTER	70	37	20.4	15.6	7.8	2.6
186-190	MM1	70	50	39.9			
191-205	MM1+MASTER	70	50		27.4	15.1	5.1
207-225	SCH-MASTER	70	50	20.4	15.1	7.6	2.5
226-230	MM1	100	50	59.3			
231-245	MM1+MASTER	100	50		40.5	22.4	7.6
246-265	SCH+MASTER	100	50	29.4	22.4	11.2	3.7
266-270	MM1	100	37	60.8			
271-285	MM1+MASTER	100	37		42.1	23.1	7.8
286-305	SCH+MASTER	100	37	30.3	23.2	11.6	4.0
306-310	MM1	20	40	11.2			
311-325	MM1+MASTER	20	40		7.6	4.3	1.5
328-347	SCH+MASTER	20	40	5.5	4.2	2.1	0.7
353-372	SCH+MASTER	55	37	15.7	11.9	6.0	2.0
373-380	SCH+MASTER	55	37	15.7	6.0		TWISTED BEND
381-391	MM1+MASTER	70	50	27.1	15.0	5.4	REP. TEST
392-401	MM1+MASTER	70	50	27.2 1)	27.2 2)	27.2 3)	
402-404	MM1+MASTER	70	50	27.2 4)			
405-408	MM1+MASTER	70	50	27.2 5)			
409-411	SCH+MASTER	70	50	19.7			REP. TEST
413-425	SCH	70	37	10.4	20.5	25.6	5.1

1) LOOSE CLAMPS MM1

2) TIGHT CLAMPS MM1

3) MM1 ZERO ADJUSTED

4) TWISTED BEND

5) POWER OFF ON ALL OTHER METERS

TABLE 2

CALIBRATION RESULTS
MICRO MOTION METER 1

PRES (bar)	TEMP (deg C)	FLOWRATE (tonnes/h)	SPECIFIED ACCURACY	AIM OF TEST ACCURACY	OBTAINED ACCURACY
70	37	41.0	± 0.47	± 1.00	1.70
		28.1	± 0.59	± 1.00	0.90
		15.5	± 0.90	± 1.00	-0.07
		5.3	± 2.26	± 1.00	0.70
70	50	39.9	± 0.47	± 1.00	1.12
		27.4	± 0.60	± 1.00	1.21
		15.1	± 0.92	± 1.00	1.86
		5.1	± 2.33	± 1.00	5.97
100	50	59.3	± 0.38	± 1.00	0.39
		40.5	± 0.47	± 1.00	0.95
		22.4	± 0.69	± 1.00	0.72
		7.6	± 1.64	± 1.00	2.28
100	37	60.8	± 0.38	± 1.00	0.70
		42.1	± 0.46	± 1.00	1.65
		23.1	± 0.67	± 1.00	1.56
		7.8	± 1.60	± 1.00	2.95

Note: All accuracies are given in percent of mass flowrate.
The specified accuracies are for the mass flowmeter used for metering liquid.

TABLE 3

CALIBRATION RESULTS
MICRO MOTION MASTER METER AT 100 BARS

AFTER SENSOR:	TEMP (deg C)	FLOWRATE (tonnes/h)	SPECIFIED ACCURACY	AIM OF TEST ACCURCAY	OBTAINED ACCURACY
MM1	37	42.1	± 0.46	± 1.00	1.33
MM1	37	23.1	± 0.67	± 1.00	0.03
MM1	37	7.8	± 1.60	± 1.00	0.61
SCH	37	30.3	± 0.56	± 1.00	2.08
SCH	37	23.2	± 0.67	± 1.00	1.99
SCH	37	11.6	± 1.14	± 1.00	1.69
MM1	50	40.5	± 0.47	± 1.00	0.99
MM1	50	22.4	± 0.69	± 1.00	0.81
MM1	50	7.8	± 1.60	± 1.00	3.51
SCH	50	29.4	± 0.57	± 1.00	1.26
SCH	50	22.4	± 0.69	± 1.00	2.47
SCH	50	11.2	± 1.17	± 1.00	3.90

Note: All accuracies are given in percent of mass flowrate.
The specified accuracies are for the mass flowmeter used for metering liquid.

TABLE 4

CALIBRATION RESULTS
MICRO MOTION MASTER METER AT 70 BARS

AFTER SENSOR:	TEMP (deg C)	FLOWRATE (tonnes/h)	SPECIFIED ACCURACY	AIM OF TEST ACCURACY	OBTAINED ACCURACY
MM1	37	28.1	± 0.59	± 1.00	1.78
MM1	37	15.5	± 0.90	± 1.00	1.37
MM1	37	5.3	± 2.26	± 1.00	5.35
SCH	37	20.4	± 0.73	± 1.00	3.32
SCH	37	15.6	± 0.92	± 1.00	2.52
SCH	37	7.8	± 1.60	± 1.00	3.59
MM1	50	27.4	± 0.60	± 1.00	3.36
MM1	50	15.1	± 0.92	± 1.00	5.92
MM1	50	5.1	± 2.33	± 1.00	16.67
SCH	50	20.4	± 0.73	± 1.00	3.73
SCH	50	15.1	± 0.92	± 1.00	3.71
SCH	50	7.6	± 1.64	± 1.00	4.32

Note: All accuracies are given in percent of mass flowrate.
The specified accuracies are for the mass flowmeter used for metering liquid.

TABLE 5

CALIBRATION RESULTS
SCHLUMBERGER MASSMASTER 150

PRES (bar)	TEMP (deg C)	FLOWRATE (tonnes/h)	SPECIFIED ACCURACY	AIM OF TEST ACCURACY	OBTAINED ACCURACY
70	37	20.4	± 0.40	± 1.00	1.09
		15.6	± 0.44	± 1.00	0.66
		7.8	± 0.63	± 1.00	0.08
		2.6	± 1.40	± 1.00	-1.18
70	50	20.4	± 0.40	± 1.00	1.82
		15.1	± 0.45	± 1.00	-0.19
		7.6	± 0.64	± 1.00	-0.23
		2.5	± 1.45	± 1.00	-0.06
100	50	29.4	± 0.35	± 1.00	-0.46
		22.4	± 0.38	± 1.00	-0.19
		11.2	± 0.51	± 1.00	0.66
		3.7	± 1.06	± 1.00	1.32
100	37	30.3	± 0.35	± 1.00	0.51
		23.2	± 0.38	± 1.00	-0.06
		11.6	± 0.51	± 1.00	-0.22
		4.0	± 1.00	± 1.00	0.80
20	40	5.5	± 0.79	± 1.00	1.04
		4.2	± 0.96	± 1.00	0.36
		2.1	± 1.68	± 1.00	-0.34
		0.7	± 4.62	± 1.00	-5.22
55	37	5.5	± 0.79	± 1.00	-0.02
		4.2	± 0.96	± 1.00	-0.39
		2.1	± 1.68	± 1.00	-0.48
		0.7	± 4.62	± 1.00	-1.14

Note: All accuracies are given in percent of mass flowrate. The specified accuracies are for the mass flowmeter used for metering liquid.

Main Index

Norwegian
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Chartered Engineers

NORTH SEA FLOW MEASUREMENT WORKSHOP

OCTOBER 22. - 24. 1991
SOLSTRAND FJORD HOTEL, BERGEN - NORWAY

FIELD EXPERIENCE WITH CORIOLIS MASS METER ON HYDROCARBON LIQUID

Lecturer:

Mr. Sveinung Myhr
Norsk Hydro A/S

HYDRO

FIELD EXPERIENCE WITH CORIOLIS MASS METER ON HYDROCARBON LIQUID

Sveinung Myhr
Norsk Hydro a.s. Rafnes

0. SUMMARY

At Norsk Hydro's petrochemical plant at Rafnes, we have used Coriolis mass meters, for custody transfer metering of hydrocarbon liquid, for nearly 2 years.

The Coriolis meters are installed in series with a turbine meter in three different metering stations.

During the time of operation we have found that the Coriolis meters show about 1 % lower readings than the turbine meters. This is also proved from in situ calibration of a Coriolis meter.

The linearity of the Coriolis meters was found to be within ± 0.2 % when the flowrate was above 10 % of the sensor maximum flowrate. Below this limit the meters tends to drop off. In addition to the observed offset, this necessitate an in situ calibration of the Coriolis meter at operating condition.

Eccept from the above mentioned, the Coriolis meters have shown stable performance, and there have not been any operational problems with them.

CONTENTS

1. INTRODUCTION

Hydro Rafnes petrochemical facility lies in the southeastern part of Norway, about 200 km from Oslo.

The facility consist of three different plants, one ethylene plant, one vinyl chloride plant and one chlorine plant.
The ethylene plant has an annual production of 420 000 tons of ethylene and 80 000 tons of propylene. The raw material is NGL, shipped to Rafnes mainly from Teesside.
The VCM plant has an annual production of 480 000 tons of vinyl chloride monomer (VCM). The raw material is ethylene and chlorine. The major part of the chlorine is produced in the chlorine plant at the facility. This plant has an annual production of 130 000 tons of chlorine, and 142 000 tons of sodium hydroxide (NaOH) as a by-product.

There are about 700 employees at Hydro Rafnes.

The three Coriolis installations which are refered to in this paper are all installed in the ethylene plant.

2. METERING STATIONS

At Hydro Rafnes we have three installations with Coriolis mass meters on hydrocarbon liquid for custody transfer metering. There are two metering stations on propane and one on propylene.

The three metering stations are constructed as shown in fig. no. 1. Meter A is a turbine meter, and a density meter, which in combination with the turbine gives the mass reading from this meter. Meter B is a Coriolis meter. The two meters are connected directly in series, and the mass reading from the two meters can then be compared to each other. A compact prover can be connected to the metering station upstreem meter A, in order to calibrate the meters in situ at operating conditions.

3. METERING RESULTS

Metering Station no 1.

Operating condition:

Medium: Propane
Temperature: 10 - 15 ^{0}C.
Pressure: 15 bara.
Density: 520 - 540 kg/m^3.

The Coriolis meter in this metering station has been in operation since November 1989. The meter was installed with the origional meter factor from the water calibration at the factory.
The turbine meter was last calibrated in-line by the compact prover in February 1988, and was not recalibrated until November 1990.
During the first year of operation, the relative deviation between the two meters was within ± 0.5 %. After recalibration of the turbine meter in November 1990 we found a shift of 1 % in the meter factor. We did not calibrate the Coriolis meter at this time, and after adjusting the turbine meter factor, the readings from the Coriolis meter was now systematically 1 % lower than the turbine meter. The long term repeatability and the linearity of the Coriolis meter seemed however to be quite good. (See diagram no. 2).

Metering Station no 2.

Operating condition:

Medium: Propylene
Temperatur: 25 - 30 ^{0}C.
Pressure: 20 - 30 bara.
Density: 500 - 520 kg/m^3.

The Coriolis meter was installed in February 1990. The origional meter factor from the water calibration at the factory was used. For the first month of operation the relative deviation between the turbine meter and the Coriolis meter was within ± 0.2 %. The turbine was last calibrated in December 1989. After recalibration of the turbine meter in March 1990, the meter factor shifted 1 %. The readings from the Coriolis meter was now systematically 1 % lower then from the turbine meter. The long term repeatability and the linearity has been quite good for this Coriolis meter too. (See diagram no. 3).

Metering Station no 3.

Operating condition:

Medium: Propane
Temperature: 20 °C.
Pressure: 75 bara.
Density: 525 – 550 kg/m^3.

This is our latest installation of Coriolis meter. It has been in operation since May 1991. Also for this meter we have used the original meter factor from the water calibration.
The turbine meter at the time of installation of the Coriolis meter was last calibrated by the prover in January 1988. During the first two months of operation, the Coriolis meter showed systematically 2 % lower readings then the turbine meter. In August 1991 we replaced the turbine meter. This meter was overhauled and calibrated with water in our calibration lab. The relative deviation of the Coriolis meter in proportion to the turbine meter was after this time – 1.5 %. (Fig. no. 4). We have not been able to calibrate this turbine meter in-line with the prover yet, due to some operational problems in the plant. As for the two other Coriolis meters, the offset in proportion to the turbine meter has been stable, and the long term repeatability and linearity seem to be good.

4. CALIBRATION RESULTS

As mentioned above, the Coriolis meters were installed by using the origional meter factor from the water calibration. It was two reasons for this. Firstly, we were not sure how to calibrate these meters in situ because there were no international recommendation regarding this, and secondly, we wanted to collect metering data to see how the Coriolis meters perform in proportion to the turbine meters.

We have however calibrated the Coriolis meter in the propylene metering station lately, by using the master meter method. We used the turbine meter in the metering station in series with the Coriolis as the master meter.
The flowrate was varied from 5 to 30 m^3/h, that means 2.5 – 15 t/h. This represent 3 – 20 % of the sensor maximum capasity. The pressure varied from 20 bara by minimum flowrate to 27 bara by maximum flowrate.
First we calibrated the turbine meter by the compact prover, to find the

meter factor at the actual flowrate. Then we reprogrammed this new meter factor into the prover computer and the turbine meter flowcomputer. Simultanious readings were taken from the two meters over a period of time, for each flowrate. To keep the unsertainty of the readings at approximately 0.1 %, we found that we had to displace about 8.5 tonns through the meters during the test period. This was also chosen under consideration of the available time for the whole calibration operation.
During the complete test period the Coriolis meter was calibrated against the turbine meter, the turbine meter was calibrated by the prover, to keep the meter factor under control. Over the whole flowrange the repeatability for the turbine meter was better than 0.03 % (Fig. no. 5).

As mentioned earlier, we used the origional meter factor from the factory calibration with water for the Coriolis meter. The meter was then calibrated over a range of 2.5 – 25 t/h. (Fig. no. 6).

From the master meter calibration we found that the Coriolis meter showed 1 % lower readings than the master meter in the range of 7 – 15 t/h. This is the same offset that we have experienced during normal operation with the Coriolis meter.
Below 7 t/h the error in proportion to the master meter increased, and at 2.5 t/h the reading from the Coriolis meter was 2.5 % lower than the master meter. (Fig. no. 7).

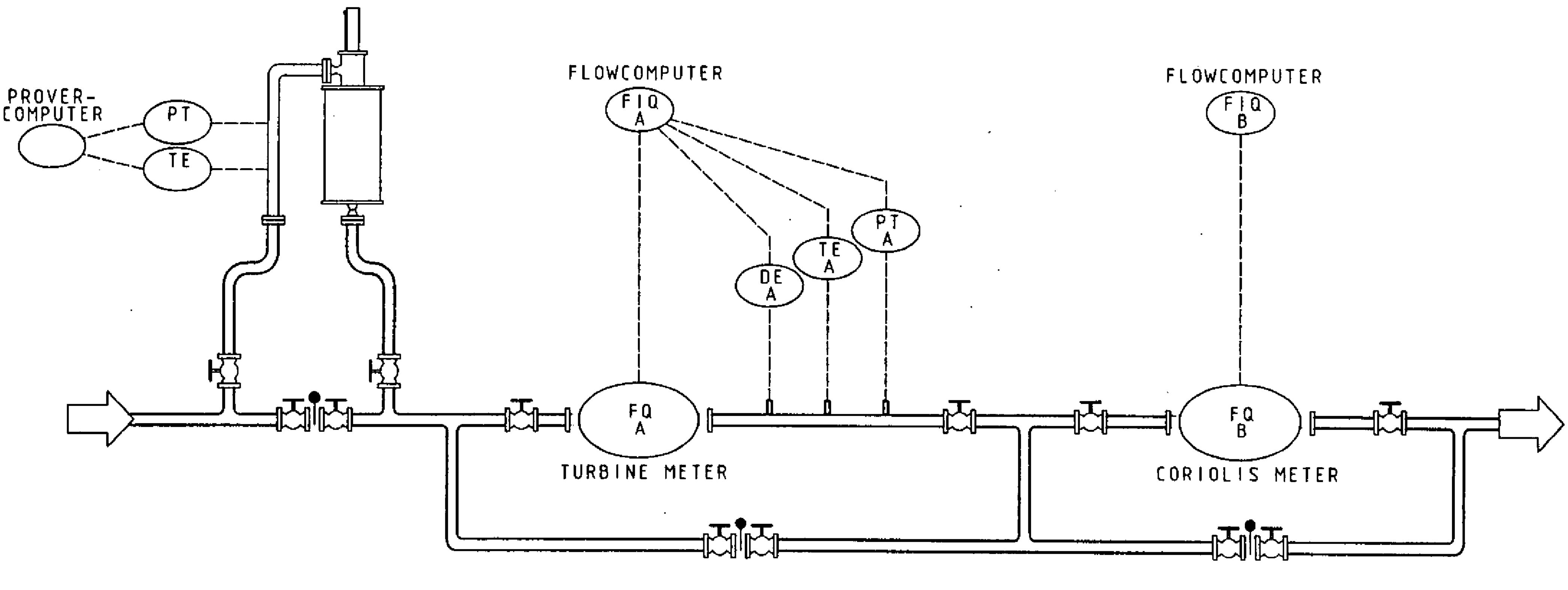
5. CONCLUSION

What has been told earlier, that the Coriolis meters are to a very small degree sensitive to changes in pressure, density and viscosity, and that a calibration with water in a calibration lab can be transfered to an installation on "any" fluid, do not seem to be the fact in the "real life".

Our experience is that the Coriolis meters also have to be calibrated in situ with the actual medium at operating conditions to get control over the systematic error.
The linearity of a Coriolis meter in an actual installation is not as good as from a water calibration of the sensor. This could be due to pressure effects and installation effects. The meter accuracy tends to drop off when the flowrate is below 10 % of the sensor maximum flowrate.
Abow this limit, the linearity of the Coriolis meter has proven to be within the specification of ± 0.2 %.

6. LIST OF FIGURES

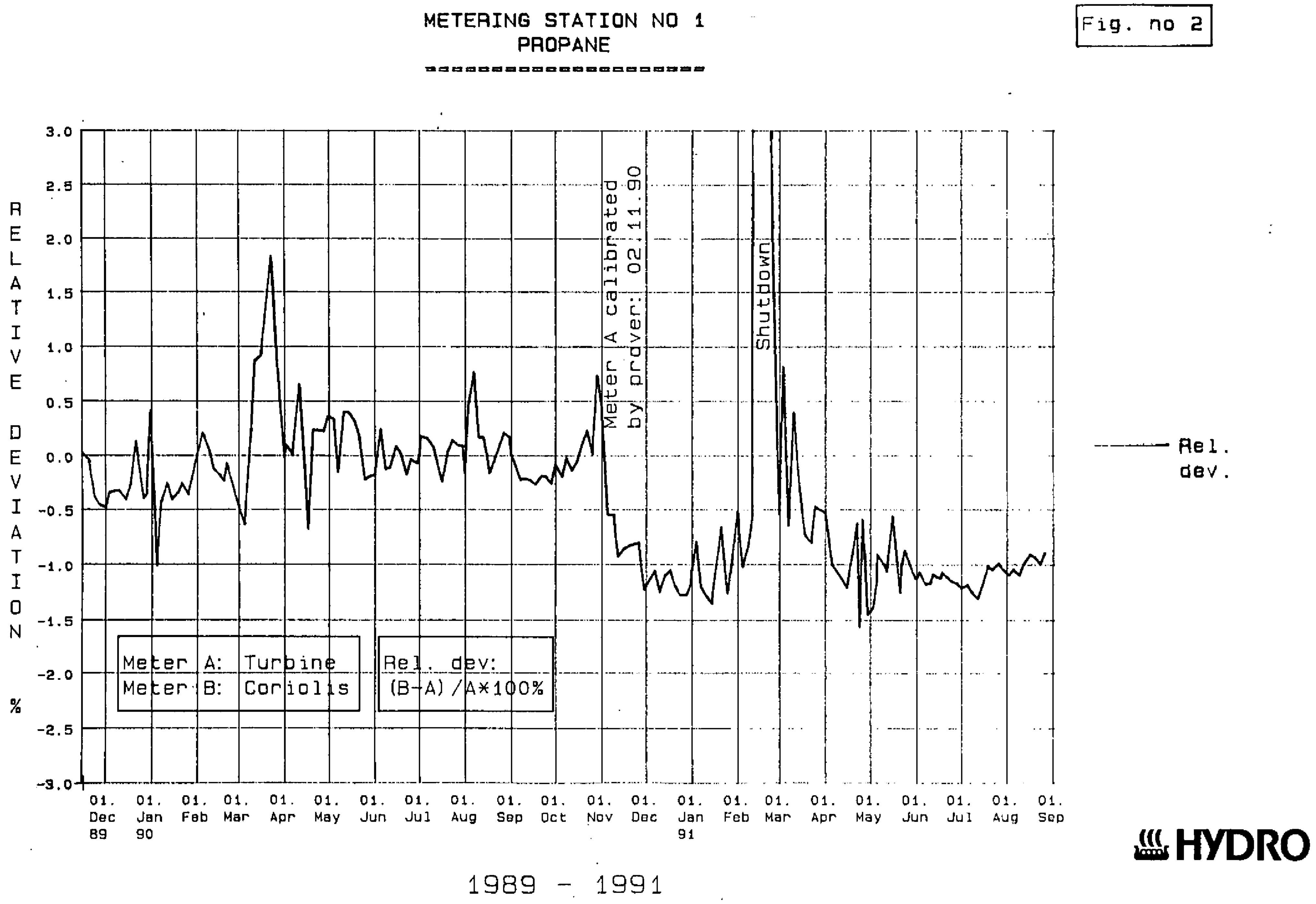
Fig. no 1



METERING STATION WITH CORIOLIS MASSMETER

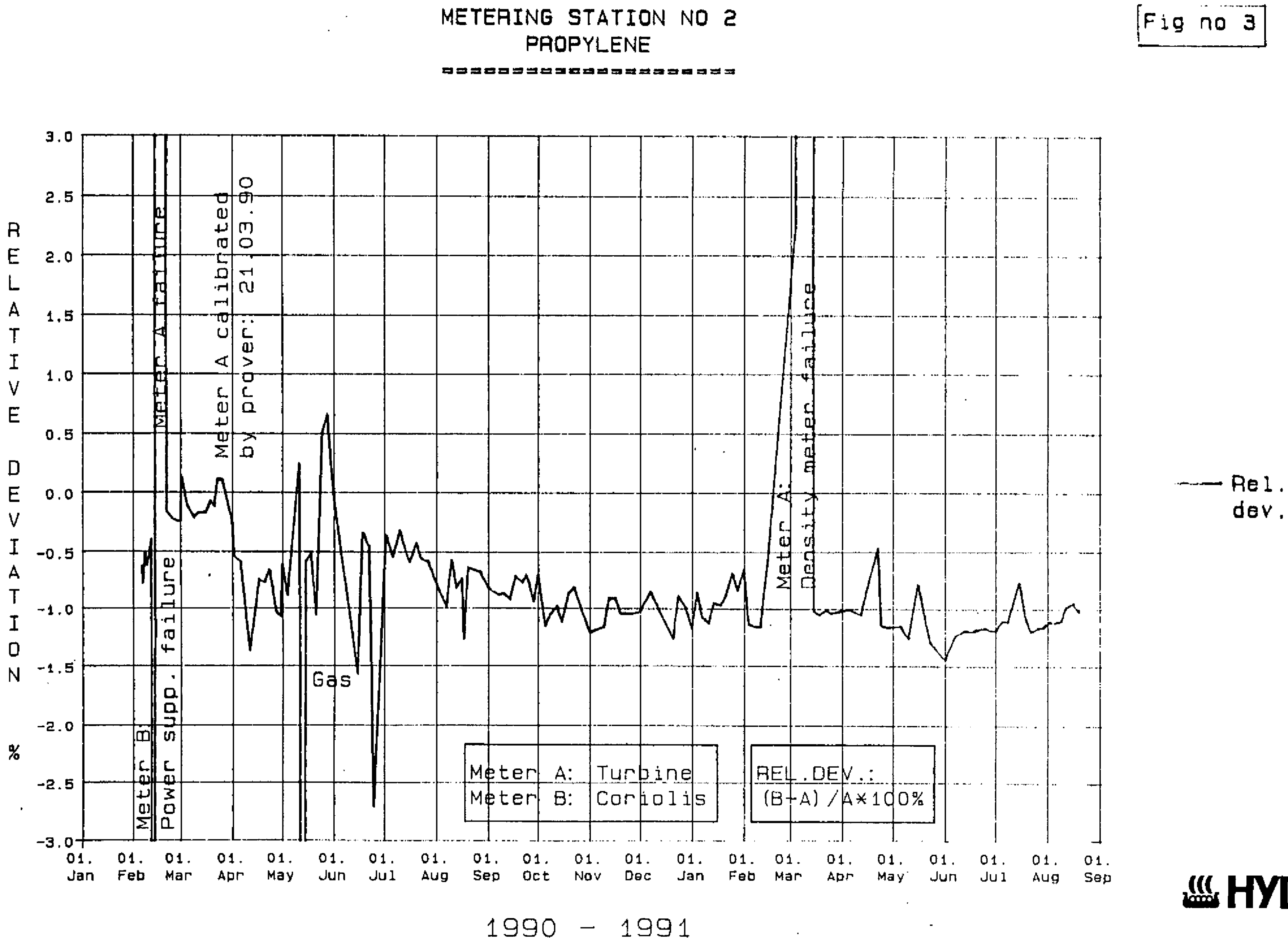
HYDRO

d:\hcl\ustn\dgn\i_svm01.dgn Sep. 23, 1991 12.24.32



METERING STATION NO 1
PROPANE
Fig. no 2
RELATIVE DEVIATION %
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Meter A calibrated by prover: 02.11.90
Shutdown
Meter A: Turbine
Meter B: Coriolis
Rel. dev:
(B-A)/A*100%
Rel. dev.
01. Dec 89
01. Jan 90
01. Feb
01. Mar
01. Apr
01. May
01. Jun
01. Jul
01. Aug
01. Sep
01. Oct
01. Nov
01. Dec
01. Jan 91
01. Feb
01. Mar
01. Apr
01. May
01. Jun
01. Jul
01. Aug
01. Sep
1989 - 1991
HYDRO

Fig no 3



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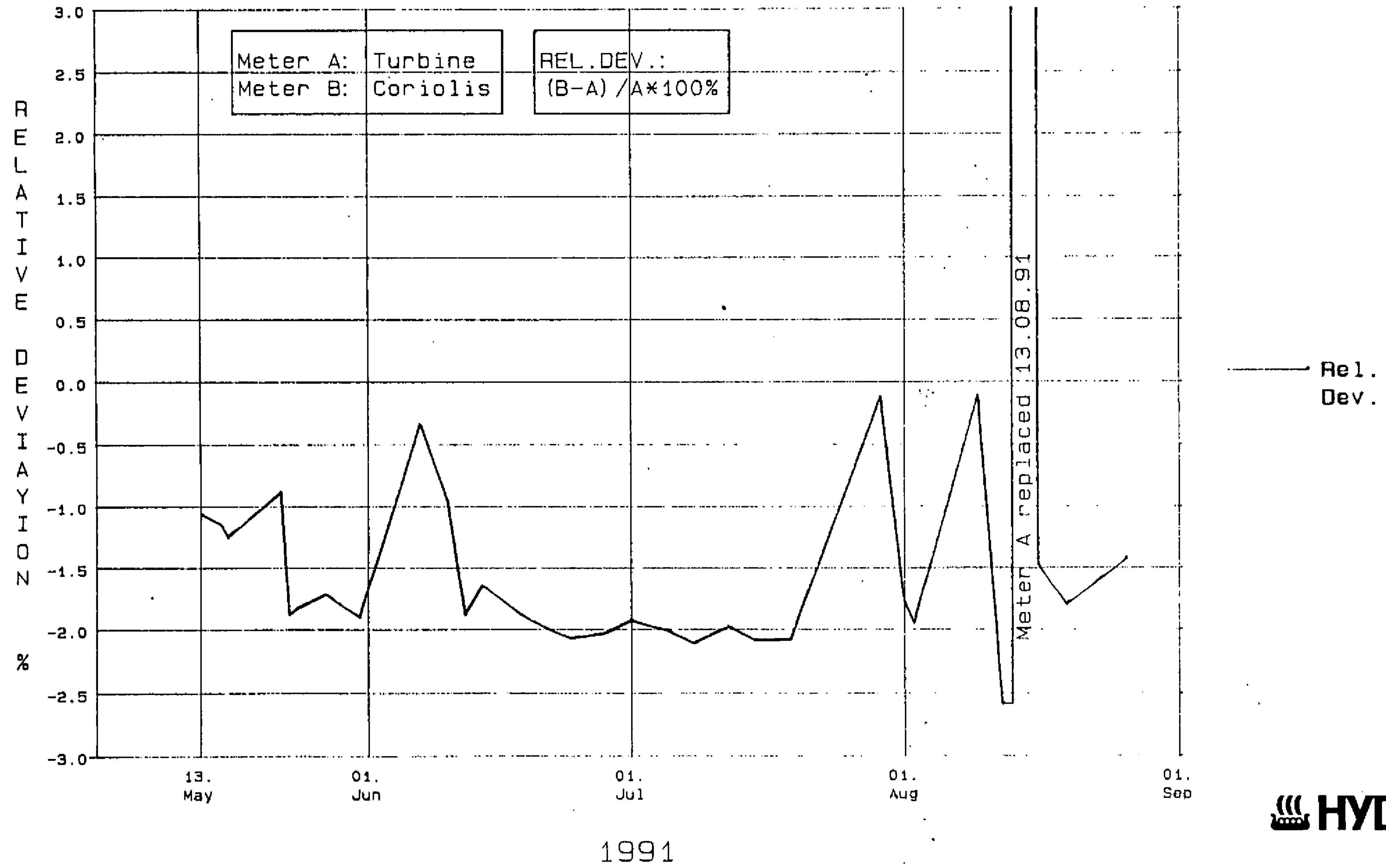
METERING STATION NO 3
PROPANE

Fig. no 4



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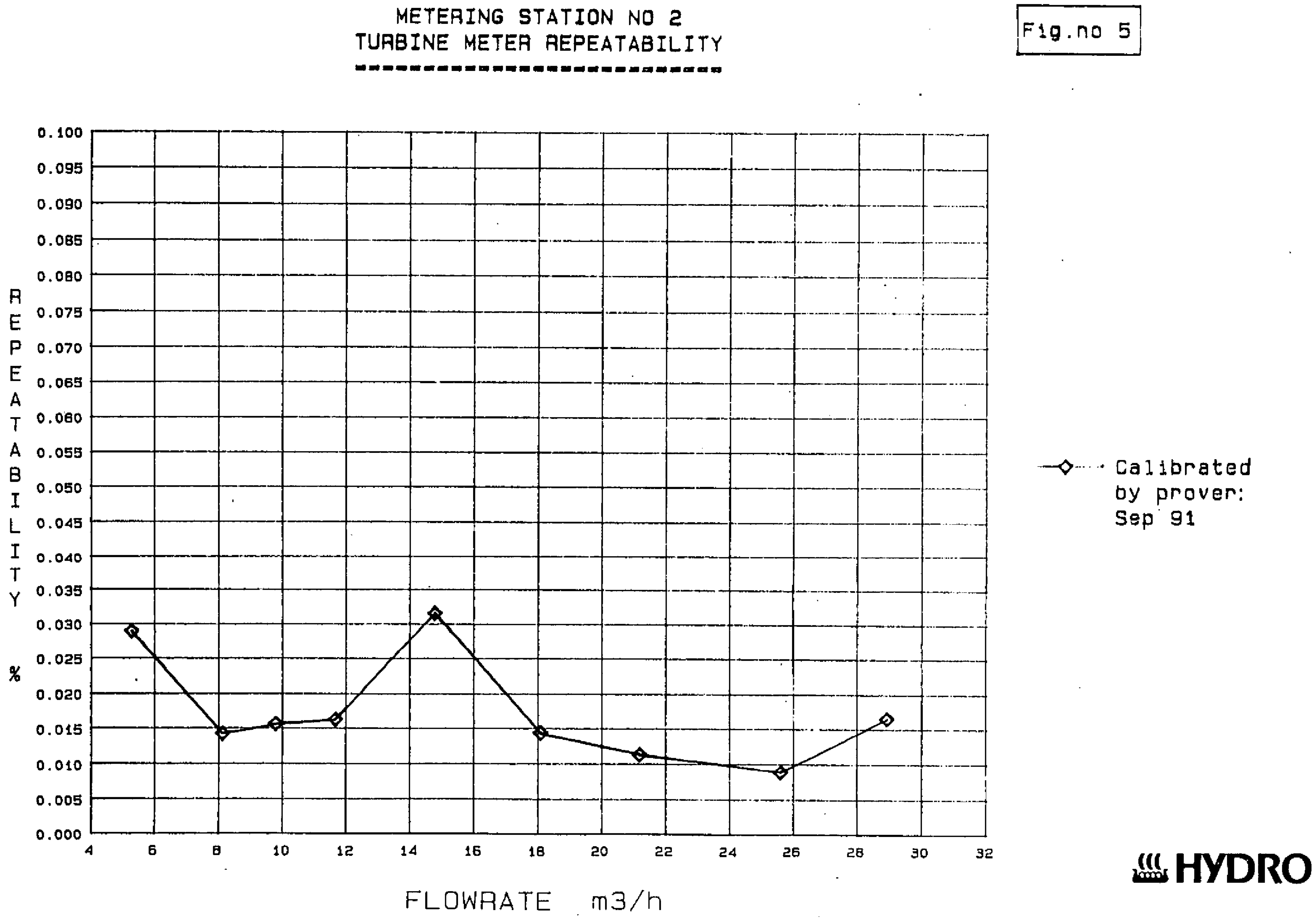
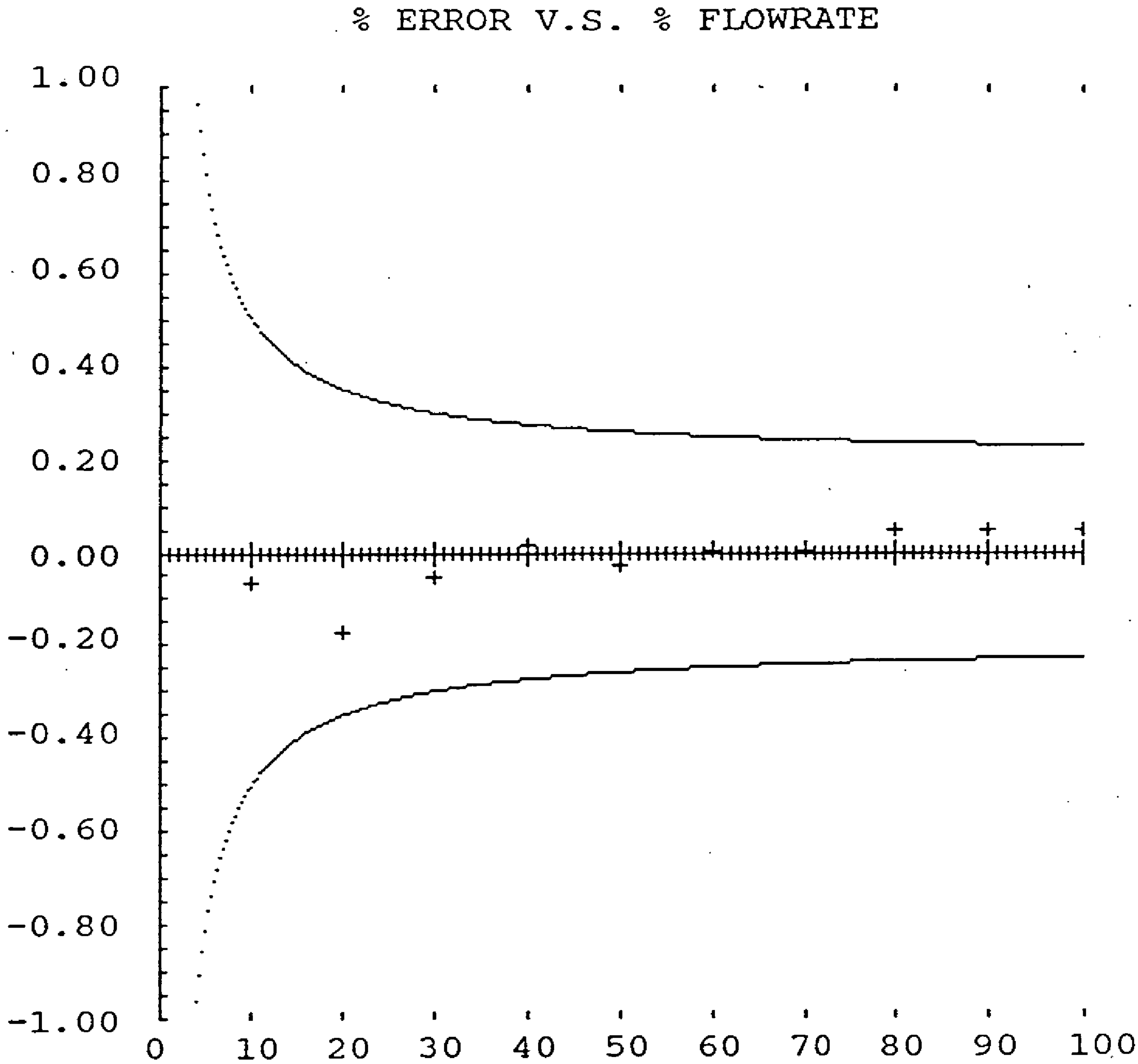

METERING STATION NO 2
TURBINE METER REPEATABILITY
Fig.no 5
REPEATABILITY %
0.100
0.095
0.090
0.085
0.080
0.075
0.070
0.065
0.060
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
FLOWRATE m3/h
Calibrated by prover: Sep 91
HYDRO

Fig. no 6

CALIBRATION DATA SHEET



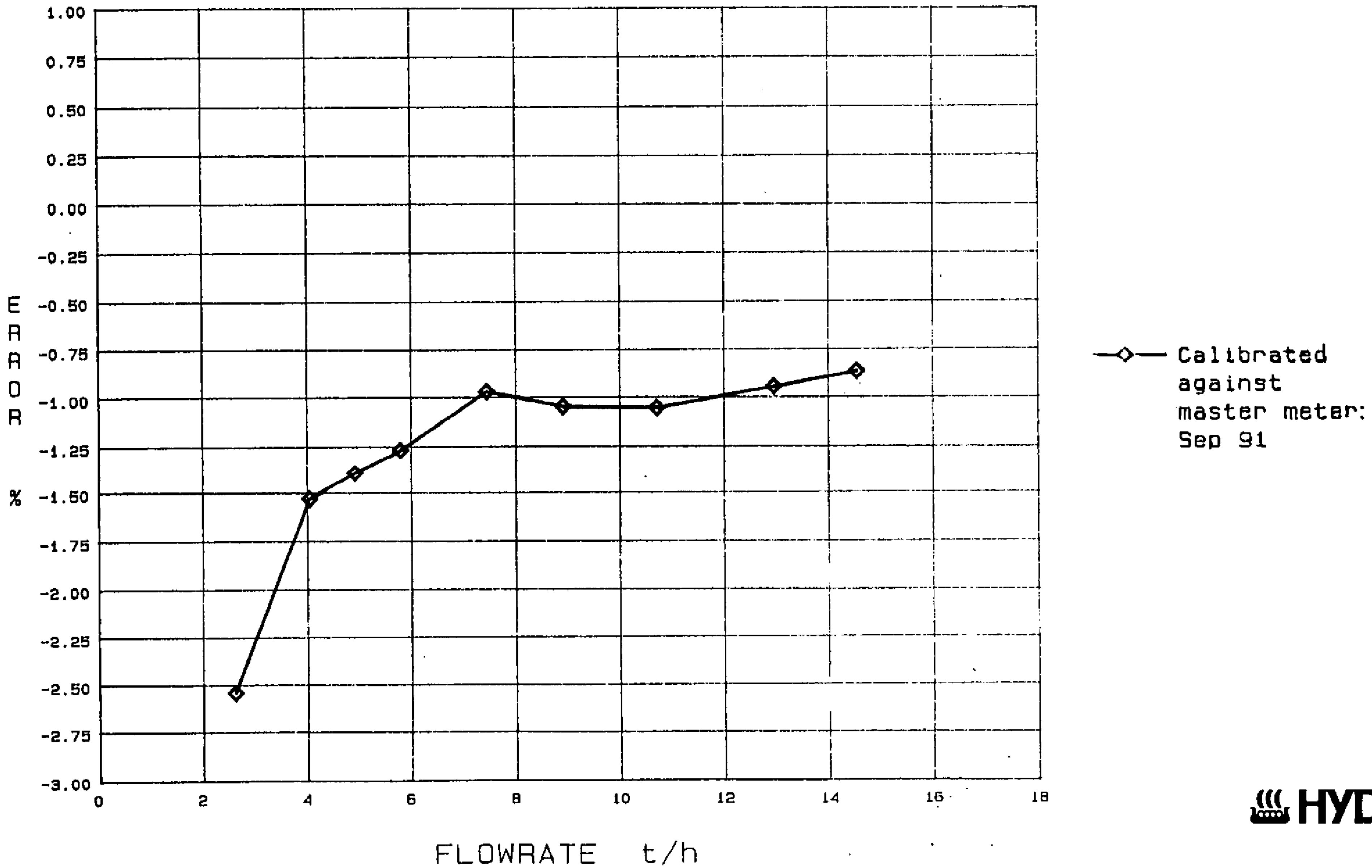
HORIZONTAL AXIS : % OF FLOW
VERTICAL AXIS : % ERROR

CUSTOMER REFERENCE : AI 275
SERIAL NUMBER : 225490
100 % FLOW : 25 t/hr
DATE : 89- 8-28

HYDRO

METERING STATION NO 2
CORIOLIS METER ERROR CURVE

Fig. no 7



HYDRO

TESTING AND QUALIFICATION OF METERS:

SESSION II

Norwegian
Society of
Chartered Engineers

NORTH SEA FLOW MEASUREMENT WORKSHOP

OCTOBER 22. - 24. 1991
SOLSTRAND FJORD HOTEL, BERGEN - NORWAY

ULTRASONIC GAS FLOW METERS CONTINUE THEIR RISE

Lecturer:

Mr. Karst Van Dellen
Daniel Industries Inc.

INTRODUCTION

The introduction of multipath ultrasonic flow metering for custody transfer, also requires proper explanation of the principles to the customer.
Often heard remarks and questions are: " ...but it must be dependent on the speed of sound!?", ".... how valid are the appropriate weighting factors, and how are they determined?", ".... what is self checking and how does it work?", ".... what is the value for the price?", "What are the experiences of people who bought the system and why did they decide on ultrasonic flow measurement?" "Will it be approved for custody transfer?"

These are all valid questions if ultrasonic flow measurement is considered. This paper will answer the above.

The ultrasonic theory is approached from a different perspective. A new look is presented on the velocity measurement, speed of sound and the effect of velocity profiles. The speed of sound is used to check the validity of the measurements, and supports the self checking capabilities of ultrasonics.

The paper demonstrates velocity profiles influencing the measurement and the compensation by multiple paths and appropriate weighting factors. A math-model is used to calculate the effect of velocity profiles on a four path meter. The effect will be demonstrated with velocity profiles from an upstream 90° bend on the meter error.

Possible error sources in ultrasonic flow metering are discussed and how they are revealed in practice.
The value/price ratio in relation to orifice systems is discussed and shows possible savings. Also total station weight and length savings are conceivable with ultrasonic flow meter systems when compared to conventional systems.

Over 40 meters have been sold and some have been put into operational service. Others have been flow calibrated and are being installed at their operational sites. In the mean time test work is continuing.

For the future, Daniel is pursuing the second generation of the Ultrasonic Meter, with improved performance and extended applications.

EXTENDED THEORY

The flow equation for time of flight ultrasonic metering can be derived using a different approach. The new derivation takes in

account that the travel path of the signal (acoustic path) is not a straight line.
The difference with the common known derivation is that the velocity vectors are resolved to an independent orthogonal coordinate system along the pipe wall and across the pipe. See figure 1.

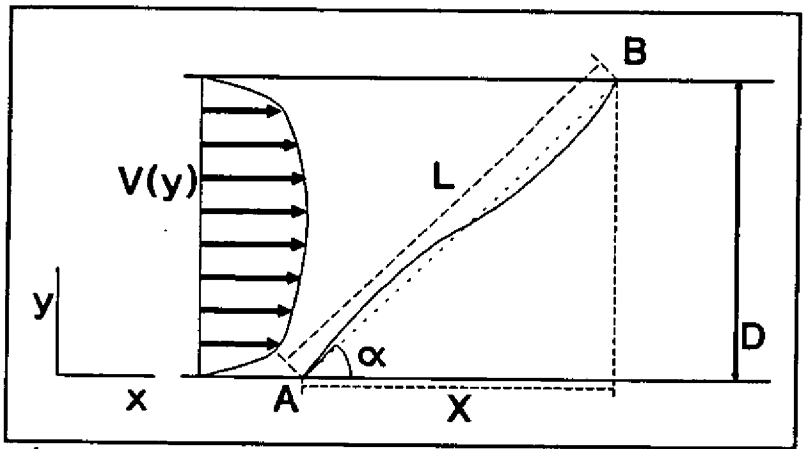


Figure 1 Parameters for derivation of flow equations in schematic setup.

At t = 0 a pulse is fired from A in direction α. The pulse leaves transducer A with the speed C.
The component in the y direction is: $C \cdot \sin(\alpha)$.
The component in the x direction is: $C \cdot \cos(\alpha)$.

The medium is flowing in the x-direction with velocity V(y). The velocity is not uniform over the diameter.

After time t the pulse position in the y-direction is given by:

$$y = C \cdot t \cdot \sin(\alpha) \qquad (1)$$

At time T (=transit time) the pulse is to arrive at the other side and has travelled the distance D in the y-direction.

$$D = C \cdot T \cdot \sin(\alpha) \qquad (2)$$

The velocity in the x-direction at time t is given by:

$$V_x = C \cdot \cos(\alpha) + V(y) \qquad (3)$$

with y given by equation (1).

The distance covered in the x-direction between t and t+dt is dx,

$$dx = V_x \cdot dt = [C \cdot \cos(\alpha) + V(y)]\ dt$$

Hence the distance covered in the x direction between t=0 and t=T is X and is given by

$$\int_0^T [C\cdot\cos(\alpha) + V(y)]\, dt = X$$

Since $t = y/[C\cdot\sin(\alpha)]$ therefore $dt = 1/[C\cdot\sin(\alpha)]\, dy$

Also by definition $\int_0^D V(y)\, dy = VD$
with V is the mean velocity of the fluid across D.

Note : Since V(y) is not uniform the acoustic path is not a straight line.

Continuing,

$$X = CT.\cos(\alpha) + VD/[C\cdot\sin(\alpha)]$$

Then using (2)

$$= [C\cdot\cos(\alpha) + V]\cdot T \qquad (4)$$

From eq. (2) : $C\cdot\sin(\alpha) = D/T$
From eq. (4) : $C\cdot\cos(\alpha) = X/T - V$

Combining these equations results in:

$$C^2 [\sin^2(\alpha) + \cos^2(\alpha)] = [D/T]^2 + [X/T - V]^2 = C^2$$

Combined with the similar equation for the downstream traveling signal it can be written as:

$$\overline{V} = \left(\frac{L}{T} - \frac{L}{T'}\right)\frac{L}{2X}$$

$$\overline{V} = \frac{L^2}{2X}\left(\frac{T - T'}{T.T'}\right)$$

The last equation is identical to the one commonly known for ultrasonic flow metering. The equation is worked towards the known (and measurable) physical dimensions of the measuring section.
It is derived without any assumptions and the dependency on the angle α is eliminated. The equation is independent of the speed of sound and the velocity distribution.
Even if α is a function of x,y or t, since α is eliminated in the derivation, it does not matter. The only assumption is that C does not change between the firing of the upstream and downstream

travelling pulses.

The equation calculates the average gas velocity on a path and it is dependent on two transit times and some geometrical dimensions. Provided the dimensions are known and the transit times are properly measured, the velocity can be calculated. Once the velocity is known, the flow rate can be calculated.

VELOCITY PROFILES

The calculated gas velocity is the average velocity on the line AB (line velocity, figure 1). This is not equal to the average pipe velocity (area velocity).
If the velocity profile was flat, the line average velocity and the area average velocity would be equal. The velocity profile is not flat in real pipe flows. So a correction is needed to adjust the line velocity to the average pipe velocity.

Fully developed flow will be represented by the non-uniform Power Law. The exponent N of the Power Law is not constant, it is dependent on Reynolds number and wall roughness. In normal gas applications N varies between 7 and 11.

Lets consider a single path ultrasonic meter on the center line. The line velocity has to be corrected to estimate the average pipe velocity. The correction factor is given, as a function of the exponent N in figure 2. It shows an average correction of about 5%, but more important it shows a 2% shift from N=7 to N=11. Thus if N (= velocity profile) changes, the correction factor changes. If the velocity profile is not known or changes with conditions the correction factor is uncertain.

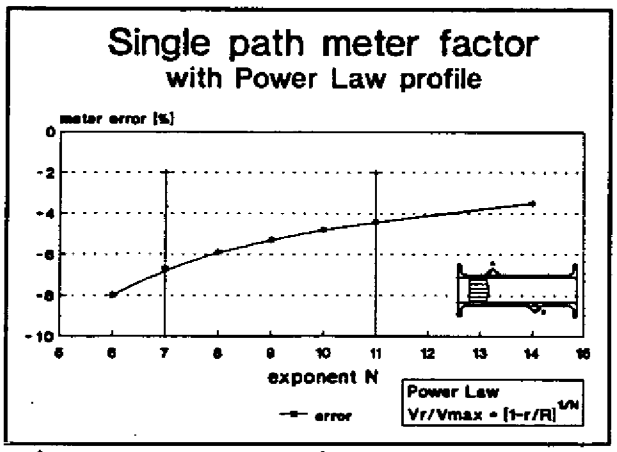


Figure 2 Single path performance

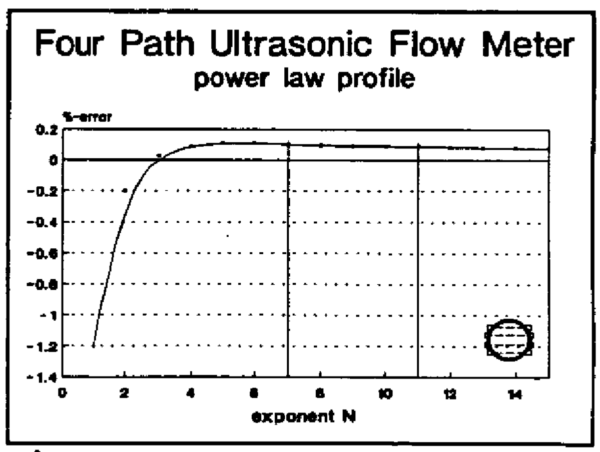


Figure 3 Four path meter performance.

Consider a four path meter, with appropriate weighting factors. Four line velocities are measured and multiplied with their weighting factor. The correction factor for a four path meter as a function of the exponent N is given in figure 3. The offset of 0.1% is caused by the discontinuity in the Power Law. The change in correction for N between 7 and 11 is smaller than 0.05%. This means that a four path meter with appropriate weighting is not dependent on fully developed velocity profiles. This effect is incorporated in the repeatability of the meter.

WEIGHTING FACTORS

How does appropriate weighting work? The weighting factors are determined mathematically, based on geometry. They are independent on the velocity profile (Gaussian integration).
The integration is based on the area of horizontal cross sections. The weighting factor associated with each path (and area) can be calculated. The weighting factor takes the associated area for a path into account. For symmetry reasons the weighting factors on the outer paths, W1 and W4, are equal and similarly W2 and W3 are equal. Together they add up to 1, figure 4.

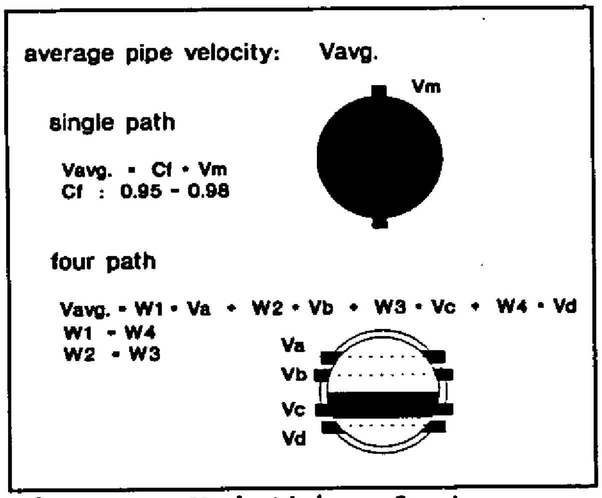


Figure 4 Weigthing factors

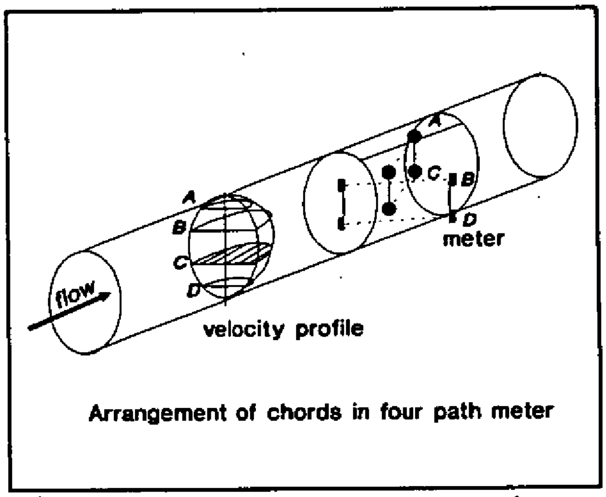


Figure 5 Path arrangement on radius

The optimized solution is obtained when the paths are at specific positions on the radius. Those positions are a fixed ratio of the bore radius, R and approximately 0.3*R and 0.8*R from the center. Figure 5.
With a computer simulation program it is possible to generate asymmetric velocity profiles and observe the theoretical performance in non ideal conditions. From reference 1 the axial velocity measurements downstream of a 90° bend were adopted. Profiles were measured in the horizontal and vertical plane at

three different positions downstream of the bend, 1.5D, 5D and 22D. The measurements were taken at a Reynolds number of 10^5 in water. This represents the lower design limit: minimum size, low pressure, minimum velocity. No data however is available for higher Reynolds numbers.

The challenge is to get the interpolation between horizontal and vertical measurement. 10th order and broken polynomials were used to match horizontal and vertical profiles and a third polynomial to smooth the interpolation.
A velocity profile in 3D representation is given in figure 6.
The axial profile appears a lazy arm chair with comfortable armrests. The armrests and the back seat disappear with increasing

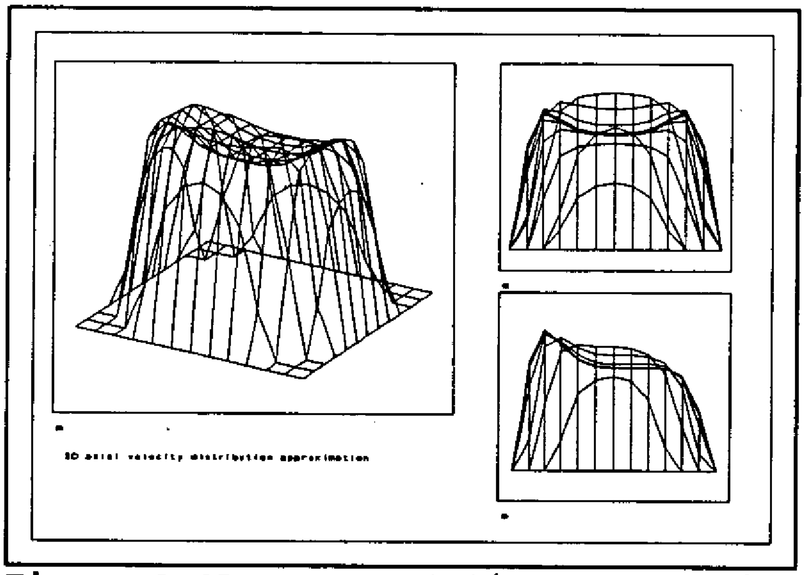


Figure 6 3D representation of velocity profile from 90° bend.

distance from the bend.
For fixed distances after the bend the hypothetical ultrasonic meter performance is given in figure 7. The performance curve is formed by rotating the meter housing relative to the bend. So the meter is rotated along its axis, while the bend is fixed. As expected the performance of the meter improves at larger distance from the
bend. This performance is not tested in practice, and it suffers some incompleteness. Turbulence, radial velocities in the flow and finite sensor size may affect this theoretical performance. The simulation program is only a tool to evaluate performance.

From these evaluations and from field testing it is believed that the weighting factors of the four path meter are appropriate in most, if not all applications. Ref 3 and 4 show test results with

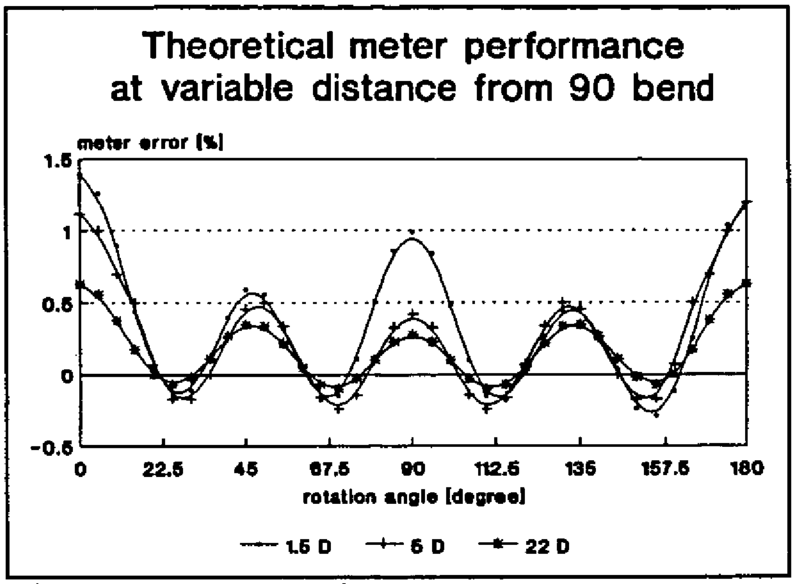


Figure 7 Theoretical meter performance at 90° bend.

distorted profiles and the performance usually is within 1% of reading. This model was also used to study the effect of machining tolerances. If the paths are not positioned as required for Gaussian integration, what change in flow performance should be expected for an "offspec" meter.
The simulations show that the weighting factors are not very sensitive to machining tolerances. The meter performance stays adequate, provided the correct dimensions are used.

SELF CHECKING

An interesting feature of the ultrasonic flow meter is the self checking capability. As already discussed in a previous paragraph, the velocity of sound is calculated from the basic set of equations. It is measured with an accuracy of about 0.1%.
The velocity of sound is a function of temperature and gas composition. However within a typical measurement time interval the velocity of sound will not change. The velocity of sound appears constant and is therefore suited to check the validity of transit time measurements.

Three examples:
Given the speed of sound and the flow rate from the previous batch, a time window is defined for the next signal to arrive. If a "signal" is outside the expected time window this measurement is not validated and removed from the total batch.

The velocity of sound on each of the four paths are in very close agreement. If they are not, this indicates something is wrong. All measurements on the disagreeing path are eliminated and an alarm is given.

The spread in the transit times is a function of flow rate. So at a specific flow rate or gas velocity the spread in the time is limited. The limited spreading is used to further qualify measurements.

In total seven tests are performed on the measurements to assure only validated measurements are used in the flow computations. If the number of rejections is extreme high something is wrong.

The self checking capabilities of ultrasonic flow meters provide useful information about the condition and quality of the flow measurement and the electronic equipment.

POSSIBLE ERROR SOURCES

The basic equation for the flow velocity reads:

$$V = \frac{L^2}{2X} * \frac{(t_1 - t_2)}{t_1 . t_2}$$

The possible error sources in the equation are errors in L, X, t_1 and t_2. The effect of small errors in L and X can be demonstrated in the (partial) differential equation for V.

$$\frac{\delta V}{V} = \frac{2.\delta L}{L} - \frac{\delta X}{X}$$

This equation shows that if $\delta L/L$ is -0.002, (-0.2% error) and $\delta X/X$ is 0.001 (0.1% error) the resulting error in the velocity V equals 2.-0.002 - 0.001 = -0.005 or -0.5%
Obviously the measurement accuracy is strongly dependent on the geometrical parameters. Added to this are the errors in the pipe area (D^2), to arrive at flow rate.

These sources, L,X and D, contribute all to a systematic offset from zero error. Figure 8 shows the hypothetical case of a systematic dimension error. The equations can also be used to calculate the effect of temperature expansion on the meter housing.

The effect of the timing accuracy on the measurement is more complicated. After some working, rearranging and defining some terms we end up with:

$$\frac{\delta V}{V} = -2 . \frac{\delta t_{avg}}{t_{avg}} + \frac{\delta t_{diff}}{t_{diff}}$$

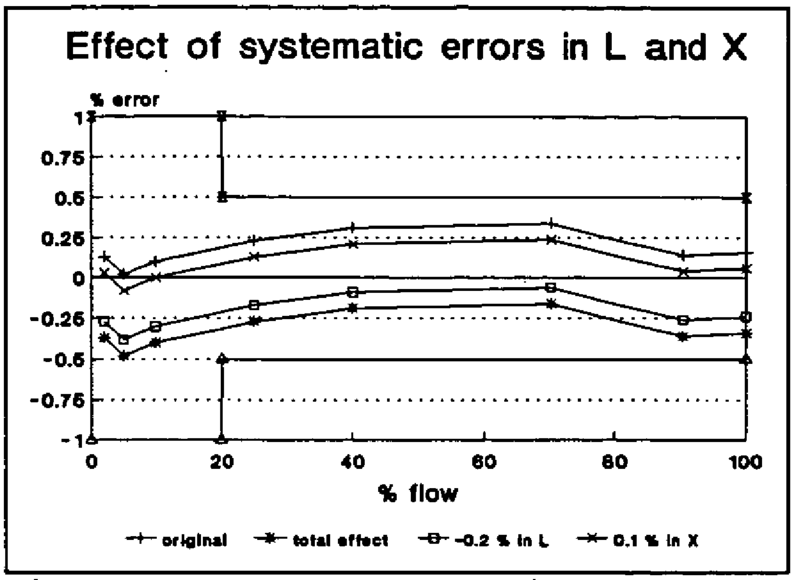


Figure 8 Effect of errors in L and X.

with t_{avg} the average transit time (proportional to vel. of sound)
t_{diff} the difference of transit times (proportional to gas vel.)

An error in the average of transit times will result in a systematic error at all flow rates. Thus 0.1 % error in average timing is 0.2% error in the velocity measurement at all velocities.

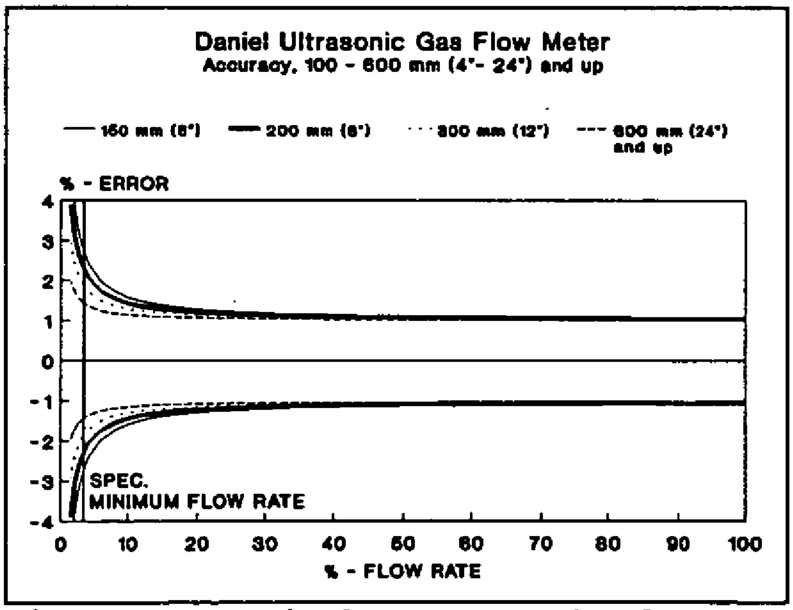


Figure 9 Typical error bands for ultrasonic meters.

The second term affects the accuracy at the low flows. The error term δt_{diff} may be constant, but t_{diff} decreases with proportionally with flow rate. This means the timing error increases with decreasing flow rate. The meter accuracy is a bell shaped error band, well known for instrumentation, figure 9.

To eliminate this last error a zero time difference has to be established. This can be performed in the factory and is part of the factory calibration.

Timing errors can result from a time base shift of the oscillator, change in signal characteristics or improper operation of the timing circuits in the electronics.

The error sources mentioned here are associated with the apparatus itself. To ensure proper operation in the field, all the components involved in the measuring process should be of equal and proper quality and operate accordingly. Provided this is all under control the ultrasonic flowmeter has all of its measurement parameters known from the factory. An ultrasonic flowmeter therefore does not need a flow calibration.

The advantage of the four path configuration is that random errors in L,X and t are compensated by averaging over four L,X and t. Systematic errors in L,X and t most likely cause parallel shift of the calibration curve.

THE VALUE OF ULTRASONIC METER SYSTEMS

Typically the flow range of an ultrasonic meter is 1.5 times the flow range of a gas turbine meter of the same size, with an equivalent turndown ratio: 20:1 (extended 50:1).

The flow rate in comparison to an orifice metering system is given in figure 10. It shows dual, triple and quadruple skid mounted orifice units on the x-axis, and the standard flow through such units on the y-axis. Those skids are compared to ultrasonic skids. It shows that a dual system with 200 mm (8") ultrasonic meters can replace a triple unit of 300mm (12") orifice meters, over the full (recommended) beta range. The savings are based on the skid mounted systems.

PROGRESS IN FIELD APPLICATIONS

Gasunie in the Netherlands decided to use ultrasonic meters as the backup meter to gas turbine meters in their export stations after an intensive evaluation. [ref 4,5]. The meters were mostly in 20" size. About fifteen meters have been flow calibrated at the

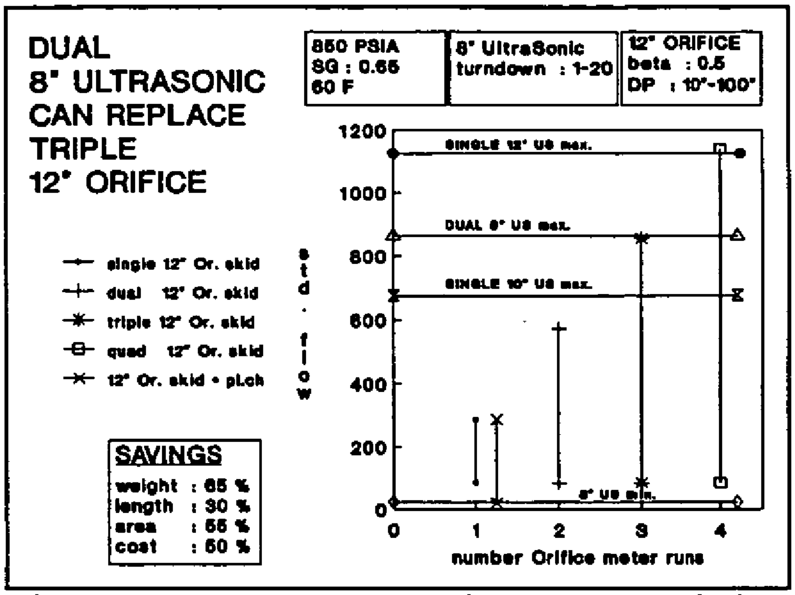


Figure 10 Flow capacity of orifice meters versus ultrasonic meters (skid mounted).

Westerbork station before their installation at the export stations. Gasunie has not released the results of the calibrations before actual operation. In general the fifteen calibrated meters have identical shaped error curves in a 0.5% band, while the calibration error was within 1% over the flow range 20-100% and within 2% in the range 5-20%. After normalization those limits were cut in half and match the ranges that Gasunie requires for turbine meters.

The Gasunie order put Daniel through the transition from the production of single meters to the production of small series of meters. This transition made us aware of the production capabilities and pointed out some areas were additional quality assurance was needed. Although each individual unit is tested before it leaves the factory some did not perform as specified. Those matters were brought to our attention and corrected.
The final installation and the operational conditions at the export station are still under investigation. The first meters will be put into operational service soon.

PROGRESS IN CUSTODY TRANSFER APPLICATIONS

It is recognized by transmission and production companies that the ultrasonic meter has potential for direct custody transfer applications. Custody transfer however requires approval of the (local) authorities. The first authorities to enter this discussion with a transportation company are the Dutch authorities NMi.

They are considering type approval in the Netherlands on the basis of the Gasunie test work.

Further testing for type approval is anticipated in the ULTRAFLOW working group. This is a group of users, whose goal is to develop a standard code of practice and performance control for ultrasonic flow metering. The ultimate goal is to pass legislation allowing ultrasonic meters for custody transfer. The group is potentially sponsored by the European community.

The work of the ULTRAFLOW group is considered as paving the way to an ISO standard. ISO TC 30 has formed a working group on ultrasonic flow meters to investigate requirements and routes for standardization.

The ULTRAFLOW group also wants to develop ultrasonic meters that are capable of measuring wet and sour gases. Those applications are not yet covered by the present meters.

THE NEAR FUTURE

Daniel is pursuing the second {next} generation in ultrasonic flow measurement. This meter will comprise a similar meter body but will have newly developed electronics and transducers. The new electronics will eliminate some boards compared to the present system. The signal detection will be fully digital and advanced statistics for signal recognition and digital filtering techniques are used.
Daniel expects extended application areas and improved performance from this second generation ultrasonic meters.
The first proto types are expected by the end of 1991. The knowhow gathered over the past years is incorporated in this new unit.

CONCLUSION

Daniel is steadily progressing in the field of ultrasonic flow metering. The present device will be updated to the newest technology. The new and updated versions will be available shortly.

It has been shown that the ultrasonic meter can meet custody transfer accuracies, as e.g. laid down in OIML requirements. The ultrasonic meter is capable of handling fully developed and distorted velocity profiles, without significant loss of accuracy.

The work by authorities, working groups and standard committees shows the validity of the ultrasonic technique for custody transfer applications.

ACKNOWLEDGEMENTS

The author likes to thank all persons involved in the project who knowingly or unknowingly contributed to this paper. Special thanks to Bill Freund and Mike Nolan. Bill did the error analysis part, and is within Daniel technically responsible for the next generation ultrasonics. Mike inspired the derivation of the ultrasonic equations.

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COMPARISON OF LINEARITY, REPEATABILITY AND REPRODUCIBILITY FOR TURBINE, CORIOLIS AND ULTRASONIC METERS TESTED AT 100 BARS ON NATURAL GAS

Lecturers:

Mr. Asbjørn Erdal and Mr. Jean F. Cabrol
K-lab

K-Lab

COMPARISON OF REPEATABILITY, REPRODUCIBILITY AND LINEARITY FOR TURBINE, CORIOLIS AND ULTRASONIC METERS TESTED AT 100 BARS ON NATURAL GAS

Paper presented at the North Sea Flow Measurement Workshop, Solstrand 1991.

Asbjørn Erdal and Jean F. Cabrol,
K-Lab, P.O.Box 308, N-5501 Haugesund, Norway

ABSTRACT

The important characteristics to check in order to provide a reasonable accuracy for a gas meter are the repeatability, the reproducibility and the linearity of the deviation curves from the reference meter. This paper presents and analyses experimental calibration data obtained at K-Lab at high pressure (100 bars) with respect to these three properties for 6 turbine meters, 2 Coriolis meters and 1 ultrasonic meter. The statistical method of analysis recommended by the standards has been systematically utilised and has been compared, for calibration conditions, with other analysis methods. A more friendly use of statistical analysis for metering specialists is developed in this paper. Eventually, some meters of each type have been compared with respect to their common behaviour concerning these three metering properties by using the same method of analysis.

INTRODUCTION

Normally people are interested in the accuracy of a gas meter. But for those meters which have to be re-calibrated regularly, 3 other factors are very important. That are the repeatability, the reproducibility and the linearity of the meters. If these properties follow the calibration requirements, the meters can be expected to have a constant and reasonable accuracy over the whole range of flow conditions. Typical examples are turbine meters and

Coriolis mass meters. The idea behind the ultrasonic meters (USM) is that only the electronic transducers should be calibrated. But as long as they are linked to a flow-computer the possibility always exists to introduce an adjustment factor (Meter Factor) and to adjust their calibration curves if they are not linear and horizontal enough.

This paper presents data on repeatability, reproducibility and linearity measured for 6 turbine meters, 2 Coriolis mass meters and 1 USM. The calibrations are carried out at 100 bars absolute and approximately 37°C.

It is well known that turbine meters have good repeatability both for successive identical runs and on a long term basis at identical conditions (known as reproducibility as well) and that they are reasonably linear (reference 1). But so far no systematic repeatability and linearity study and even calibration results at high pressure (100 bars) are available in the literature. Regarding Coriolis mass meters and USM some calibration curves at high pressure have already been published (see references 2 and 3), but limited information is available on repeatability, reproducibility and linearity criteria.

A great number of meters have been calibrated at K-Lab during the past few years. This paper presents data about the repeatability, reproducibility and linearity which have been observed in the tests carried out at K-Lab.

METHODS

The ISO/TC30/SC9 document "Methods of specifying flowmeter performance" has been used as guideline in this paper (reference 4).

<u>REPEATABILITY</u>

Repeatability is the ability of the meter to duplicate a given output or performance for test runs with an identical set of flowing conditions. In accordance with ISO/TC30/SC9 the repeatability is calculated from 30 consecutive readings of flowrate at the maximum scale value. To begin with, the standard deviation, S_r, is calculated. Having obtained an estimate of the standard deviation, repeatability at the 95% confidence level (r_{95}) is calculated using the equation:

$$r = t_{95} * \sqrt{2} * S_r$$

where

t_{95} = Student's t at 95% confidence level.

The described method is most likely to become the **standard method** for repeatability recommended by ISO Specifications.
But it happens often that we need information about the repeatability without performing 30 runs at the maximum flowrate which may take up to one day of calibration. Often, metering people picks up some consecutive runs as raw-data from the calibration curves and evaluates the repeatability without performing any kind of statistical analysis. The alternative method that we are presenting in this paper intends to provide metering specialists with a simplified method for analysis of the repeatability, more easy and cost-saving than the standard method and more systematic than a simple scan of some calibration results. What is easily available for analysis is the calibration curve with a certain number (3 or 5) of runs at each flowrate. In this situation, the standard deviation for the whole curve can be calculated as:

$$S_r = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(X_{ij} - \bar{x}_i)^2}{n-1}}$$

n = number of flowrates
m = number of repeatable runs on each flowrate

In the following, this method will be referred to as **Range Repeatability**. Both the standard method and the Range Repeatability are used and compared in this paper.

REPRODUCIBILITY

The **Standard reproducibility** (reference 6) is calculated as the difference in percentage between the Meter-Factors over a long term basis.

LINEARITY

The Independent Linearity is expressed in ISO/TC30/SC9 as the maximum deviation between the average deviation curve and a straight line positioned so as to minimise the deviation over the Meter range and to give a constant Meter Factor. Therefore each range may have a different **Standard Linearity**.

The definition of linearity is not representative of the whole range where the meter is to be used. It is not possible to recognise if the deviation curves are fluctuating up and down or not. This is the reason why we would prefer to use the **Range Linearity** , expressed as the 95% confidence level parameter for the deviation curve over the whole flow range, in order to take care of all the flowrates. Both methods are used and compared in this paper.

RESULTS

TURBINE METERS

Six 6 inch turbine meters from different manufacturers have been calibrated against the K-Lab sonic nozzles at 100 bars absolute and approximately 37°C. The meters were installed according to AGA7 (see reference 5). The integration time have been 3 minutes in all the tests. The frequencies measured by the counters have been sampled each second.

On 2 of these meters, meter A and B, a standard repeatability test with 30 runs has been performed at maximum flowrate. On all turbine meters the Range Repeatability is calculated. The results are shown in Table 1 and Figures 1 and 2.

Two turbine meters (meter A and B) are checked for the day-to-day reproducibility. The results are shown in Table 2 and Figures 3 and 4. Reproducibility data for these two meters have been obtained at 100 bars, 37°C and flowrates from 10% of Q_{max} to Q_{max}. The K-Factor has been measured as the average on each run. For turbine meter A, 5 flow rates and 3 runs have been considered. For turbine meter B, 5 flow rates and 5 runs have been considered. The **Standard Reproducibility** is the absolute value of the difference in percentage between the two K-Factors measured at different time.

The linearity for all 6 meters and the mean value are shown in Table 3. Both the ISO/TC30/SC9 method and the confidence interval method were used. In Fig. 5 and Fig. 6 two examples of linearity for turbine meters are shown (meter A and B).

CORIOLIS MASS METERS

Two 1.5 inch Coriolis mass meters have been calibrated. They were installed in a bypass line located in the K-Lab 6" test section with good clamp supports.

Some calibrations were performed in September 1990. The difference in integration time between 3 minutes and 5 minutes was tested (see reference 2). No differences were then noticed and 3 minutes was therefore selected as integration time.

But later experiences with Coriolis mass meters have demonstrated that the integration time must be longer to obtain better reproducibility. Figure 7 and Table 4 compare the repeatability of a Coriolis mass meter with 3 minutes integration time and 15 minutes integration time. The first curve was obtained before changing the meter factor and the second curve after the meter factor was adjusted. Table 4 also shows the range of repeatability for an integration time of 3 minutes and 5 minutes for two Coriolis mass meters.

Table 5 and Fig. 8 show the reproducibility after one year for Coriolis Meter A.

In Fig. 9 the linearity for meter A is plotted. Table 6 shows the linearity and the 95% confidence interval for 2 Coriolis mass meters.

ULTRASONIC METER

For a 6" USM which has been calibrated the optimum integration time was found to be 4 minutes.

Table 7 and Fig. 10 show the results of a repeatability test. Table 7 also shows the Range Repeatability.

Table 8 shows the day to day reproducibility.

Table 9 and Fig. 11 show the Independent Linearity. Table 9 shows the Range Linearity at the 95% confidence level as well.

DISCUSSION

TURBINE METERS

6 different 6 inch turbine meters have been calibrated. Turbine meters are well known to have good properties. However, these tests have shown some variation in the characteristics of the turbine meters.

Table 1 shows the Repeatability results: The K-Lab sonic nozzles have a repeatability of about 0.04%. The standard repeatability tests with 30 consecutive runs took approximately 5 hours so it has only been performed for 2 meters. This long time might be considered as the intrinsical weakness of the standard repeatability method. It can be seen that meter A has a very good repeatability of 0.03. But turbine meter B has a higher repeatability of 0.17%. This difference can be explained by looking at Fig. 2 where the flowrate measured on meter B is slightly increasing during the repeatability test whilst the reference volume flow was stable.

The Range Repeatability is practical to calculate and to analyse for all the meters. As expected, this method for calculating the repeatability might give a higher value for the repeatability because it takes into account also the low flowrates where we noticed a large dispersion of the results as a constant trend. Moreover the same error would become larger at low flowrates because the deviation from the reference volume flow is calculated in percentage. Nevertheless the repeatability range for the turbine meters vary between 0.11% up to 0.48%. The mean value for all the turbine meters is 0.24% which compares well with the Standard Repeatability. The table shows also that the Range Repeatability has roughly the same value if 3 or 5 runs were performed at each flowrate. All these results and their comparisons may be an encouragement to use this criterion on a regular basis when calibrating turbine meter.

For these turbines, we cannot produce long time reproducibility data. However, the day-to-day reproducibility data we measured, show that the calibration curves obtained some days later had almost exactly the same shape (see Figure 2).

The independent linearity of the meters varies from 0.21% to 0.74%. The mean linearity for all turbine meters is 0.42%. This demonstrates why turbine meters of the same size are to be calibrated individually for the range to be defined. Table 3 also shows that this standard linearity compares very well with the range linearity at the 95% confidence interval. The two ways of measuring the linearity will give almost the same results if the calibration curve is horizontal which is a specific case of linearity. But, if the calibration curve is fluctuating, the range linearity will be take account of it while the standard linearity will remain the same.

CORIOLIS MASS METERS

Concerning these calibrations, we can pinpoint that the values obtained by Coriolis mass meters are fluctuating so much that a long integration time is needed to obtain a repeatability which is acceptable. To have a good repeatability of the mass meters is very important as the flow factors in the meters have to be adjusted after each calibration. The meters cannot be adjusted correctly if the results obtained are not giving a correct picture of the performance of the meters. But these calibrations also show that the repeatability of the meters is improved from 1.11 to 0.57 when the integration time is increased from 3 minutes to 15 minutes. The drawback with 15 minutes integration time is that it takes a long time to do a calibration, and especially to do a repeatability test.

On Coriolis mass meter A data from the long term reproducibility test are available. It shows that the calibration factor has changed about 0.47% in one year. But here it must be noted that the calibration curves were obtained in two different ways which might have affected the results. The first year 5 runs on each flowrate were obtained with an integration time of 3 minutes. The year after 3 runs on each flowrate with an integration time of 15 minutes was used.

The linearity of the two meters which have been tested are 0.99% and 1.29%. The 95% confidence interval is larger than the standard linearity which means that the calibration curve is not linear but is bending. This can be seen easily on Figure 9.

These meters are of the 1.5 inch type. Our experience with 3 inch Coriolis mass meters from the same manufacturer shows that the larger meters have the same properties. The difference is mainly that the maximum flow rate is larger on a 3" meter.

ULTRASONIC METERS

Only one USM had so far been tested at K-lab. The results obtained with this meter shows that the repeatability and reproducibility are good, but that the linearity, which equals about 2%, is not good at all. If this lack of horizontal calibration curve is caused by the meter itself (for instance bad 0-calibration) or by an installation effect, is currently investigated.

COMPARISON OF ALL THE METERS

Fig. 12 compares some meters of each type. It can be seen that turbine meter A is very good. It shows that not all the turbine meters have the same accuracy. It shows also that the Coriolis mass meters in the test have larger repeatability, reproducibility and linearity than the turbine meter. This bar chart also shows the linearity of the USM compared with the other meters.

CONCLUSION

Standard and Range Repeatability, Reproducibility and Standard and Range Linearity have been successfully gone through and applied to 6 turbine meters, 2 Coriolis mass meters and 1 Ultrasonic flowmeter at 100 bars.

Each method has been carefully considered by taking into account the conditions of use and the so-called Range Methods are shown to be more easy to use from a metering point of view.

The results given by each method compares very well for Turbine Meters, Coriolis Meters and Ultrasonic Meter concerning linearity. The two repeatability methods compares well in order of magnitude for turbine meter and Coriolis mass meters, and USM to a less extent. The differences in repeatability observed with Turbine Meters and Ultrasonic Meter are explained by the fact that the standard method at maximum flowrate does not take into account the relatively more important effect of a constant deviation at low flowrates. The slight differences in linearity between each methods are shown as the result of a better consideration of the fluctuation in the deviation curves over the whole flow range by the alternative method.

Eventually the comparison of these properties has been fully analysed for some meters of each type. It seems from the present results that turbine meters are more repeatable, more reproducible and more linear devices than the new meters in development. On the other hand, the good results concerning repeatability and reproducibility allow to consider ultrasonic meters as promising device considering their calibration simplicity and the fact that they are non-intrusive. However the linear flow range should be improved. Experience with the use of Coriolis meters in gas has been gained through this test programme. Additional tests are however required in order to obtain a better data base for different type of meters.

ACKNOWLEDGEMENTS

This Meter Calibration and tests campaign would not have been possible without the support of the turbine meter manufacturers (Daniel, Elster, Equimeter, Faure Herman, Hydril, and Instromet) and the Coriolis mass meter user (Phillips Petroleum Company Norway) who has kindly allow us to use the calibration data.

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TURBINE METERS	STANDARD REPEATABILITY DEVIATION CURVE (%)	STANDARD REPEATABILITY SONICS NOZZLES (%)	RANGE REPEATABILITY ON THE WHOLE CURVE 5 RUNS (%)	RANGE REPEATABILITY ON THE WHOLE CURVE 3 RUNS (%)
METER A	0.03	0.05	0.13	0.14
METER B	0.17	0.03	0.22	0.17
METER C	//////////////	//////////////	//////////////	0.48
METER D	//////////////	//////////////	//////////////	0.39
METER E	//////////////	//////////////	//////////////	0.15
METER F	//////////////	//////////////	//////////////	0.11
MEAN OF THE 6 TURBINES	//////////////	//////////////	//////////////	0.24

TABLE 1: REPEATABILITY TABLE FOR 6 TURBINE METERS AT 100 BARS AND 37°C FROM 10% of Q_{max} TO Q_{max}.

TURBINE METERS	DIFFERENCE BETWEEN K-FACTOR (%)
METER A	0.044
METER B	0.004

TABLE 2: REPRODUCIBILITY TABLE FOR 2 TURBINE METERS AT 100 BARS

TURBINE METERS	STANDARD LINEARITY (%)	95% CONFIDENCE LEVEL $l_{95} = t_{95}\ \sigma$ (%)	Qmax (acmh)
METER A	0.21	0.20	1000
METER B	0.74	0.75	1600
METER C	0.22	0.22	1000
METER D	0.49	0.51	1000
METER E	0.33	0.37	1600
METER F	0.50	0.55	1600
MEAN OF THE 6 TURBINES	0.415	0.433	/////////

TABLE 3: LINEARITY TABLE FOR 6 TURBINE METERS AT 100 BARS AND 37°C FROM 10% of Q_{max} TO Q_{max}.

CORIOLIS METERS	STANDARD REPEATABILITY DEVIATION CURVES 3 MINUTES (%)	15 MINUTES (%)	RANGE REPEATABILITY 3 MIN. 5 RUNS (%)	15 MIN. 3 RUNS (%)
METER A	1.11	0.57	1.90	0.85
METER B	////////////	/////////////	1.24	0.93

TABLE 4: REPEATABILITY TABLE FOR 2 CORIOLIS METERS AT 100 BARS

CORIOLIS METERS	DIFFERENCE BETWEEN METER FACTOR OVER 1 YEAR (%)
METER A	0.47

TABLE 5: REPRODUCIBILITY TABLE FOR 2 CORIOLIS METERS AT 100 BARS

CORIOLIS METERS	STANDARD LINEARITY (%)	95% CONFIDENCE LEVEL $l_{95} = t_{95}\,\sigma$ (%)	Qmax (kg/min)
METER A	1.29	1.48	300
METER B	0.99	1.85	300

TABLE 6: LINEARITY TABLE FOR 2 MASS METERS AT 100 BARS ABSOLUTE

ULTRASONIC METER	STANDARD REPEATABILITY DEVIATION CURVE (%)	RANGE REPEATABILITY ON THE WHOLE CURVE (%)
METER A	0.17	0.72

TABLE 7: REPEATABILITY TABLE FOR 1 ULTRASONIC METER AT 100 BARS

ULTRASONIC METER	DIFFERENCE BETWEEN METER FACTOR (%)
METER A	0.1

TABLE 8: REPRODUCIBILITY TABLE FOR 1 ULTRASONIC METER AT 100 BARS

ULTRASONIC METER	STANDARD LINEARITY (%)	95% CONFIDENCE LEVEL $l_{95} = t_{95}\,\sigma_{95}$ (%)	Qmax (kg/min)
METER A	1.71	2.05	1300

TABLE 9: LINEARITY TABLE FOR 1 ULTRASONIC METER AT 100 BARS

Fig 1: REPEATABILITY TEST AT 100 BARS, Qmax AND 37 DEG C

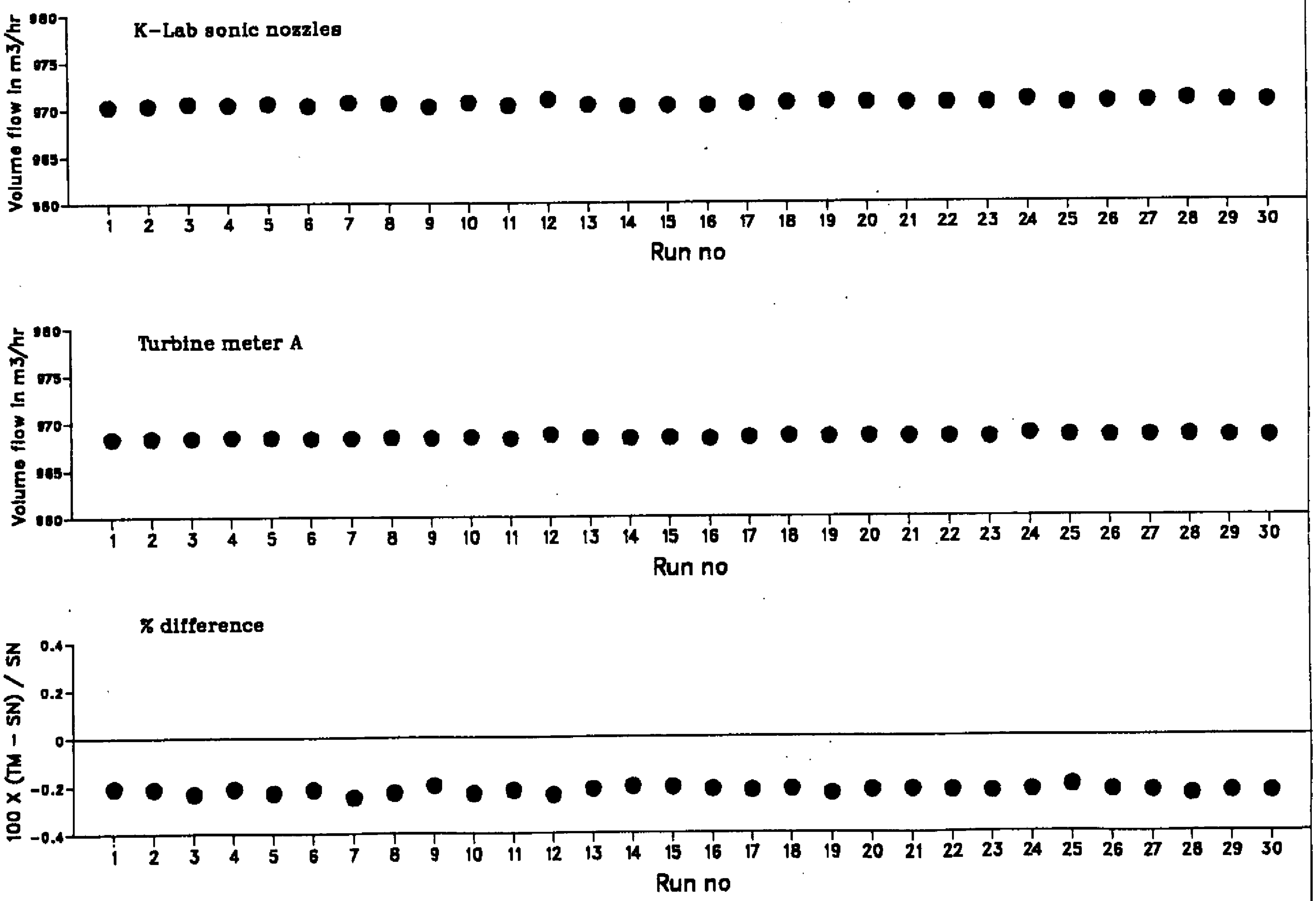
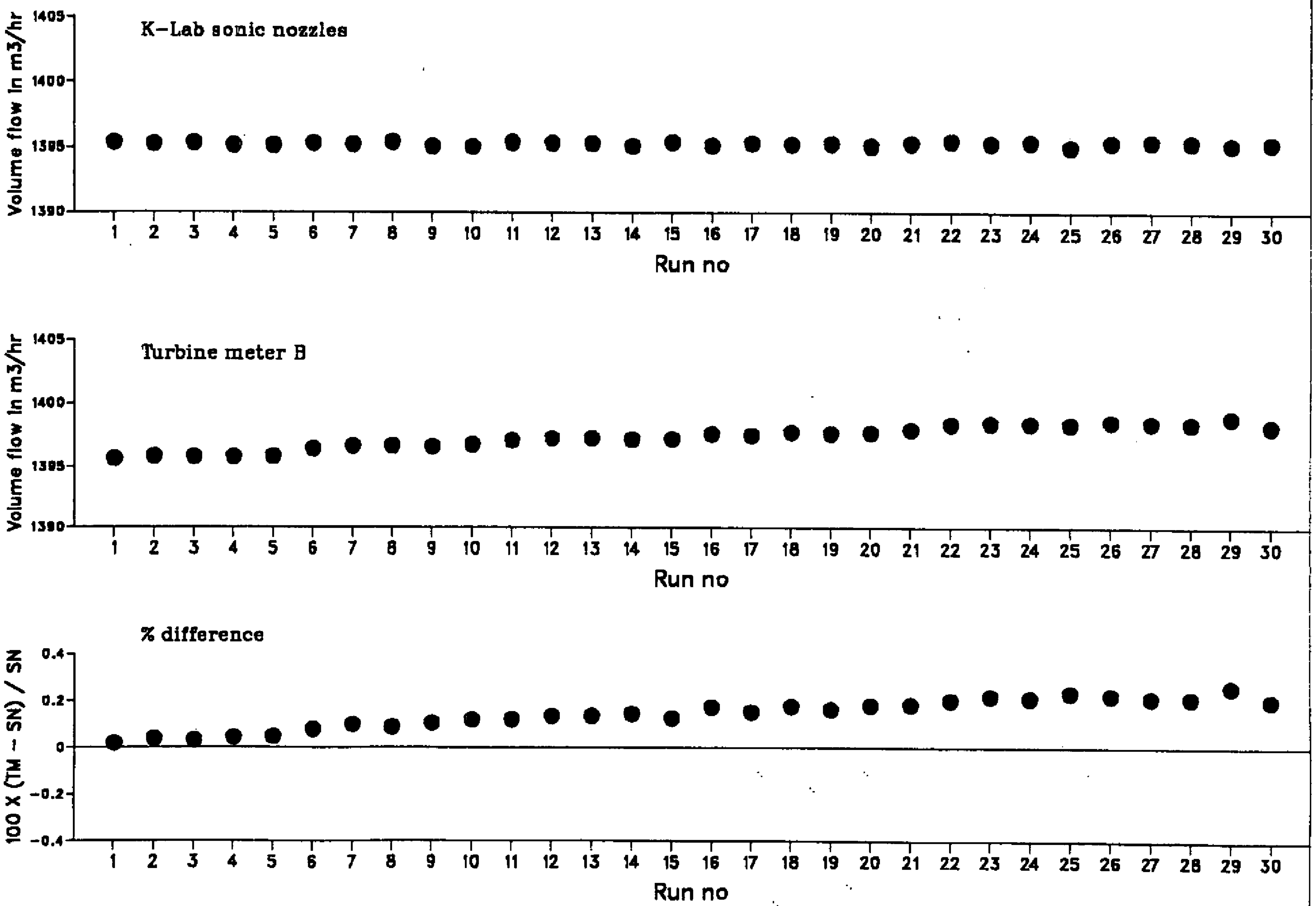


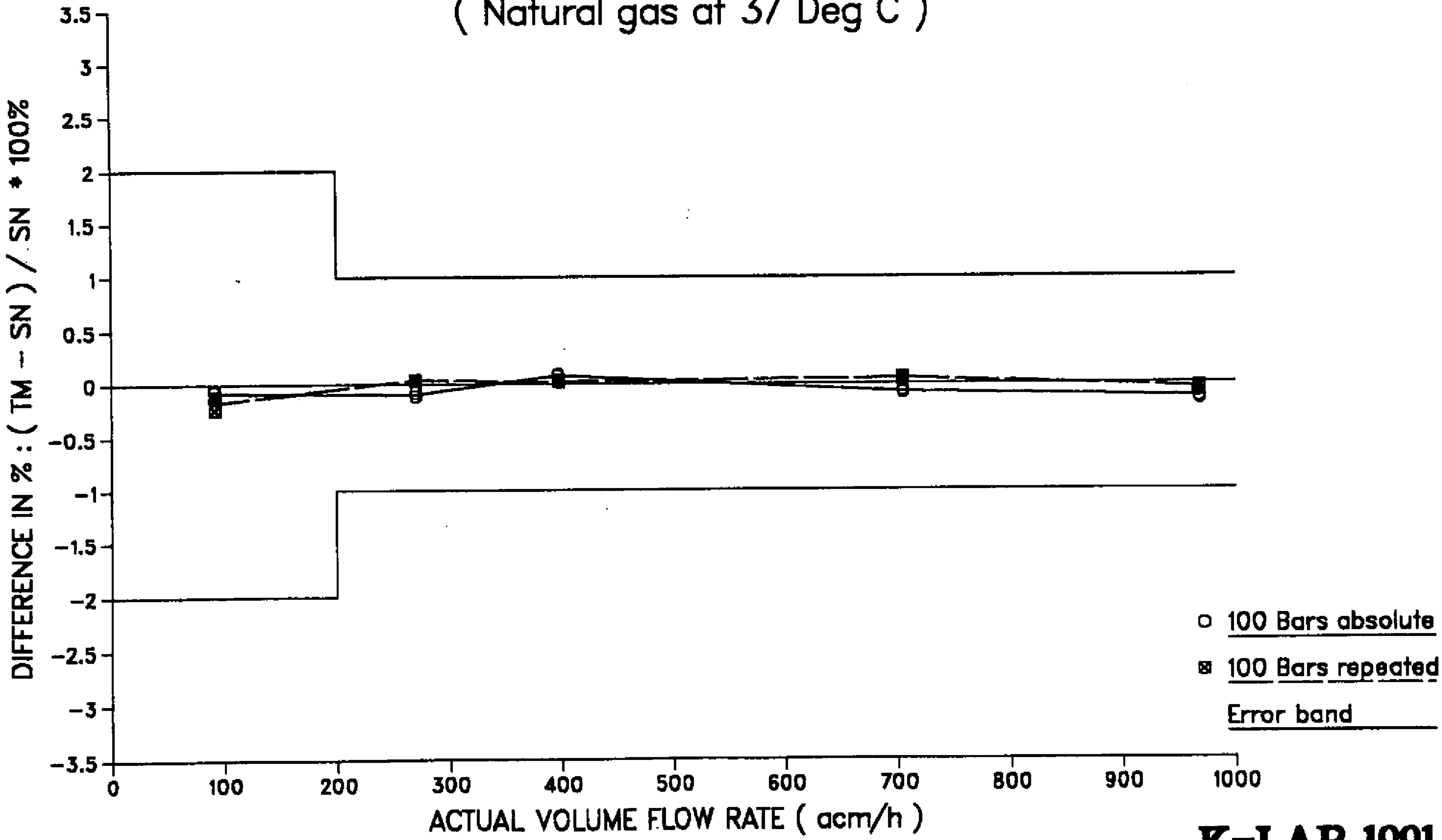
Fig 2 : REPEATABILITY TEST AT 100 BARS AND 37 DEG C



TURBINE METER A CALIBRATION RESULTS

Fig. 3 : REPRODUCIBILITY CURVES

(Natural gas at 37 Deg C)



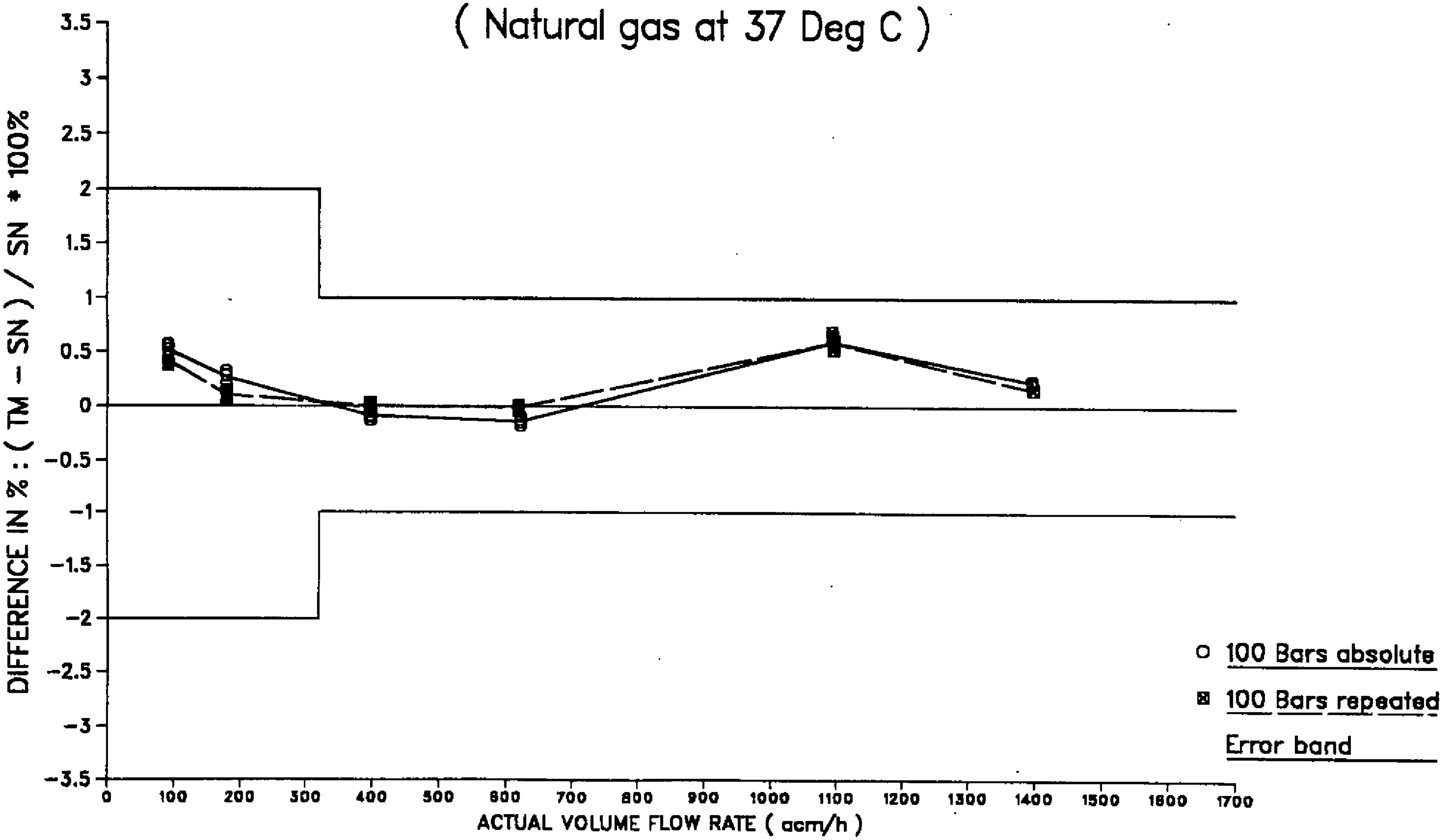
Difference in percentage between the two K–Factors measured at different days = 0.044 %

K–LAB 1991

TURBINE METER B CALIBRATION RESULTS

Fig. 4 : REPRODUCIBILITY CURVES

(Natural gas at 37 Deg C)



Difference in percentage between the two K−Factors measured at different days = 0.004 %

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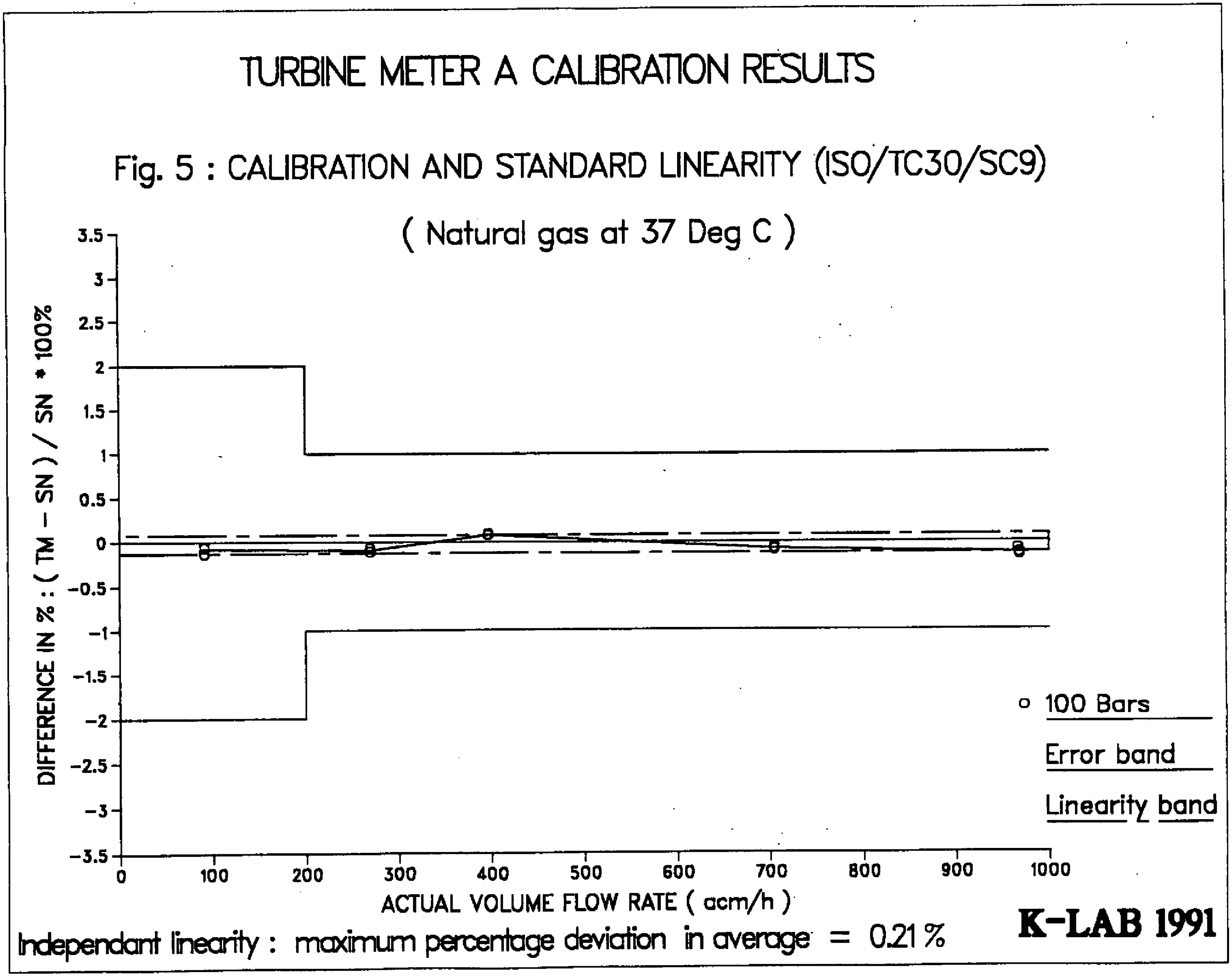
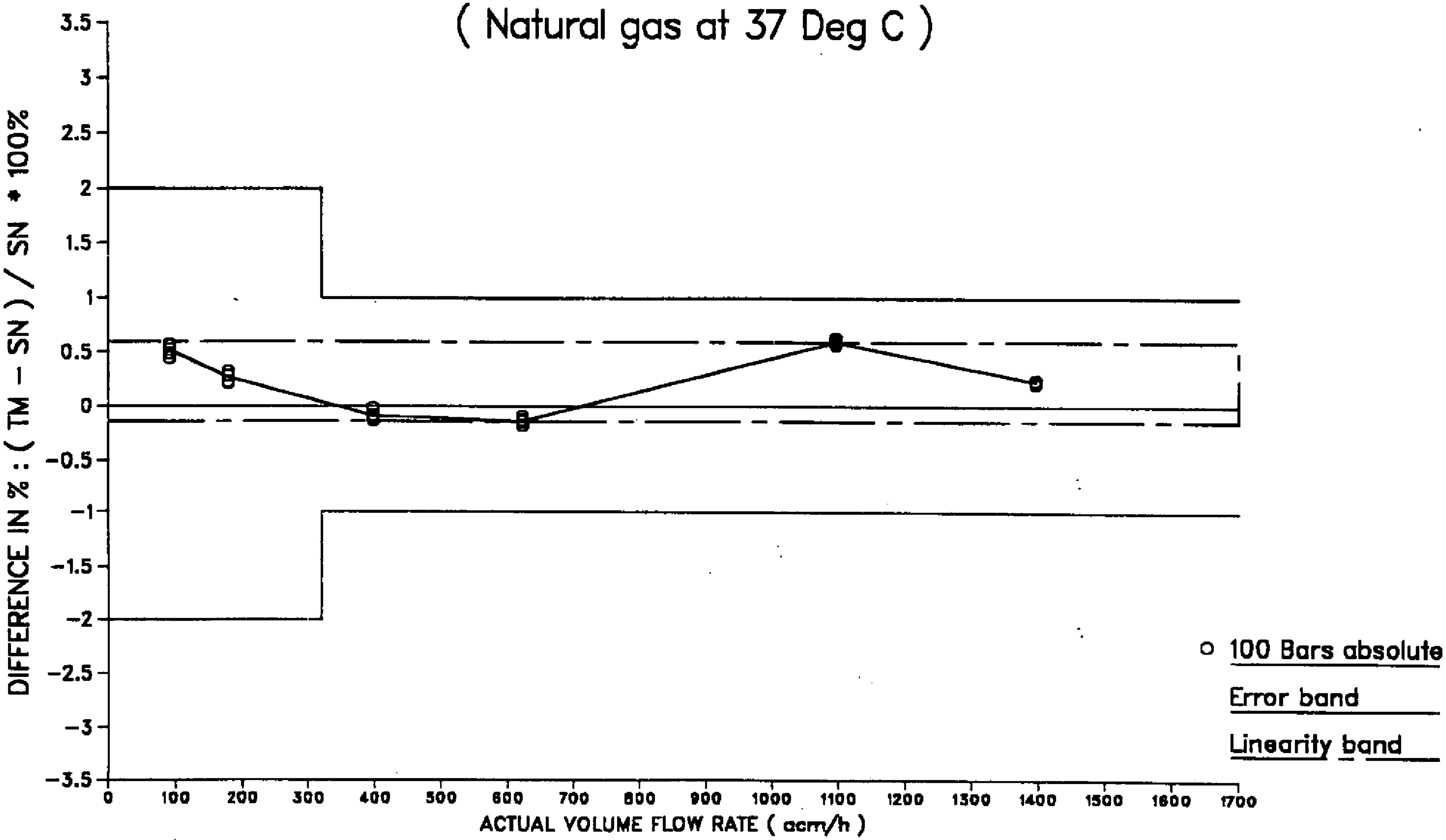


TURBINE METER A CALIBRATION RESULTS
Fig. 5 : CALIBRATION AND STANDARD LINEARITY (ISO/TC30/SC9)
(Natural gas at 37 Deg C)
DIFFERENCE IN % : (TM - SN) / SN * 100%
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0
100
200
300
400
500
600
700
800
900
1000
ACTUAL VOLUME FLOW RATE (acm/h)
100 Bars
Error band
Linearity band
K-LAB 1991
Independant linearity : maximum percentage deviation in average = 0.21 %

TURBINE METER B CALIBRATION RESULTS

Fig. 6 : CALIBRATION AND STANDARD LINEARITY (ISO/TC30/SC9)

(Natural gas at 37 Deg C)



Independant linearity; Maximum percentage deviation in average = 0.74 %

K−LAB 1991

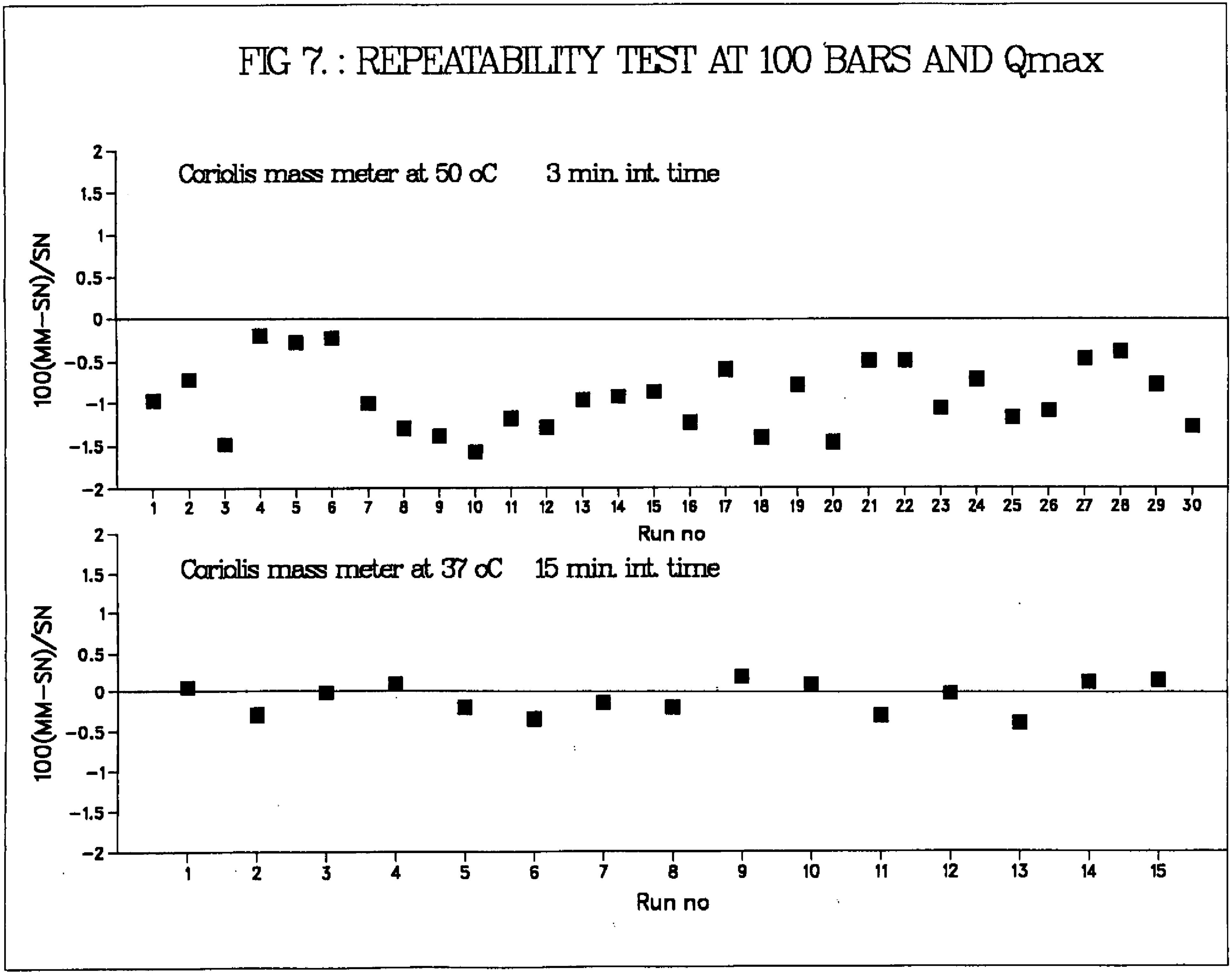
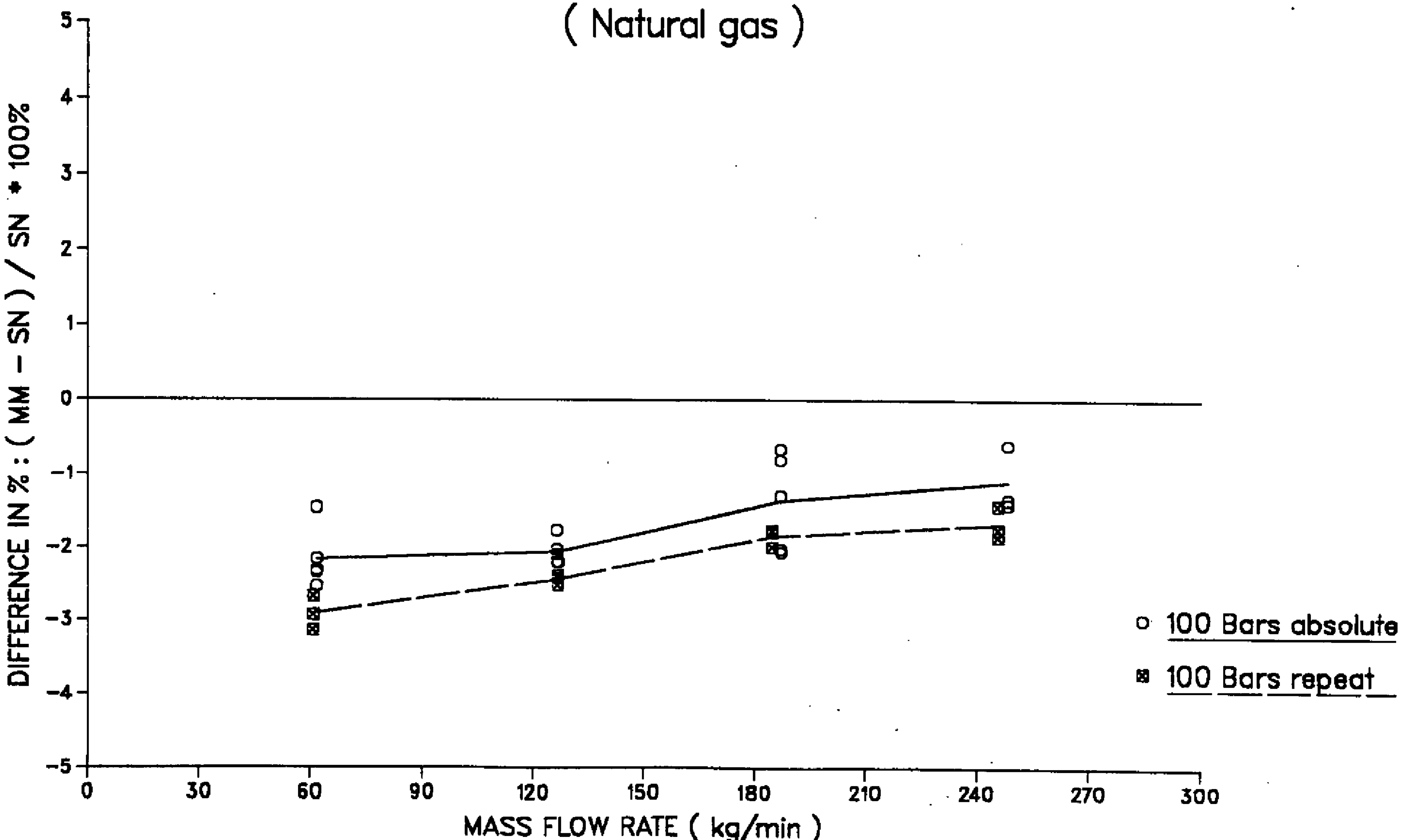


FIG 7. : REPEATABILITY TEST AT 100 BARS AND Qmax
Coriolis mass meter at 50 oC 3 min. int. time
100(MM-SN)/SN
Run no
Coriolis mass meter at 37 oC 15 min. int. time
100(MM-SN)/SN
Run no

CORIOLIS METER A CALIBRATION RESULTS

Fig. 8 : REPRODUCIBILITY CURVES

(Natural gas)



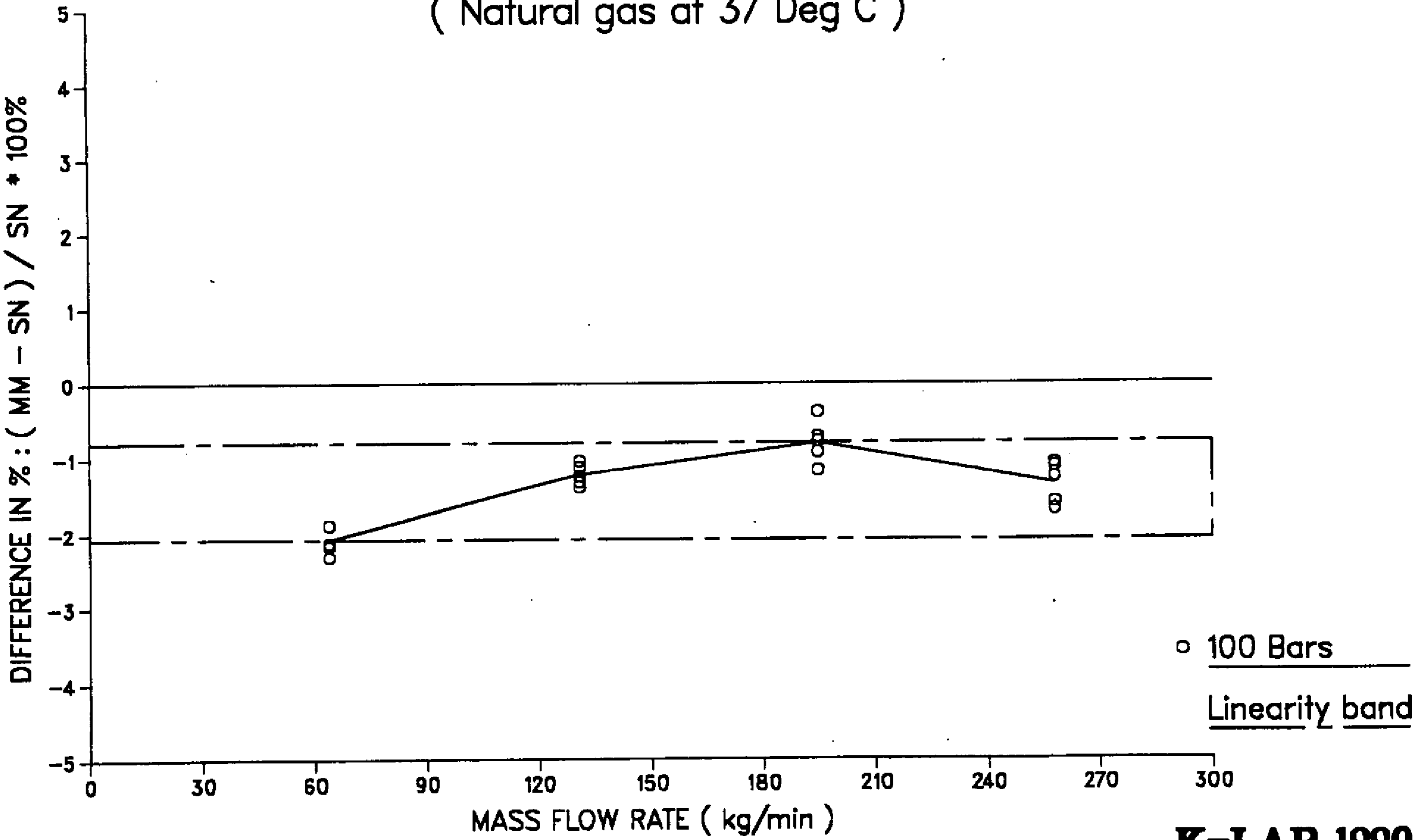
Difference in percentage between the two Meter Factors measured over 1 year = 0.47 %

K-LAB 90/91

CORIOLIS METER A CALIBRATION RESULTS

Fig. 9 : CALIBRATION AND STANDARD LINEARITY (ISO/TC30/SC9)

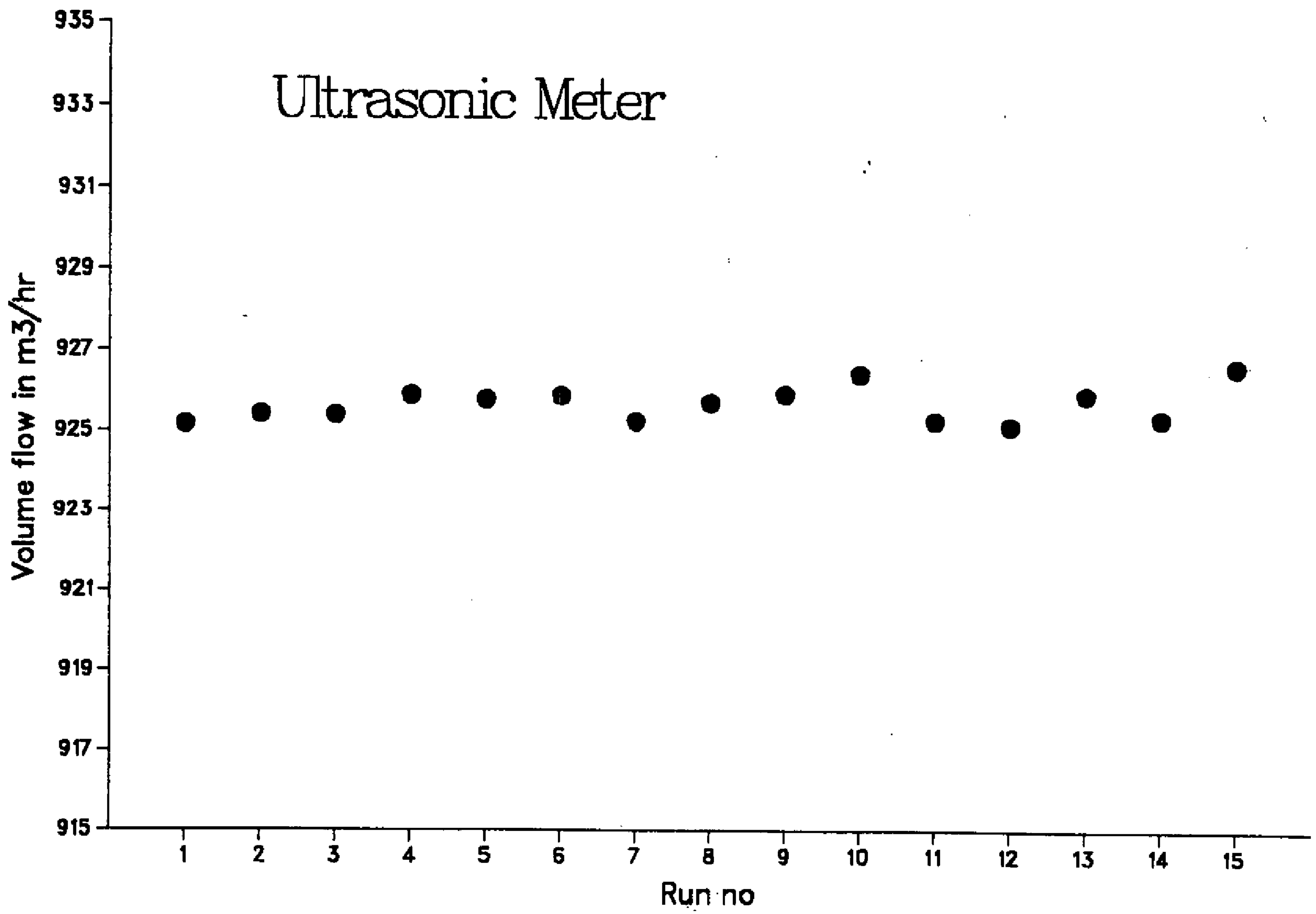
(Natural gas at 37 Deg C)



Independant linearity : maximum percentage deviation in average = 1.29 %

K-LAB 1990

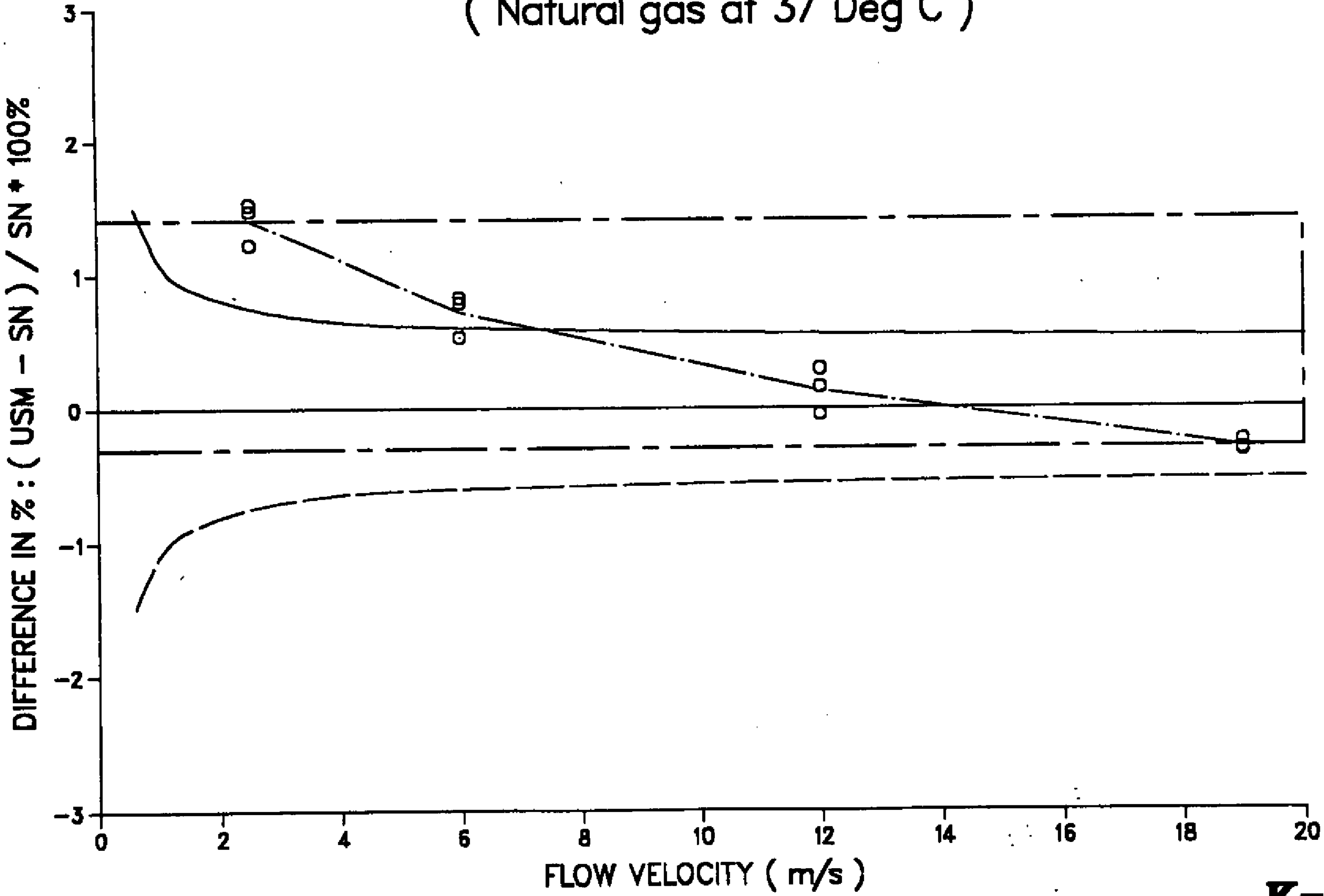
Fig 10 : REPEATABILITY TEST AT 100 BARS AND 37 DEG C



ULTRASONIC METER A CALIBRATION RESULTS

Fig. 11: CALIBRATION AND STANDARD LINEARITY (ISO/TC30/SC9)

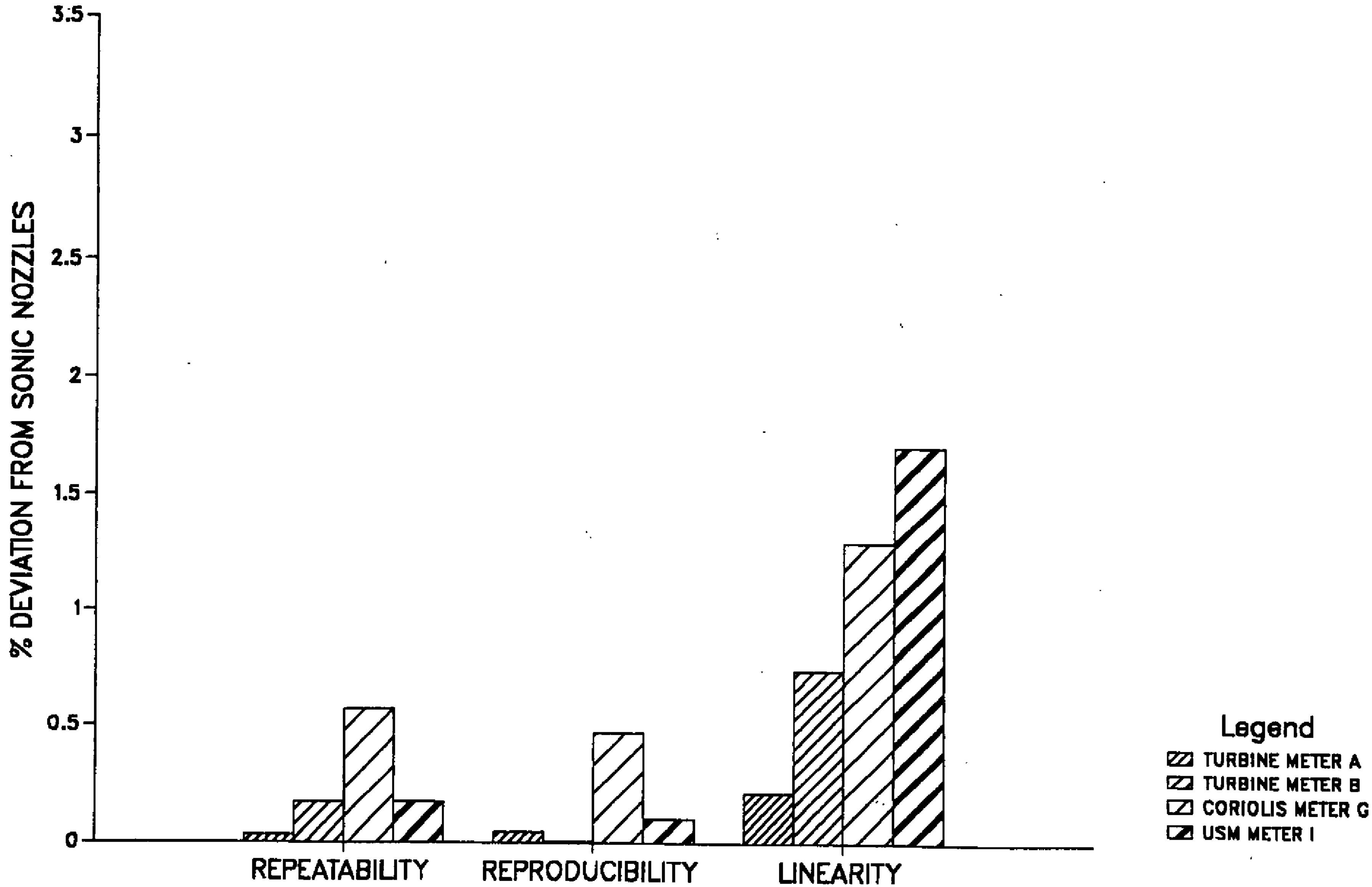
(Natural gas at 37 Deg C)



Independant Linearity : maximum percentage deviation in average = 1.71 %

K−LAB 1990

Fig. 12 : COMPARISON OF DIFFERENT PROPERTIES FOR TURBINE, CORIOLIS AND ULTRASONIC METERS



NEW DEVELOPMENTS

Main Index

Norwegian
Society of
Chartered Engineers

NORTH SEA FLOW MEASUREMENT WORKSHOP

OCTOBER 22. - 24. 1991
SOLSTRAND FJORD HOTEL, BERGEN - NORWAY

METERING STUDY TO REDUCE TOPSIDES WEIGHT

Lecturer:

Mr. Nils-Erik Hannisdal
Aker Engineering

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1 SUMMARY

Alternative metering concepts with the same accuracy of todays conventional concepts, are investigated. The alternatives presented are:

Fiscal oil metering:

Alt. 1: Compact prover as alternative to conventional prover.
Alt. 2: Compact prover combined with turbine meters with extended range and K-factor calibration curves in the computer.

Fiscal gas metering:

Alt. 1: Alternative orifice plate metering (flow straightener, increased β-ratio and differential pressure range).
Alt. 2: Ultrasonic flow meter.

Alternative metering concepts with the same accuracy of todays conventional concepts, might reduce space and weight with more than 50 % compared to present layouts.

The total cost savings might be the double of the actual procurement cost of the metering skid.

2. INTRODUCTION

A group in Aker Engineering (AE) has completed a metering study as part of AE's continuous work in optimising platform topside weight and space. Three aspects have been basis for the work:

A The fiscal metering regulations in Norway have recently been revised. These NPD-regulations invite the operators to suggest alternative solutions, if these are superior and beneficial seen from an overall point of view.

B The global concern of carbondioxide emmission has as known initiated a CO2-fee in Norway - this has such increased the focus on other types of critical flow metering, as fuel and flare gas metering.

C The last couple of years new concepts for fiscal/critical metering has moved from "interesting products with potential" to "proven products". Out of several interesting and proven products and techniques, the following have been evaluated in this report:

* Compact prover as alternative to conventional prover (oil metering).

* Flowcomputers using K-factor calibration curves which enable use of turbine meters with extended range (oil metering).

* Ultrasonic meters as alternative to orifice plate metering (gas metering).

* Alternative orifice metering - as use of flow straighteners, increased orifice bore (β-ratio) and increased maximum differential pressure (gas metering).

* Coriolis meters as alternative to turbine meters (oil metering) and orifice plate metering (gas metering).

This paper will not focus on technical details of these new products, but will summarise key features and give an estimate of the space, weight and cost savings the alternative metering concepts will give.

3 NEW METERING PRINCIPLES

3.1 Compact Prover (Oil alternative 1)

A conventional oil metering system in the North Sea is shown in Fig.1. Typically, a number of turbine meter runs including instrumentation and valves, are physically surrounded by a huge calibration unit - a prover. As an alternative to conventional provers, new types with smaller volume - often called **compact** provers - have been on the marked for some years.

The Brooks compact prover is considered and presented here, as this type has been extensively tested by Statoil and is presently used offshore.

The Statoil tests were performed in 1987 with diesel oil and a "typical" amount of sand for a period which correspond to 10 years of proving operation for two turbine meters.

The repeatability for total of 64 750 strokes or "passes" (equals to 2590 final proving reports) were within 0.03%. Most of them were within 0.02%.

The average stability (long term repeatability) was less than 0.011% per. year.

This prover showed a better repeatability than a conventional prover. All other aspects (weight, cost, maintenance) are superior.

At a Dutch offshore oil platform, three compact provers were installed. After 26000 passes, the following failures were reported:

- Score marks which affected repeatability in one prover barrel, caused by a welding particle from the commissioning. The complete time for replacement of a spare tube was 24 hours.
- One defect poppet valve "O"-ring. Replaced.
- One unpredictable optical switch. Replaced.
- Total downtime: 4 days
- Recommendations: A vertical positioning of the prover may reduce the possibility of abrasive substances remaining in the tube and reduce the chance of severe wear.

An offshore oil platform on the Norwegian sector (Hod) has also recently installed a compact prover. The reports are positive so far (ref. paper from this Flow Metering Workshop).

References is given in Chapter 12.

Below is given a summary of evaluations of compact compared to a conventional prover.

ADVANTAGES

1) Less floor area (1/10 of conventional) and volume.

2) Less weight (1/4 of conventional)

3) Cheaper

4) Better repeatability and long term stability

5) Less instrumentation (no 4-way valve with leak detection, only one pressure and temp. transmitter required).

6) Easier prover calibration (only water draw can is needed).

7) Special material for special applications (cold products, etc.), beneficial experience for operators involved in LPG and LNG where conventional provers seem to fail easily.

8) Internal surface defects less critical (compact prover cylinder can be replaced easily, while a damaged internal surface on a conventional prover is a big problem).

9) Larger range (beneficial if max capacity is increased in connection with future tie-ins, etc. or if extended range is used for turbine meters) and better low flow performance (important late in the field life time and beneficial if other meters shall be used in the future).

10) Easier access to meter run instruments and valves.

DISADVANTAGES

1) Relatively new equipment with limited experience.

2) Not manufactured by metering supplier. (one additional interface to subsupplier).

3) More vulnerable to foreign solid particles (sand, welding particles, etc).

4) Require pulse interpolation in computers.

5) Require turbine meters with high stability due to pulse interpolation.

3.2 K-factor Calibration Curves and Extended Range Turbine Meters (Oil alternative 2)

Modern flow computers have the ability to calculate flow by using the turbine meters' full K-factor calibration curve - as an alternative to the traditional one K-factor for the complete range of the turbine meters. This will drastically reduce the linearity effect of the turbine meters. A typical K-factor curve is given in Fig. 2

Turbine meter manufacturers often operate with a normal flow range of about 1:10 (e.g. 50-500 m3/hr). This range is limited by the turbine meters linearity, as experienced by suppliers, engineering companies and operators during testing.

K-factor calibration curve reduce/ eliminate the linearity effect, and the turbine meters repeatability will be the limiting effect. However, turbine meter manufacturers use the same repeatability requirements for an extended flow range, typically 1:15 or 1:20. This will reduce number of meter runs or meter size required for a given flow capacity.

3.3 Alternative Orifice Plate Metering (Gas alternative 1)

A conventional gas metering system in the North Sea is shown in Fig. 3. Such systems are recognised by a number of orifice plate meter runs with long upstream straight lengths, instrumentation and valves.

Three alternatives are investigated in order to reduce space and weight for the orifice plate metering stations:

1) Flow straighteners
2) Increased orifice bore (β-ratio)
3) Increased maximum differential pressure (max dp)

The Kårstø Laboratory (K-Lab) has done promising testing with flow straighteners especially designed for developing a fully turbulent flow regime within 15 x ID in a gas flow line.

K-Lab report that accuracy requirements are maintained also at larger orifice bores (higher β-ratios) and higher differential pressures (dp) than given as maximum by NPD. This is confirmed by others. Metering suppliers' own calculations have shown that a β = 0.70 and dp = 700 mbar will not give decrease in accuracy.

Detailed investigations done by Statoil, Aker, KOS and PECO in a recent project show that an increase of differential pressure to max. 700 mbar will give no buckling effect on the orifice plate (additional uncertainty less than 0.001%).

3.4 Ultrasonic Flow Meters (Gas alternative 2)

Ultrasonic flow meters for fiscal gas applications have the following features:

ADVANTAGES

1) A multi-path ultrasonic high pressure gas meter is capable of metering accurately (i.e. to the best standards achieved by an orifice meter run or a gas turbine meter) with 10D straight pipe upstream and 3D downstream. There are also definite indications that the meter could be used in installation where 10D was not available upstream of the meter and still provide acceptable results, particularly if the meter is not operating at the maximum end of the flow range.

2) Degrees of swirl and turbulence in a disturbed flow can be indicated.

3) Small skids due to the meters high turndown and capacity.

4) One meter will in most applications be capable of taking full flow (due to large capacity and range); which will give a lot better flexibility with regards to operation of valves (manual or operated from PCDA).

6) Applicable for high pressure ratings.

7) Easy and cheap to calibrate and maintain.

8) Self checking, to a certain degree.

9) Interchangeable with turbine meters (beneficial for uncertainty diagnosis).

10) Negligible pressure drop.

DISADVANTAGES

1) No international standard yet (draft is expected shortly).

2) Not according to NPD-regulations (concession must be given).

3) Only one manufacturer on the marked which has a proven product.

4) Narrow temperature range: - 20°C + 40°C (valid for the applicable manufacturer).

Extensive tests have been done by Gasunie, Netherlands and K-Lab Norway (ref. ch. 12). About 40 meters have presently been sold, the first metering skid to fiscal standard in the Norwegian part of the North Sea was sold to Statoil this year.

3.5 Coriolis Flow Meter

Coriolis flow meters have been on the market for some years, the main features are:

ADVANTAGES

1) Direct mass flow measurements.
2) No upstream straight length required.
3) Density and temperature as a secondary reading. (Possible to measure water in oil).
4) Large temperature ranges.
5) Reliable instruments.
6) Relatively accurate.

DISADVANTAGES

1) Mainly small meters.
2) Accuracies not proven to be of fiscal standard yet.
3) Uncertainties with regard to pressure and erosion/sand problems due to thin walls.
4) High pressure loss at max. capacity.
5) Uncertainties with regard to installation effects.

References are given in Ch. 12

Based on the factors above, coriolis meters are not regarded to be an alternative for fiscal oil or gas metering in this paper. However, we are awaiting test results to be presented at this Flow Metering Workshop.

For critical flow metering with smaller quantities, as fuel or test separator metering, coriolis meters are considered to be an interesting substitute to conventional meters.

4 WEIGHT AND SPACE COMPARISONS

Conventional metering skids installed in the North Sea are compared with alternative concepts as described above. In this analysis, certain normalising assumptions have been made. In most projects, some non-typical decisions are made. This can be extra set of valves, pipe class higher than corresponding process data, etc. Such considerations are evaluated and "normalised" by calculations.

Another consideration which must be done when space and weight are compared, is to evaluate access. Simpler equipment make access easier. We can see a tendency all over the North Sea that due to low maintenance manning; the access requirements get stricter. This again require larger overall equipment sizes.

Three North Sea oil and gas metering installations are presented here, but five other installations have been evaluated and confirm the results. Savings are given as:

100 - (Alt.2/Conventional)·100 = Savings in %

Complimentary data are given in Table 1 and 2, behind in this paper.

OIL SPACE COMPARISONS

Capacity (Sm3/hr)	Conv. (m3)	Alt. 1 (m3)	Alt. 2 (m3)	Savings (%)
1051	148	80	56	62
1457	205	112	80	61
8600	729	364	301	59
			Average:	61 %

OIL WEIGHT COMPARISONS

Capacity (Sm3/hr)	Conv. (tonnes)	Alt. 1 (tonnes)	Alt. 2 (tonnes)	Savings (%)
1051	22	14	9	59
1457	26	18	13	50
8600	106	71	56	47
			Average:	52 %

GAS SPACE COMPARISONS

Capacity (mill.Sm3/d)	Conv. (m3)	Alt. 1 (m3)	Alt. 2 (m3)	Savings (%)
3.9	70	34	12	83
4.6	97	51	12	88
35.0	625	327	54	91
			Average:	87 %

GAS WEIGHT COMPARISONS

Capacity (mill.Sm3/d)	Conv. (tonnes)	Alt. 1 (tonnes)	Alt. 2 (tonnes)	Savings (%)
3.9	20	13	10	50
4.6	23	17	10	57
35.0	133	106	50	62
			Average:	44 %

6 TOPSIDE SAVINGS

In order to discuss cost benefits due to savings in space and weight, it is useful to know which factors are generating the cost, and the effect of these. Even if the cost benefit of a small metering skid in itself is small, the overall savings will be considerable.

First of all, platform topside represent a major part of the total platform cost. The fraction of the cost will vary dependant of the reservoir, quantities, infrastructure, etc. - but might be as high as 75 % of total, and should be (but are not always) the main target for cost reductions.

The key items on the platform are the process equipment itself. Other items - such as steel, cables, lights, fire protection, lifeboats, ... - can be regarded as a function of the process equipment (bulk and steel function). A larger and more complex mechanical package will give more instruments and cables, and need more structural steel and lights. Engineering will be more complex, construction will be more time consuming and commissioning will require more resources.

A smaller and simpler equipment will then of course give the same savings. The question is how much ? Aker Engineering have data bases which estimate such savings.

A metering station in the North Sea will have a procurement cost of about 100-300 NOK/KG, somewhat dependant of pressure classes, quantities, etc., but an average of 200 NOK/KG apply. Adding the cost for engineering, construction at site, atshore, inshore and offshore commissioning and modifications will give the metering package a price tag of about 600 NOK/KG.

Structural steel will have a total price of 44 NOK/KG and bulk (anything which is not equipment or steel) 255 NOK/KG in the examples investigated. This following cost reductions can therefor be calculated:

Oil capacity	Reductions				
	Dry weight (tonnes)		Cost (in mill. NOK)		
(Sm3/hr)	Metering	Bulk & Steel	Metering	Bulk & Steel	Total
1051	13	16	7.8	1.7	9.5
1457	13	13	7.8	1.3	9.1
8600	50	59	30.0	6.2	36.2

Gas capacity	Reductions				
	Dry weight (tonnes)		Cost (in mill. NOK)		
(mill. Sm3/d)	Metering	Bulk & Steel	Metering	Bulk & Steel	Total
3.6	10	7	6.0	0.4	6.4
4.6	13	16	7.8	1.7	9.5
35.0	80	89	48.0	9.3	57.3

So, even if the alternative metering equipment in itself will not give major savings, the total cost will be considerably reduced.

Combining the cost for fiscal oil and gas metering, adding cost for fuel and flare metering and other critical metering as test separator, reinjection and produced water metering - and then adding the cost for operation and maintenance the total topside savings will reach 50 - 100 mill. NOK.

6 CONCLUSION

Alternative metering concepts with the same accuracy of todays conventional concepts, might reduce space and weight with more than 50 % compared to present layouts.

The total cost savings might be the double of the actual procurement cost of the metering skid.

FISCAL OIL METERING, CONVENTIONAL

Capacity (Sm3/hr)	Length (m)	Width (m)	Height (m)	Area (m2)	Weight* (tonn)	Number of runs	Max.press (Bara)
1051.00	10.0	3.7	4.0	37.0	20.3	3 x 6"	36.0
8600.00	18.0	9.0	4.5	162.0	89.0	5 x 12"	40.0
1457.00	12.0	3.8	4.5	45.6	24.1	4 x 6"	48.1

* Dry weight

FISCAL OIL, ALT. 1; COMPACT PROVER

Capacity (Sm3/hr)	Length (m)	Width (m)	Heigth (m)	Area (m2)	Weight* (tonn)	Number of runs	Max.press (Bara)
1051.00	7.6	2.5	3.5	21.3		3 x 6"	36.0
	+1.5	+1.5	+6.0				
8600.00	18.0	5.4	3.5	101.2		5 x 12"	40.0
	+2.0	+2.0	+6.0				
1457.00	10.0	2.8	3.5	30.5		4 x 6"	48.1
	+1.5	+1.5	+6.0				

* Dry weight

FISCAL OIL, ALT. 2; COMPACT PROVER & EXTENDED RANGE TURBINE METERS

Capacity (Sm3/hr)	Length (m)	Width (m)	Height (m)	Area (m2)	Weight* (tonn)	Number of runs	Max.press (Bara)
1051.00	7.6	1.6	3.5	14.4		2 x 6"	36.0
	+1.5	+1.5	+6.0				
8600.00	18.0	4.4	3.5	83.2		4 x 12"	40.0
	+2.0	+2.0	+6.0				
1457.00	7.6	2.5	3.5	21.3		3 x 6"	48.1
	+1.5	+1.5	+6.0				

* Dry weight

Table 1: Space and weight data for 3 North Sea oil metering skids

7 ACKNOWLEDGEMENTS

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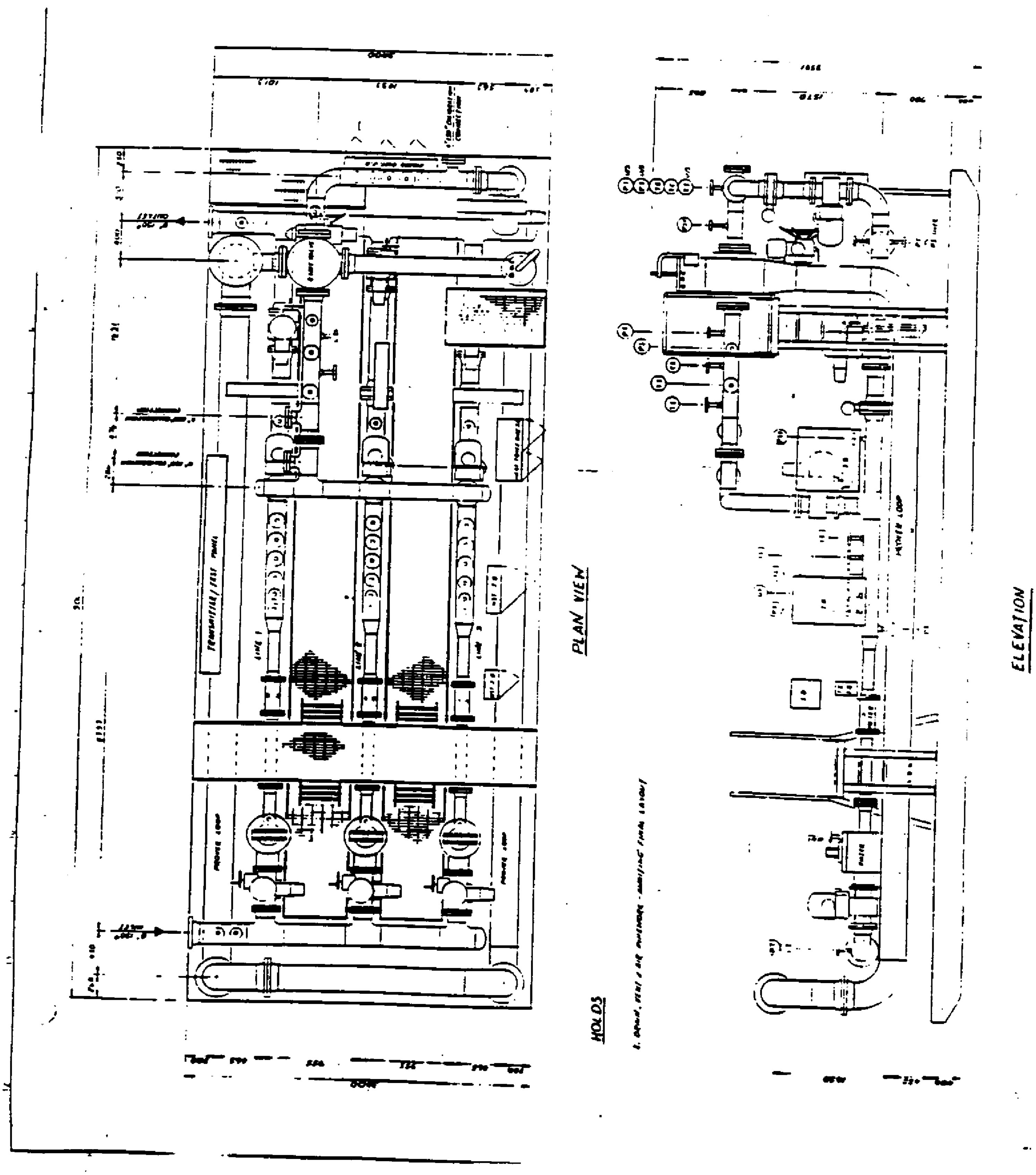
Fig. 1: Conventional Fiscal Oil Metering Skid
(printed with permission from KOS/PECO)



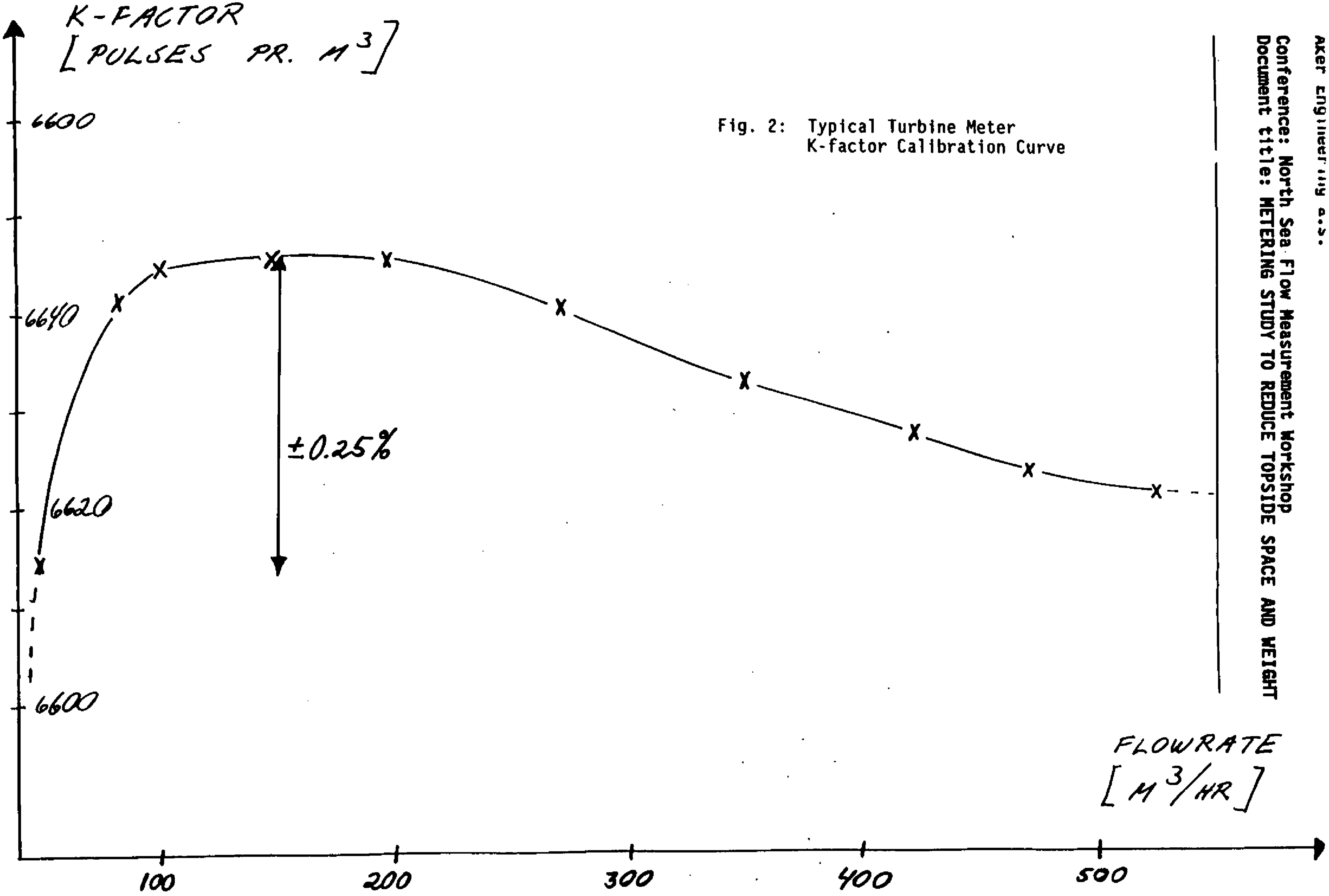
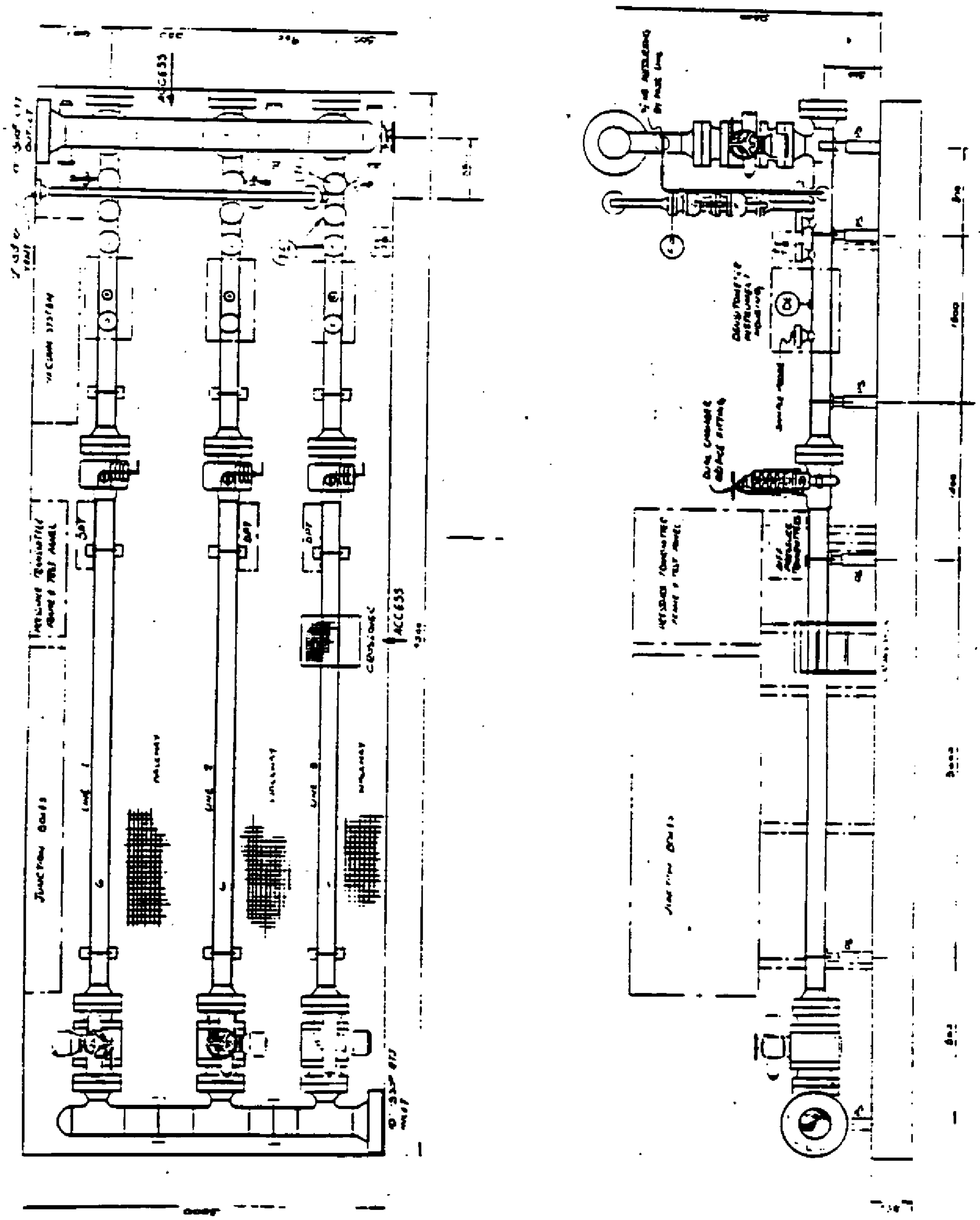


Fig. 2: Typical Turbine Meter K-factor Calibration Curve

Fig. 3: Conventional Fiscal Gas Metering Skid (printed with permission from KOS/PECO)



FISCAL OIL METERING, CONVENTIONAL

Capacity (Mill.Sm3/day)	Length (m)	Width (m)	Height (m)	Area (m2)	Weight* (tonn)	Number of runs	Max.press (Bara)
1051.00	10.0	3.7	4.0	37.0	20.3	3 x 6"	36.0
8600.00	18.0	9.0	4.5	162.0	89.0	5 x 12"	40.0
1457.00	12.0	3.8	4.5	45.6	24.1	4 x 6"	48.1

* Dry weight

FISCAL OIL, ALT. 1; COMPACT PROVER

Capacity (Mill.Sm3/day)	Length (m)	Width (m)	Heigth (m)	Area (m2)	Weight* (tonn)	Number of runs	Max.press (Bara)
1051.00	7.6	2.5	3.5	21.3		3 x 6"	36.0
	+1.5	+1.5	+6.0				
8600.00	18.0	5.4	3.5	101.2		5 x 12"	40.0
	+2.0	+2.0	+6.0				
1457.00	10.0	2.8	3.5	30.5		4 x 6"	48.1
	+1.5	+1.5	+6.0				

* Dry weight

FISCAL OIL, ALT. 2; COMPACT PROVER & EXTENDED RANGE TURBINE METERS

Capacity (Mill.Sm3/day)	Length (m)	Width (m)	Height (m)	Area (m2)	Weight* (tonn)	Number of runs	Max.press (Bara)
1051.00	7.6	1.6	3.5	14.4		2 x 6"	36.0
	+1.5	+1.5	+6.0				
8600.00	18.0	4.4	3.5	83.2		4 x 12"	40.0
	+2.0	+2.0	+6.0				
1457.00	7.6	2.5	3.5	21.3		3 x 6"	48.1
	+1.5	+1.5	+6.0				

* Dry weight

Table 1: Space and weight data for 3 North Sea oil metering skids

FISCAL GAS METERING, CONVENTIONAL

Capacity (Mill.Sm3/day)	Length (m)	Width (m)	Height (m)	Area (m2)	Weight (tonn)	Number of runs	Max.press (Bara)
35.0	26.9	7.3	3.1	196.0	133.2	5 x 16"	173.0
4.6	10.3	4.7	2.0	48.4	22.5	4 x 8"	231.0
3.9	11.6	3.0	2.0	34.8	19.8	3 x 8"	201.0

FISCAL GAS, ALT. 2; ULTRASONIC METERING

Capacity (Mill.Sm3/day)	Length (m)	Width (m)	Height (m)	Area (m2)	Weight (tonn)	Number of runs	Max.press (Bara)
35.0	9.0	3.0	2.0	27.0	50.0	3 x 16"	173.0
4.6	6.0	1.0	2.0	6.0	10.0	2 x 6"	201.0
3.9	6.0	1.0	2.0	6.0	10.0	2 x 6"	231.0

Ultrasonic meters: two meters on top of each other

FISCAL GAS, ALT. 1; ALTERNATIVE ORIFICE PLATE METERING

Capacity (Mill.Sm3/day)	Length (m)	Width (m)	Height (m)	Area (m2)	Weight (tonn)	Number of runs	Max.press (Bara)
35.0	17.6	6.0	3.1	105.6	106.0	4 x 16"	173.0
4.6	7.8	3.3	2.0	16.9	16.9	3 x 8"	201.0
3.9	8.6	2.0	2.0	17.2	13.2	3 x 8"	231.0

Table 2: Space and weight data for 3 North Sea gas metering skids

Norwegian
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NORTH SEA FLOW MEASUREMENT WORKSHOP

OCTOBER 22. - 24. 1991
SOLSTRAND FJORD HOTEL, BERGEN - NORWAY

A NEW OIL AND MULTI-PHASE FLOW LABORATORY AT NEL

Lecturer:

Mr. Nicholas W. King
NEL

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Nicholas W King

NEL, East Kilbride, Glasgow

NORTH SEA FLOW MEASUREMENT WORKSHOP

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SUMMARY

NEL is currently building a new and larger Oil and Multiphase Flow Measurement Laboratory as part of the UK National Flow Measurement Standard. A description of the new laboratory is given, and in particular the new Multiphase Flow Measurement Standard which will be the first of its kind in the world.

Because the laboratory has been built as a service to the oil industry it is important that the new laboratory meets the present and future needs of that industry. This paper is therefore presented firstly to inform the oil industry of the capabilities of the new UK Standard for Oil and Multiphase Flow Measurement, and secondly to invite comments and suggestions from all those with an interest in oil and multiphase flow measurement.

INTRODUCTION

NEL has had a long involvement with the Offshore industry and has developed many skills and facilities in the fields of structures, materials, pump and valve design and testing, and particularly in the flow measurement of oil, gas and water.

NEL is the custodian of the UK National Flow Measurement Standards for oil, water, and gas with separate laboratories for each of these three fluids. Because of the increasing demand from the North Sea oil industry it became necessary to expand the size and capability of the oil flow laboratory, not only in flow range, but also in the type of oils used and the testing capability. Funding of $5 million was therefore provided for the construction of a totally new and larger Oil Flow Measurement Laboratory. Named after James 'Paraffin' Young, the nineteenth century Scottish entrepreneur who is widely regarded as the founder of the world's mineral oil industry, the building to house the new laboratory was initiated in August 1990 and completed in May 1991. The first facilities were installed for the official opening of the laboratory which was performed by Robert Horton, the Chairman and Chief Executive of BP in September 1991. Design and construction of the remaining facilities and the multiphase flow measurement facility are presently underway and all facilities are expected to be commissioned by early 1993.

SPECIFICATION OF THE NEW OIL AND MULTIPHASE FLOW LABORATORY

Working on the experience gained from operating the original Oil Flow laboratory and in anticipation of future needs, the specifications for the new laboratory were set as:-

* Three Gravimetric Flow Measurement Primary Standards, 1 to 100 l/s flowrate for each of kerosine, Gas Oil and 15 cSt oil. Measurement uncertainty to be better than 0.05 per cent of volume at the 95 per cent confidence level.

* One high Flow Measurement Secondary Standard of 1 to 200 l/s using any one of the above oils.

* Two small Gravimetric Flow Measurement Primary Standards of 0.1 to 10 l/s and 0.01 to 2.5 l/s of user defined oils. Measurement uncertainty to be better than 0.05 per cent of volume at the 95 per cent confidence level.

* One Water-in-oil Flow Facility of 1 to 50 l/s for flow studies.

* One Multiphase Flow measurement Secondary Standard of 1 to 80 l/s oil and water flow and 1 to 100 l/s of air or nitrogen flow with 60m of horizontal and 12m of vertical pipe runs.

* All liquids and gases to be safe for use at all operating conditions.

* All facilities to be capable of pressures up to 8 bar and temperatures from 0 to 70^{o}C to $\pm$ 1^{o}C control.

In addition, all the test facilities, including the control and data acquisition systems, should be adaptable and capable of further expansion to meet future needs.

Descriptions of the James Young building and each flow facility are given below:-

THE JAMES YOUNG BUILDING

The main working bay of the James Young building measures some 80m long by 20m wide by 11m high and is serviced by two 5 tonne overhead travelling cranes. A separated and ventilated basement 4.5m deep has been built under part of the working floor space to accommodate oil storage tanks and the pump room. Entrance foyer, office accommodation, plant room and other services are provided in a single storey 16m by 15m annex at one end of the main building.

A schematic of the general building layout is given in fig. 1 which shows the various facilities and the control rooms sited at each end of the laboratory for control and data logging purposes. Attached to one of the control rooms are three small laboratories to accommodate chemical analysis equipment and special facilities which can include the use of crude oils.

METHOD OF CALIBRATION

All three Flow Measurement Standards at NEL, ie those for oil, water and gas, are based on gravimetric standards, as opposed to volumetric standards used by some other standards laboratories. The NEL standards therefore measure the total mass of fluid passed through the flowmeter in a given time, so that Flow is measured against traceable mass and time standards.

In oil flow measurement it is more common that a flowmeter is used to measure total bulk flow, rather than flowrates and hence normal calibration is by the 'Standing start and finish' method. In this a flowmeter is installed in a test line and oil circulated through the lines to remove all trapped air. The stop/start valve is then closed and the weightank is weighed empty and the meter readings noted or set to zero. The stop/start valve is then opened and the weigh tank filled. The stop/start valve is then closed and the weight of oil in the weigh tank measured after a constant level drain device has settled to its permanent level and the readings on the meter recorded. The net weight of oil, after correction for air buoyancy, when divided by the oil density at the prevailing temperature gives the volume to be compared with the meter reading.

For those flowmeters which may be affected by an abrupt flow change a 'Flying start and finish' calibration is used. In this the meter is calibrated against a high quality reference meter, usually of positive displacement type and so unaffected by flow changes. This can either be accomplished while the reference meter is itself being calibrated against the gravimetric standard, or if this is not practical, then directly against the reference flowmeter which is then checked against the gravimetric standard at the start and finish of the calibration.

A more detailed explanation of the flow measurement standards at NEL can be obtained from ref. 1 and of flow measurement principles in general from ref. 2.

MAIN FLOW MEASUREMENT PRIMARY STANDARD

The main primary standard comprises three separate flow circuits using Kerosine, Gas Oil and 15 cSt oils respectively and each with a flow capacity of 100 l/s - lines a, b and c in fig 1. By controlling the operating temperature it is possible to obtain any viscosity required over the continuous range between 1.5 and 20 cSt. All oils are refined mineral oils with flash points in excess of 70°C.

Fig. 2 shows a schematic of one of the three flow circuits which comprise the main primary flow standard. All pipework and tanks, except for the main test lines, slope slightly so that liquids can be drained from the low points and gases vented from the high points. The oil for each circuit is stored in 30 m^3 tanks located in the basement and maintained within ± 1°C of a pre-determined temperature anywhere between 0 and 70°C. Temperature control is effected by circulating the contents of the tank via a 10 l/s pump through heat exchangers for heating using the building heating water supply, or cooling using a supply of cooled glycol pumped from chiller units outside the building. The chiller units are linked to all the facilities in the James Young building and have a total cooling capacity of 300 kw. A 100 micron filter circuit is also installed so that the oil in the tanks can be regularly cleaned.

Each flow circuit is designed to operate either two independent test lines at half full flow capacity or one test line at full flow capacity depending on demand. There is accordingly provision for two test lines in each circuit which can be used either as independent test lines or to allow one test line to be built up or dismantled while the other line is in use.

To enable this dual test line utilisation, two separate variable speed positive displacement screw pumps of 50 l/s capacity at 8 bar head receive oil via 200mm diameter outlets from each storage tank. Separate 150mm diameter pipes lead from each pump along under-floor conduits to the inlet of the test lines at the other end of the laboratory. A system of cross-over valves enables the two pumps to be used either independently or together, and also allows one or two test lines to be accommodated in each circuit.

The test lines themselves consist of 30m straight horizontal runs across the main floor of the laboratory. A collection of reducer and expansion pieces and telescopic joints allow a range of flowmeter sizes and types to be accommodated in the test lines and also a wide range of pipe configurations to be used as required. The long horizontal lengths allow for adequate upstream and downstream straight sections to ensure minimal installation effects on the calibrations.

At the outlet end of each test line, valves direct the flow directly back to the storage tanks or to either the 6 tonne or the 1.5 tonne weigh tanks shown in fig. 3. Each weigh tank comprises an appropriate capacity tank mounted on a precision weighing platform with a resolution of 1 in 50,000 which in turn is mounted on a support stand. Although calibrated by the supplier and stated to have negligible drift, because they are used as part of the National Flow Measurement Standard, it is necessary to re-calibrate the weighing platforms at regular intervals. This is achieved relatively quickly by a system of dedicated calibration weights mounted on hydraulic jacks beneath the platforms which can be operated in such a way that a sequence of three calibration weighings can be made. The weights themselves can be removed from the weightank assembly for recalibration. Using this system, measurement uncertainty better than 0.01 per cent of mass and 0.05 per cent of volume at the 95 per cent confidence level is expected.

The weightanks have a closed venting system so that vapour displaced on filling is channelled to the storage tanks in the basement, hence reducing oil losses. On discharge from the weightanks, the oil is directed by means of a three way diverter, down into the respective storage tank.

HIGH FLOW MEASUREMENT SECONDARY STANDARD

The maximum flow obtainable in the original oil flow laboratory was 80 l/s and this was too low to calibrate 150 or 200mm turbine flowmeters. The new facility therefore has the capability to calibrate up to 200 l/s in a high flow measurement secondary standard - line d in fig. 1.

Essentially line d is identical to lines a, b and c except that variable speed centrifugal pumps are used and the pipeline sizes are larger, 200mm instead of 150mm diameter on the main lines for instance. Pipework is provided to transfer either the Kerosine, Gas Oil or 15 cSt oil of lines a, b or c, into the storage tank of line d.

Two or more reference flowmeters calibrated up to 100 l/s in either lines a b or c, depending on the oil required, can be inserted into line d to give a total reference flow of 200 l/s. Because the test meter is calibrated against the reference flowmeters and not against the weightanks, this is a secondary standard with a correspondingly higher measurement uncertainty of about 0.1 per cent of volume.

SMALL FLOW MEASUREMENT PRIMARY STANDARDS

An increasing amount of work performed in the 'mezzanine' section of the original oil lab was performed on flows less than 10 l/s. To meet this demand in the new laboratory, two small Gravimetric Flow Measurement Primary Standards of 0.1 to 10 l/s and 0.01 to 2.5 l/s of user defined oils are to be built - lines e and f in fig. 1. These will be built on the floor of the main bay with their storage tanks and pumps in the basement. Each of the lines will have its own weightank built to an essentially scaled down design of the weightanks used in lines a, b and c. Again, measurement uncertainty better than 0.05 per cent of volume at the 95 per cent confidence level is expected.

WATER-IN-OIL FLOW FACILITY

The NEL has gained considerable experience in water-in-oil flow studies, especially in conducting research on automatic samplers for a consortium of oil companies (ref. 3). A purpose designed facility (ref. 4) was built for this work and this will be transferred to the James Young building. The facility can circulate water and oil flows up to 50 l/s, either on a constantly mixed recirculation basis, or on a constant injection and separation of water basis and some gas injection is also possible. The water-in-oil facility is not in itself a flowmeter calibration facility but more a tool for quality rather than quantity measurements. Modular viewing perspex test sections have therefore been provided which can be mounted either in a horizontal line or a vertically upwards or downwards line.

MULTIPHASE FLOW MEASUREMENT SECONDARY STANDARD

The NEL's capability in multiphase flow measurement has steadily increased (refs. 5 to 7) and several multiphase flow facilities for the testing and development of multiphase flowmeters have been built. The drive for multiphase flowmeters for offshore use has been very intense in recent years and several developments will be installed offshore in the near future as indicated in the separate papers by Dean, Smorgrav, Frantzen and Gaisford in ref. 8. At the moment the only means of calibrating such multiphase flowmeters is against a test separator with single phase flow measurement on the outlet streams. However, the inherent large measurement uncertainties of the method combined with the lack of flow control make this of dubious advantage. Several multiphase flow facilities are available about the world, but these have been built for flow studies or meter development, and not for meter calibration. The multiphase flowmeter calibration facility currently being built at the NEL will, as far as is known, be the only such facility in the world.

As holder of the UK National Flow Measurement Standard, the NEL sees the construction of a multiphase flowmeter standard as a natural and necessary supplement to the existing single phase standards. The task of providing such a multiphase calibration facility is not an easy one however. It is not just a question of mixing together individually metered supplies of oil, water and gas and passing them through the meter to be calibrated. The phases may not necessarily flow at the same velocity, ie there may be slip between them, and the gas phase may dissolve in, or evolve, from the liquid phase depending on pressure and temperature conditions. The water may mix with the oil, or it may drop out and flow along the bottom of the pipe depending on the flow velocity and turbulence. Further, and more difficult, is the fact that a multitude of flow regimes are possible in multi-phase flow and the calibration facility will have to reproduce those regimes in which the meter to be calibrated is expected to work.

There are generally three types of multiphase flowmeter - a total flow meter of all phases, a phase fraction meter to measure the proportions of each phase, and a combination of these in an individual phase flowrate meter. Because of the additional problems of multiphase flow measurement, the measurement uncertainties are much higher than those experienced with single phase flowmeters with current developments indicating uncertainties of 5 per cent of volume though future developments are expected to improve on this.

NEL commissioned a survey of potential users, manufacturers and government agencies to identify the major requirements and usage of a multiphase flow facility. Based on this information, a calibration facility shown in schematic form in fig. 4, will be built.

The total inventory of the oil and water will be held in a vessel which will act as a combined storage tank and multiphase separator. The oil and water will be drawn from the vessel into the respective liquid pumps while the gas will be injected after the water and oil have been mixed. Reference flowmeters, calibrated in the single phase oil, water and gas flow measurement laboratories at NEL will be installed in each line prior to mixing. The design of the separator will be such that the three phases can be stored in a separated condition within the separator so that the opportunity for biological fouling is reduced.

Combined oil and water flowrates of 1 to 80 l/s and air or Nitrogen flowrates of 1 to 100 l/s will be achievable. To enable developed multiphase flow regimes to occur, a horizontal run of 60m and vertically upwards and vertically downwards runs of 12m will be provided. More severe slugging flows can be produced by controlled intermittent supply of one or more of the phases to the test section or by mixing the phases at different locations along the test lines.

MISCELLANEOUS FACILITIES

The main bay of the James Young building will have space for the construction of special purpose facilities, or to accommodate any large or complicated meter system. Provision is also made to extend the lines outside the laboratory for the testing of large equipment such as meter provers. In addition, the three laboratories attached to the control rooms will house special applications such as an oil-in-crude oil monitor evaluation facility which requires special safety provisions and ventilation. Facilities have also been provided for chemical analysis, viscosity and density measurements to be undertaken.

INSTRUMENTATION AND CONTROL

The new laboratory employs the latest instrumentation and control technology which has been designed with future expansion and greater capability in mind. A local Ethernet system provides fast communications between sensors, Progammable Logic Controllers (PLC's), dataloggers and computers in such a way that fast response times are possible and multiple redundancy and inter-changability of important components is possible for fully versatile data acquisition and control.

SUMMARY

The new UK Oil and Multiphase Flow Measurement Standard being built at NEL replaces the existing standard with a much greater capability not only in terms of flow rates and fluids available, but also with the ability to calibrate multiphase flowmeters. The investment represents the Government's commitment to helping the Oil industry and to make effective use of this investment it is necessary that NEL is advised on a regular basis of the present and future needs of the industry.

ACKNOWLEDGEMENT

This paper is presented by permission of the Chief Executive of the NEL Executive Agency.

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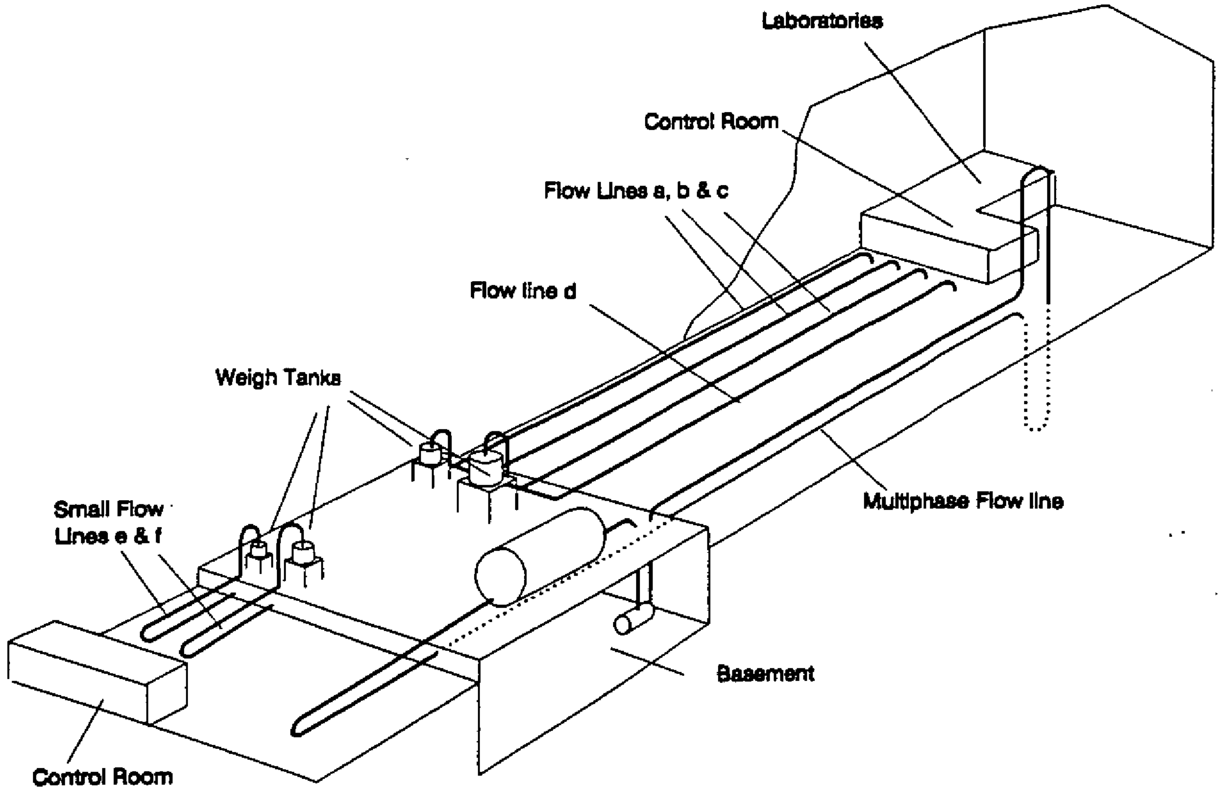

Fig. 1 General Schematic of the James Young Building

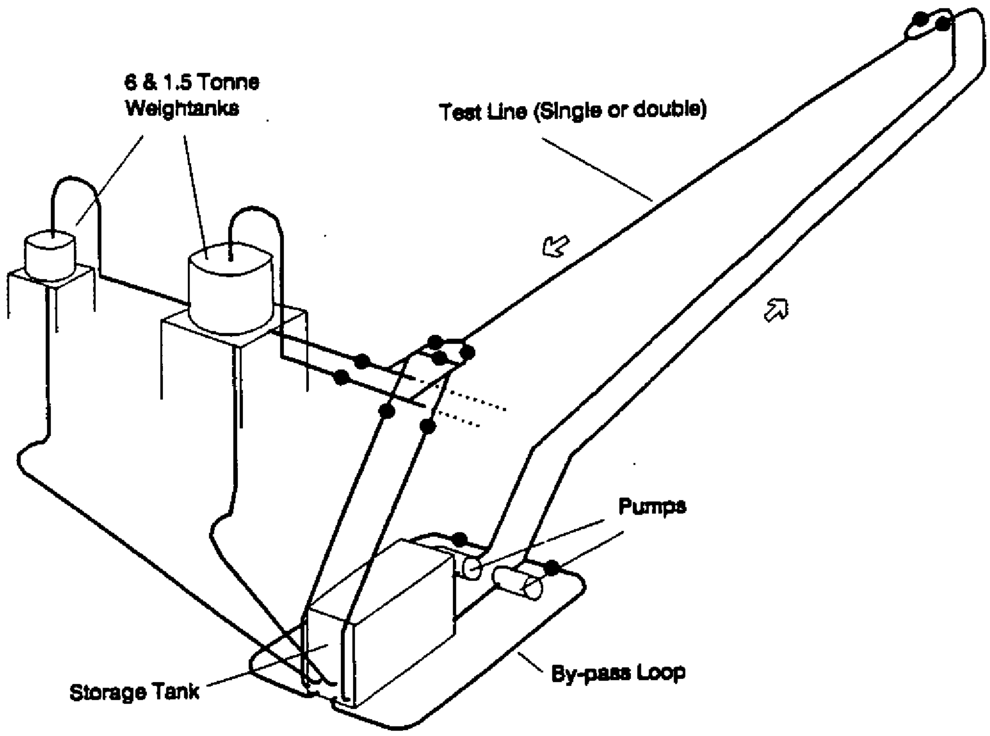

Fig. 2 Schematic of the Main Primary Flow Measurement Standard

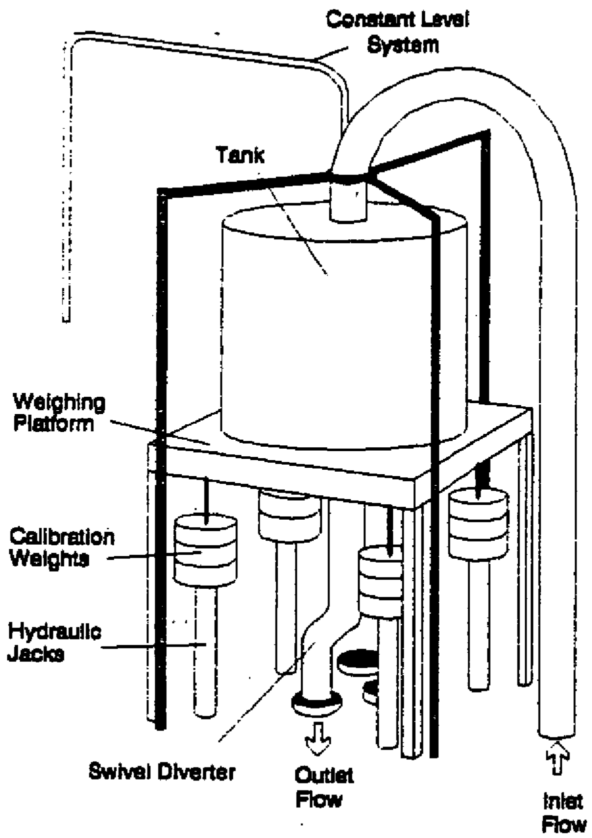

Fig. 3 Weightank System

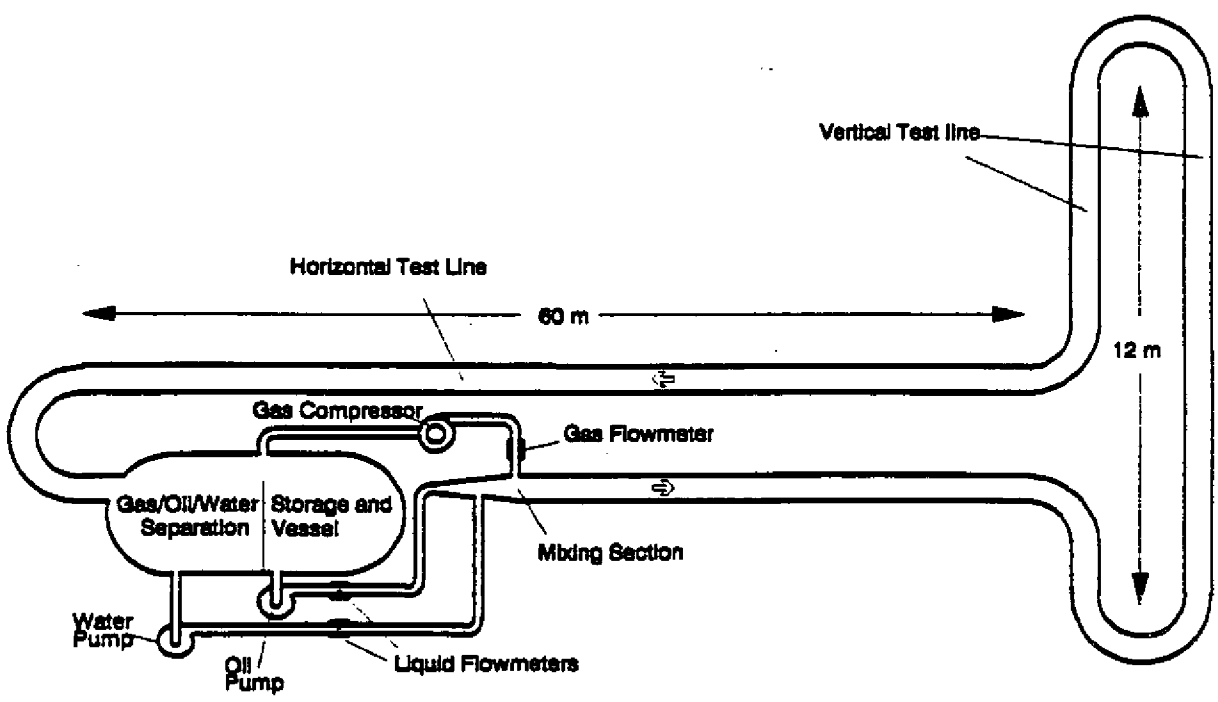

Fig. 4 Schematic of NEL Multiphase Flowmeter Calibration Facility