OPERATING EXPERIENCE WITH A COMPACT PROVER - 11

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INTRODUCTION

Experience with Waugh compact provers over several years has permitted a detailed examination of the performance of the provers and of various types and sizes of turbine meters on products ranging from gas oil to LPG.

Also the methods for calibrating the compact prover have been investigated in terms of establishing reconciliation between base volumes determined by waterdraw and master meter/prover tank.

The methods employed in estimating the repeatability or "random" uncertainty of a single measurement in a series is the frequency distribution, "histogram". Although a series of provings comprising 5 successive runs have been carried out at different flowrates it is possible to remove the influences of the variations in the means of each set by plotting the difference between each K-factor and its respective set mean value. This technique is known statistically as the "pooled" standard deviation. Special graph paper is used to establish whether the frequency distribution is Normal or Gaussian and to test for skewness and outliers and to derive the uncertainty limits for 95 percent probability.

The "moving average" is another technique used to monitor the variation in the successive mean values of 5 proving or calibration runs and to detect any long-term variation or drift.

CALIBRATION AND TRACEABILITY

Upstream and Downstream Volumes

As the meter-under-test may be situated either "upstream" or "downstream" of the compact prover and the prover base volumes are not the same in both directions, it is necessary to determine the respective volumes by direct liquid calibration methods.

In the Waugh prover the displacement of the piston shaft and the leak detection tube are the main reasons for the difference between the upstream and downstream volumes.

Flowrate Independence

One of the requirements of the new Institute of Petroleum Part X Section 3 "Code of Practice for the Design, Construction and Calibration of Pipe Provers" is to demonstrate that for any new design of prover there is no significant variation in the base volume, from the lowest flowrate when the prover is calibrated to the maximum flowrate at which the prover is operated.

Field Tests

In order to meet these requirements a number of tests were carried out using the following methods:-

a) Waterdraw Method

The volume of water displaced by the prover in each direction was measured in a 100 litre prover tank which was calibrated by a national Weights and Measures Authority. The assembly of equipment is shown in figure 1a. The calibration was carried out in the running mode by employing two solenoid valves. The flowrate was approximately 6 - 7 litres per minute.

b) Master Meter/Prover Tank Method

The master meter - (Avery - Hardoll BM500 positive displacement) was factorised by measuring water into a 2500 litre prover tank at two different flowrates viz 500 and 1300 litres per minute. The prover was then calibrated by the master meter at the same two flowrates as when proved and the appropriate meter factors applied to give the base volumes (corrected to standard conditions).The assembly of equipment is shown in figure 1b.

The results of these tests are given below: -

a) Waterdraw (into 100 litre proving tank) at approximately 7 litre per minute.

	UPSTREAM VOLUME (litre)	**DOWNSTREAM VOLUME** (litre)
	100.293	98.958
	100.296	98.953
	100.318	98.966
	100.302	98.970
	100.302	98.970
mean	100.302	98.963
sdev.	0.010	0.008
range	0.025 %	0.017 %

b) Master Meter/Proving Tank Method (2500 litre proving tank)

Master Meter Factors

The meter factors determined before and after each calibration, are:

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SUMMARY

This paper discusses the results of recent tests carried out on a Waugh compact prover where the base volume in both the upstream and downstream directions was determined by waterdraw (running mode) and master meter/prover tank calibration methods.

An analysis of meter proving data showed that there was a larger random scatter when proving turbine meters with a compact than with a conventional sphere pipe prover and that this scatter varied considerably between individual meters of the same size and make.

In order to minimise the number of runs during a calibration (master meter/master prover) the master meter should be selected which has a random uncertainty of less than 0.02 % (95 % confidence limits).

BEFORE UPSTREAM calibration / **AFTER UPSTREAM calibration**

	Before 1300 l/min	Before 500 l/min	After 1300 l/min	After 500 l/min
	0.99629	0.99587	0.99614	0.99577
	0.99632	0.99576	0.99607	0.99600
	0.99620	0.99591	0.99595	0.99584
	0.99619	-	-	-
	0.99614	-	-	-
mean	0.99623	0.99585	0.99605	0.99587

BEFORE DOWNSTREAM calibration / **AFTER DOWNSTREAM calibration**

	Before 1300 l/min	Before 500 l/m	After 1300 l/min	After 500 l/min
	0.99595	0.99601	0.99606	0.99611
	0.99593	0.99580	0.99591	0.99610
	0.99585	0.99594	0.99605	0.99614
	0.99604	0.99580	0.99593	0.99603
	0.99589	0.99582	0.99596	0.99599
mean	0.99593	0.99587	0.99598	0.99607

Prover Calibration by Master Meter (with meter factors applied)

Single Trip Base Volume when meter is UPSTREAM / **Single Trip Base Volume when meter is DOWNSTREAM**

	UPSTREAM 1300 l/min		UPSTREAM 500 l/min		DOWNSTREAM 1300 l/min		DOWNSTREAM 500 l/min	
	100.356		100.347		98.989		99.004	
	100.335		100.317		99.009		98.985	
	100.333		100.340		99.004		99.006	
	100.339		100.350		98.992		99.015	
	100.342		100.356		98.991		99.014	
	100.334		100.347		99.014		98.998	
	100.327		100.344		98.988		98.998	
	100.323		100.354		98.987		99.012	
	100.340		100.326		98.987		99.014	
mean	100.337	1	100.342	1	98.996	1	99.005	1
sdev	0.010		0.013	1	0.010	1	0.010	1

Interpretation of Test Results

a) The waterdraw method results were within a range of 0.017 % and 0.025 % respectively, which is not as good as the range normally achieved with conventional provers.

b) The master meter proving results using the 2500 litre tank showed an uncertainty of the order of 0.026 % to 0.028 % (see fig 2). The difference between the before calibration and after calibration mean meter factors are given below:

Direction,	Flowrate	Mean(before)	Mean(after)	Difference % (between means)
Upstream	500	0.99585	0.99587	+ 0.002
Downstream	500	0.99587	0.99607	+ 0.020
Upstream	1300	0.99623	0.99605	- 0.018
Downstream	1300	0.99593	0.99598	+ 0.005

The difference between any two means will depend on the size of the sample. The smaller the sample size the larger will be the potential difference between the two means, assuming that the measurements were made with the same apparatus and under the same conditions.

For samples with number of measurements (n_1 and n_2) and the same standard deviations (S) the maximum variations in the means ($\bar{x}_1 - \bar{x}_2$) is given by the following equation

$$\bar{x}_1 - \bar{x}_2 = t_{95,n-1} \; s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

where $t_{95,n-1}$ is the students t value for $n-1$ degrees of freedom for a probability = 95 %

Substituting for values obtained in Master Meter Calibration

$$\bar{x}_1 - \bar{x}_2 = 2.776 \times 0.014 \sqrt{\frac{1}{5} + \frac{1}{5}}$$

$$= 0.025\ \%$$

The conclusion is that the differences between the means before and after the prover calibrations were not due to any change in flow conditions or meter factors but entirely due to the small sample size.

The prover calibration volumes obtained by multiplying the master meter readout by the appropriate meter factor and then correcting for the effects of steel and water expansion to bring the volumes to 20°C and 1.01325 bara show a normal distribution (see fig. 3 - histograms). The random uncertainty is of the order of 0.023 % to 0.030 %. This is surprising as the scatter should be larger than that experienced with the waterdraw method as the master meter method includes an extra stage of measurement: -

There is no indication of any drift in the base volume measurements as determined by the master meter/prover tank method.

Comparison between Mean Base Volumes

A comparison of the mean base volumes obtained by the different calibration methods is given below:

Directions	Waterdraw (7 l/minute)	Master Meter (500 l/minute)	Master Meter (1300 l/minute)	Difference % max (range)
Upstream	100.302	100.344	100.337	0.042
Downstream	98.963	99.004	98.996	0.041
	1.339(1.35%)	1.340(1.35%)	1.341(1.35%)	

The uncertainty due to sample size can be estimated by adding in quadrature the uncertainties of the means, $\bar{x}_1$ and $\bar{x}_2$ of the sample of 5 measurements (n=5) and standard deviations s_1 and s_2 respectively.

$$\bar{x}_1 - \bar{x}_2 = \left[\underbrace{\left(\frac{t_{95,4} S_1}{\sqrt{5}}\right)^2}_{\text{Waterdraw}} + \underbrace{\left(\frac{t_{95,4} S_2}{\sqrt{5}}\right)^2}_{\text{Master Meter}} \right]^{1/2}$$

$$= \left[\left(\frac{2.776 \times 0.010}{\sqrt{5}}\right)^2 + \left(\frac{2.776 \times 0.020}{\sqrt{5}}\right)^2\right]^{1/2}$$

$$= 0.02\%$$

However, when comparing the means of the base volume obtained by different methods and different tanks (and size) there will be an additional error which will be partially random and partially systematic.

The overall uncertainty (random and systematic) for the tank calibration quoted by the authorities is of the order 0.015 to 0.020 %. If this is added in quadrature to the uncertainty of the difference in the mean value due to sample size than the maximum variation in the determination of the base volume employing different methods could be:

$$= \sqrt{(0.02^2 + 0.02^2)}$$

$$= 0.03\%$$

This would suggest that there is no significant error incurred in the base volume by operating (1) the prover over a very wide range of flowrate, 7 to 1300 litre /minute, in the running mode and (2) when the piston is travelling in either direction. (The waterdraw calibration is carried out with the piston moving in the opposite direction as when calibrating by the master meter/prover tank method.)

There is no evidence that the base volume is flowrate dependent as the volume at 1300 litre/minute compares more closely to the waterdraw at 8 litre/minute than to the volume determined at 500 litre/minute.

Recent tests have shown that when calibrating a conventional sphere prover (20 metre between detectors) using the same 100 litre and 2500 litre proving tanks the difference between base volume was 0.04 %.

The only valid conclusion, therefore, would appear to be that the difference between the base volumes is mainly due to the traceability and uncertainty of the two proving tanks.

PERFORMANCE OF WAUGH PROVER WITH VARIOUS TYPES OF METER AND PRODUCT

1) Influence of Same Type of Meter

Several 6" turbine meters were proved with a compact prover (15" bore, 100 litre capacity) and the random uncertainty assessed. There is evidence that the uncertainty varies from 0.018 % to 0.030 % on a purely arbitrary basis; some meters with the worst scatter gave a a number of outliers whereas those with the best scatter gave no outliers at all. A 6" turbine meter of another make was tested and was found to have a similar range of uncertainty. The problem of not being able to predict the uncertainty of a turbine meter only becomes critical where it is employed as a transfer standard for a compact master prover.

2) Influence of Flow Rate

The frequency distribution of a 6" turbine meter for flow rates over 114 m^3/h and under 65 m^3/h showed the same order of uncertainty (see figure 4).

3) Influence of Density

There was again no significant difference in the random scatter when 6" turbine meters were proved on gas oil or propane (see figure 5).

4) Influence of Meter Size

The random scatter for 4" turbine meters was within the same range as the 6" meters (see figure 6). However, there was a significant increase in uncertainty as the meter size reduced to 2 1/2 " (i.e. 0.032 %).

5) Influence of Time on Variations of Mean K-Factor

The moving averages for a series of 50 proving runs carried out on a 4" turbine meter and compact prover (not a Waugh) on water exhibited a cyclic variation or wave pattern. The individual K-factors were plotted as a histogram which showed a normal distribution. In theory if the measurements were truly random then there would be no evidence of wave patterns (see figure 7). However, this phenomenon has been observed a number of times when analysing long-term K-factor variations. In practice there is evidently a number of small systematic errors which behave in the short-term as a bias but in the long-term as random errors.

The maximum variation in the moving average can be calculated from the equation:

$$x_1 - x_2 = 2\sigma\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

where

$\bar{x}_1$ and $\bar{x}_2$ are maximum and minimum averages

2σ is the uncertainty P = 95 % for n > 30
n_1 and n_2 are the number of runs

therefore $\bar{x}_1 - \bar{x}_2 = 0.025\sqrt{\frac{1}{5} + \frac{1}{5}}$

$$= 0.015\ \%$$

This value compares closely with the maximum variation of the moving average shown in figure 4. This short-term bias could create a problem where the average K-factors have to be compared and used for master meter factors in calibrating pipe provers.

The Compact Prover as a Master Prover

In theory the repeatability of a calibrating instrument should be equal to or better than the repeatability of the instrument to be calibrated. In the majority of cases the compact prover is used to calibrate conventional sphere provers. In order to achieve the same uncertainty of the mean calibration volume as the large conventional prover the number of runs can be estimated as follows.

	Conventional Prover		Compact Prover
Uncertainty of mean of 5 runs =	$\frac{2\sigma}{\sqrt{n_1}}$	=	$\frac{2\sigma}{\sqrt{n_2}}$

Substituting for $\sigma_1 = 0.015\ \%$
$\sigma_2 = 0.025\ \%$
$n_1 = 5$

$$n_2 = \frac{0.025^2}{0.015^2} \times 5 = 14 \text{ (rounded)}$$

It is evident therefore that 15 runs are required when using the Waugh Prover in order to achieve the same uncertainty of the means for 5 round trips as when employing a conventional prover (with a distance between detectors of 20 metres).

SUMMARY OF CONCLUSION

1) A comparison of the mean base volume obtained by the waterdraw and the master meter/proving tank method at two flowrates indicated an agreement to within 0.042 %. As these methods were based on two different sizes of proving tank they would involve both random and systematic uncertainties in the traceability chain. As the difference is less than 0.05 % which is the uncertainty quoted for conventional pipe provers there is evidence that the Waugh Prover meets the criteria generally laid down for custody transfer/royalty measurement standards.

2) The upstream and downstream base volumes can be calibrated directly by both the waterdraw and master meter methods.

3) The Compact prover requires a minimum of 15 passes or runs in order to achieve the same random uncertainty of the mean K-factor as the conventional prover achieves in 5 runs.

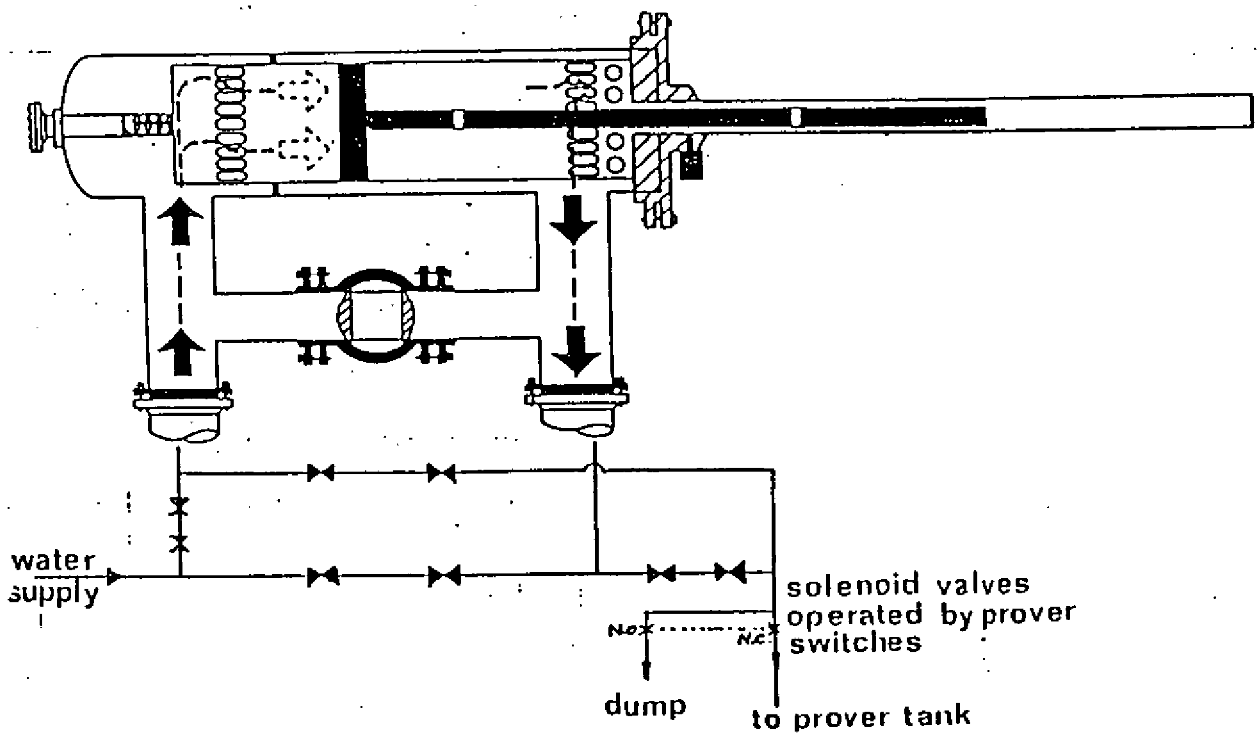
4) The random uncertainty experienced with a compact prover is mainly dependent on individual meter performance and is not unduly sensitive to flowrate or density but shows an increase with very small turbine meters. The performance of the Waugh Prover is similar to other compact provers.

References

Institute of Petroleum : Petroleum Measurement Manual, Part X, Section 3 " Code of Practice for the Design, Consruction and Calibration of Pipe Provers"(to be published shortly)

Fig 1 Assembly for Calibration of Compact Prover

a) Waterdraw [on the run]



b) Master Meter/Prover Tank

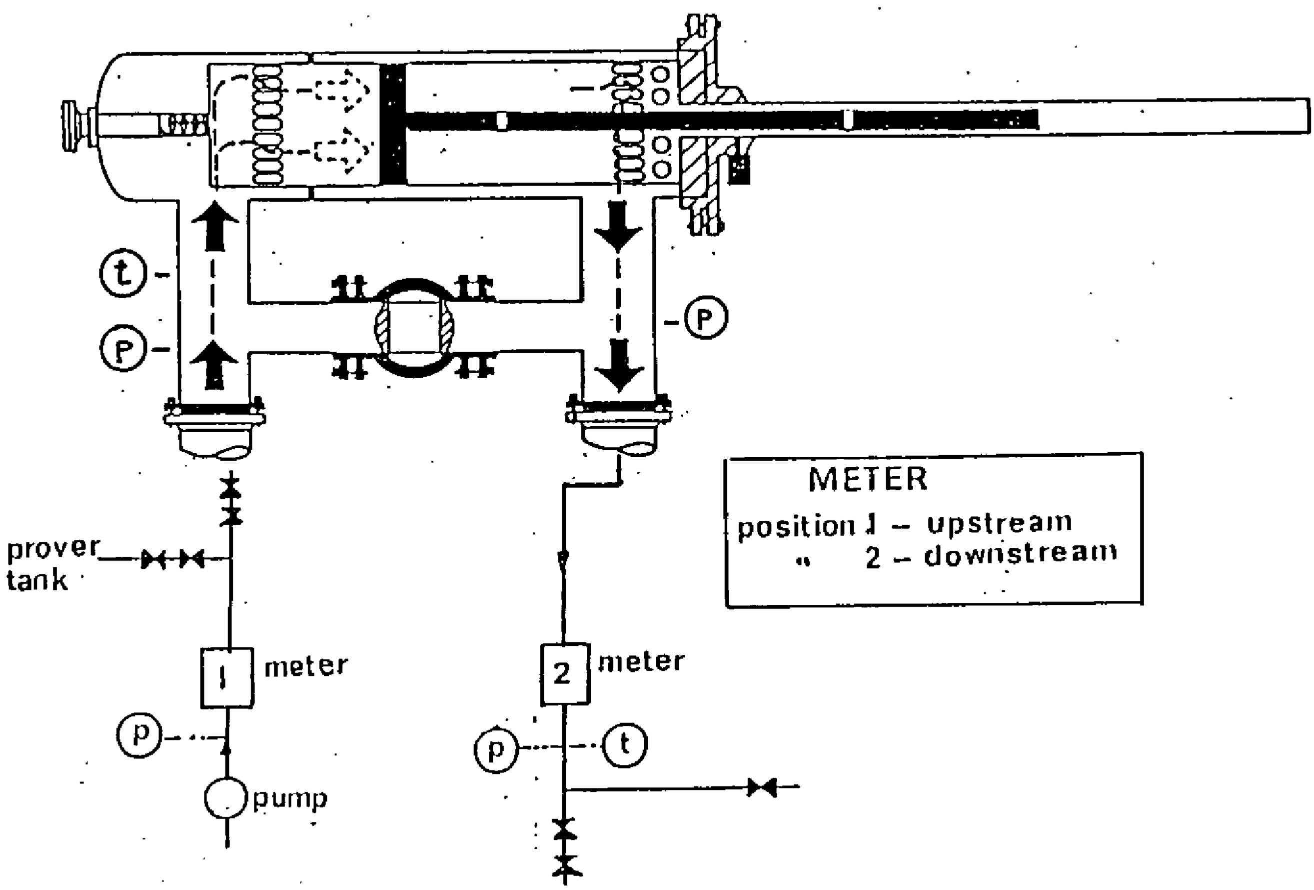
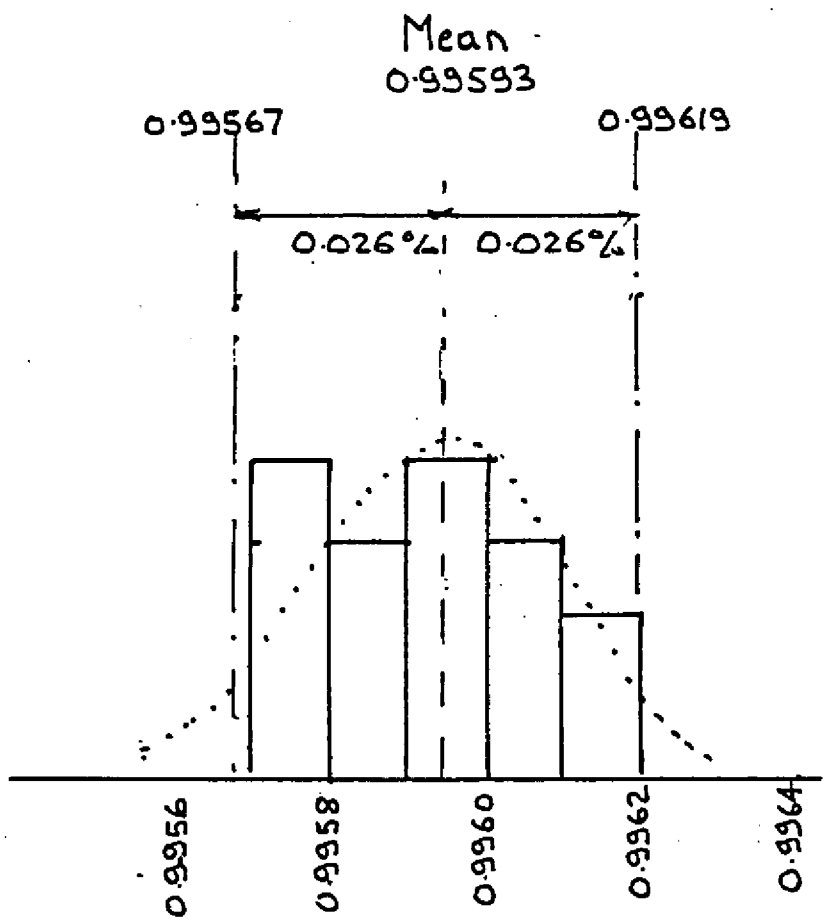
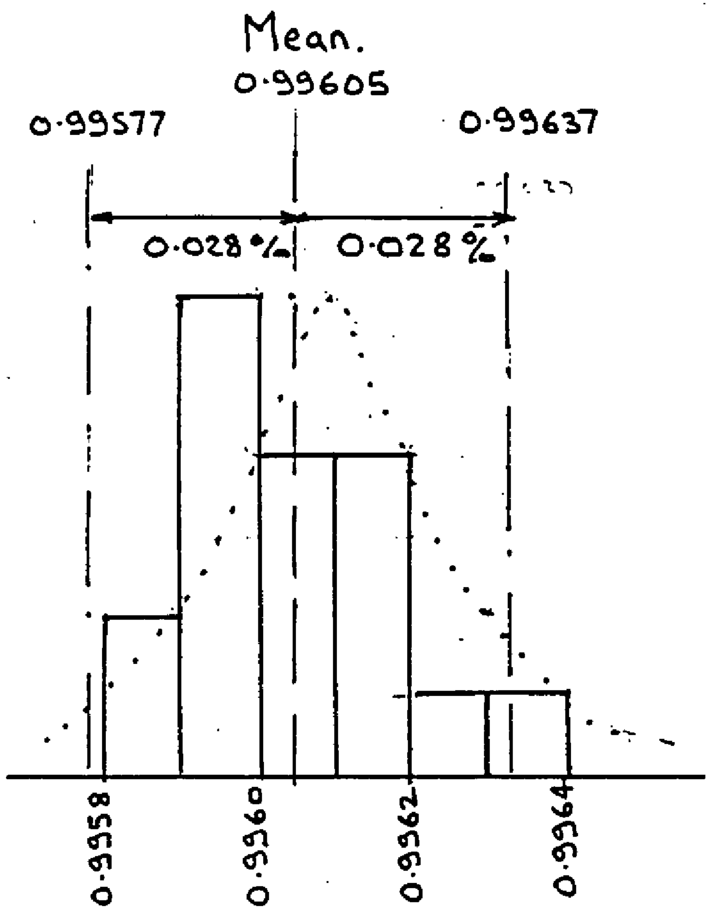


Fig 2 **Master Meter Calibration [factors]**





HISTOGRAMS

Fig 3   Calibration by Master Meter

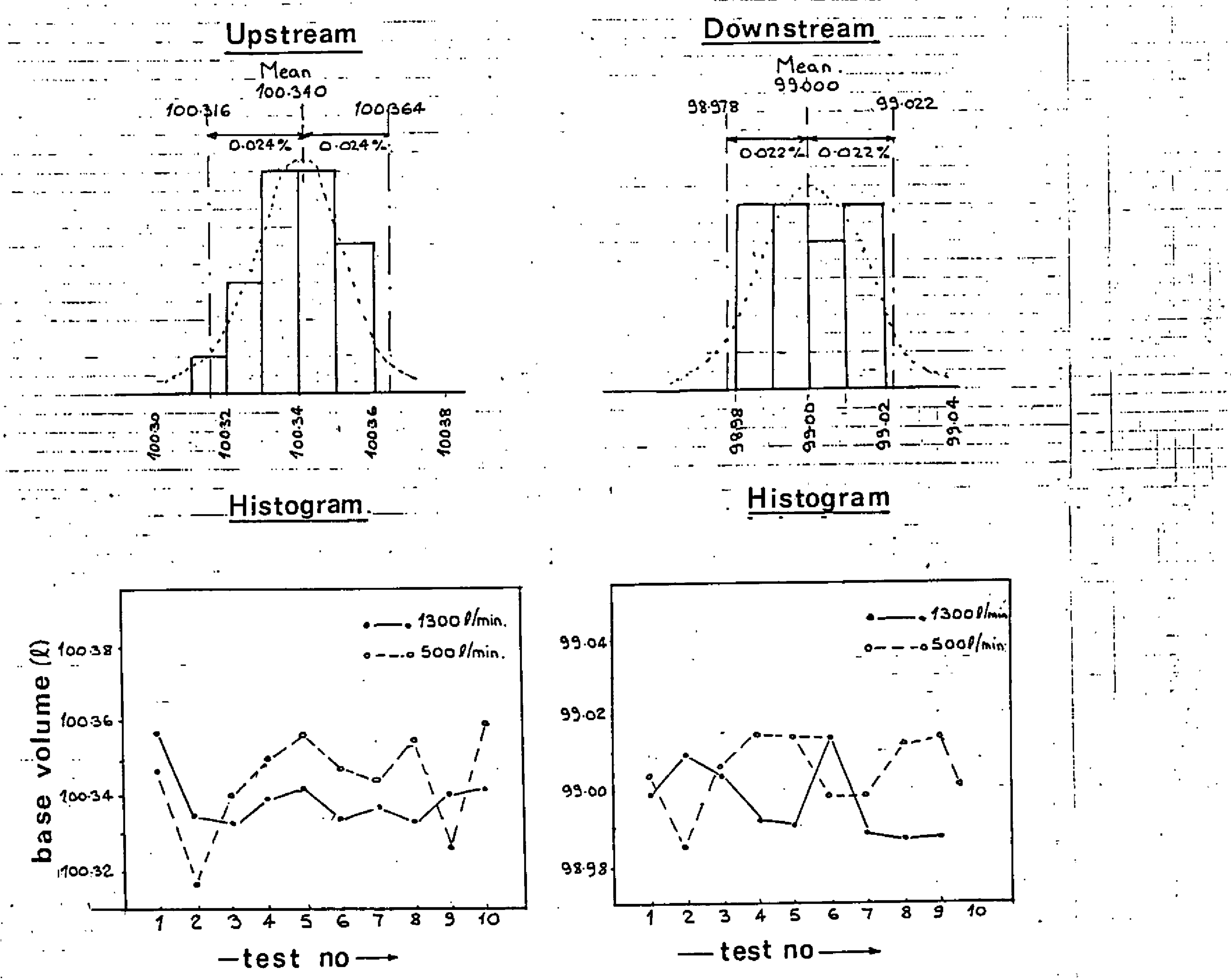
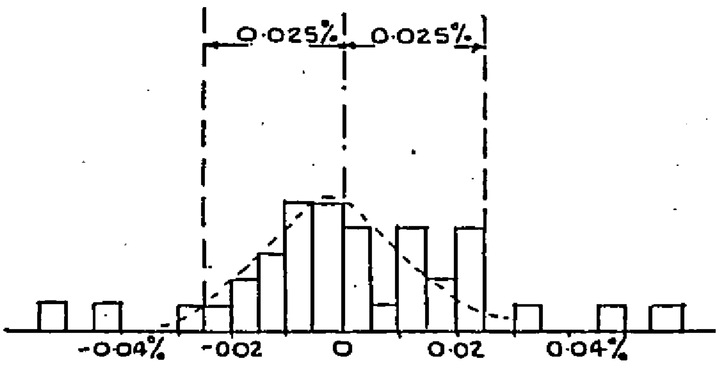


Fig 4 **Random Uncertainty**

(influence of flow rate)

6" Turbine Meters

>114 m³/h



<65 m³/h

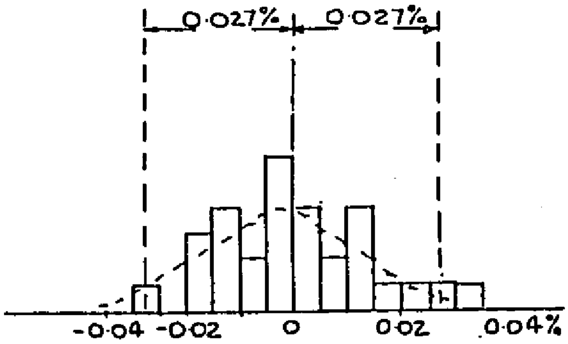
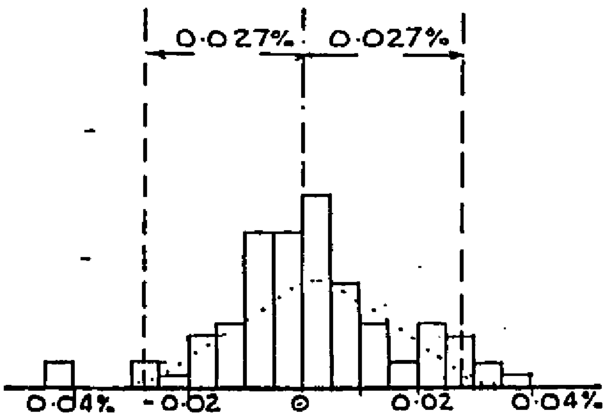


Fig 5 **Random Uncertainty**

(influence of density)

6" Turbine Meters

Density > 814 kg/m³



Density < 672 kg/m³

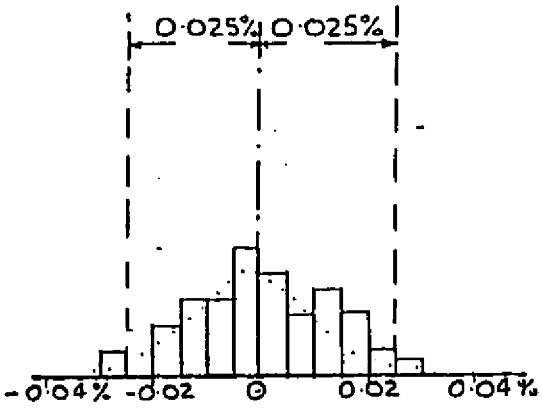
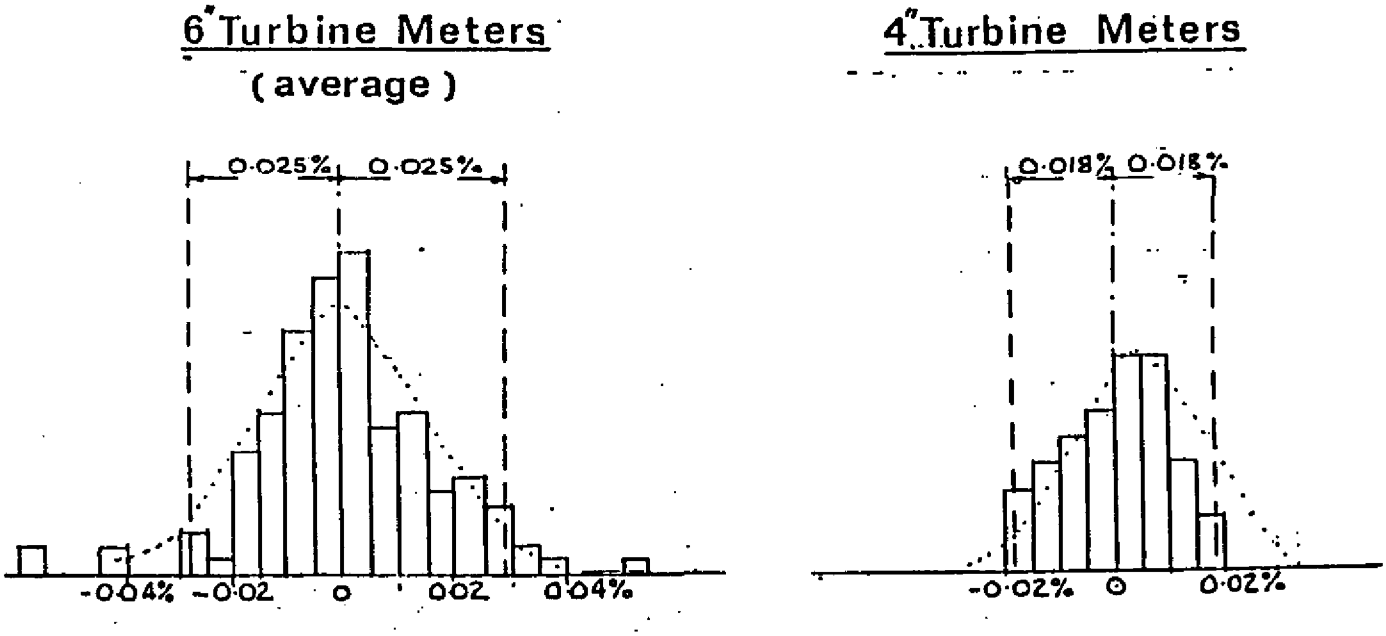


Fig 6 Random Uncertainty

(influence of size)



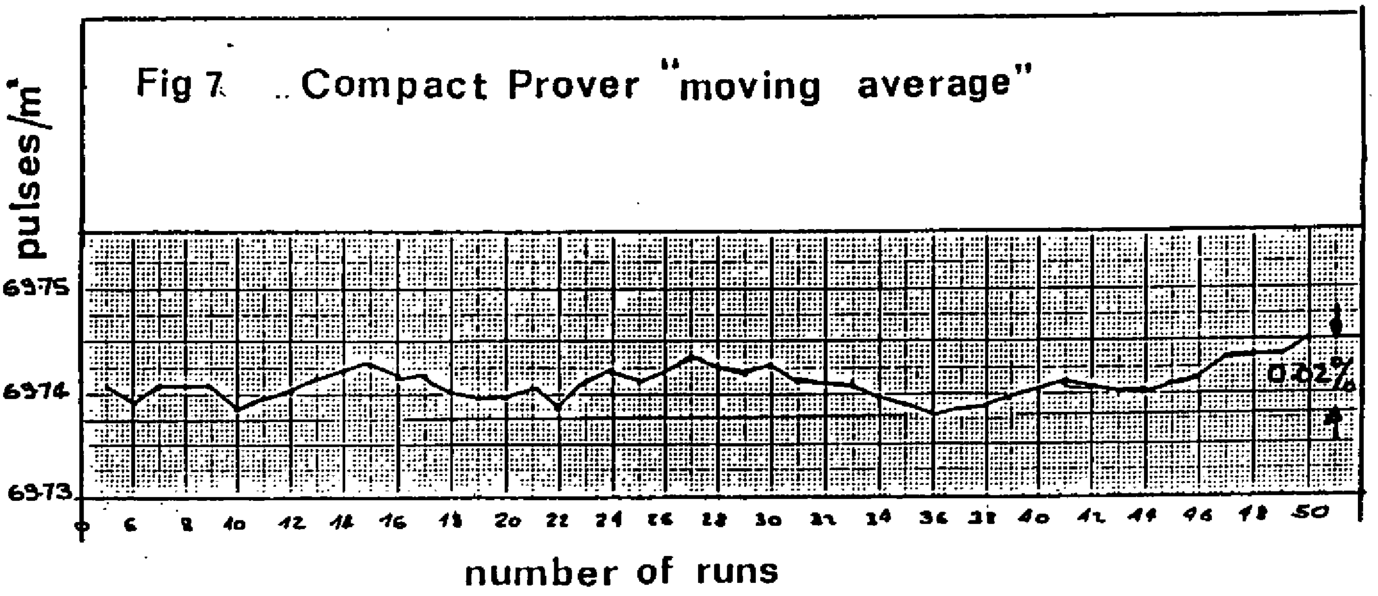


Fig 7 Compact Prover "moving average"