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FLOW METERS IN SAND SERVICE CONDITIONS

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ABSTRACT

This paper describes the findings of a project undertaken by NEL for NMSPU, Department of Trade and Industry to investigate and quantify the performance of flowmeters in sandy service conditions.

This paper presents a summary of results covering the testing of three 100 mm nominal bore (NB) turbine meters, four 50 mm nominal bore turbine meters, and a 100 mm nominal bore wedge meter together with a 75 mm nominal bore Coriolis mass meter. The initial calibration of each test meter took place in clean water followed by comparison tests in three sand concentration levels, at various velocities, over extended operating periods. This was followed by a strip-down and internal examination of each meter for any damage/wear.

Overall conclusions are given on the performance of each meter manufacturer, meter type and meter nominal bore size. Particular interest is given to the intercomparison between each group of meters with regard to meter type, size, material of construction and wear.

1 TEST SERIES BACKGROUND

Flowmeters are widely used in the offshore industry in downhole locations and increasingly used during separation. They are also utilised for exploration and production of oil and gas fields, and by other industries in dirty fluids.

In these conditions they are often subject to a variety of abrasive materials being entrained in the measurement fluid. As little performance data was available which quantified the effect of abrasive flow conditions on flowmeters, the Department of Trade and Industry, under the National Measurement Policy Unit Flow Programme decided to sponsor a programme of work to investigate this. It was decided that the test programme would cover a number of different turbine meters of 100 mm and 50 mm nominal bore as well as a Coriolis mass flowmeter and a differential pressure wedge meter. Each meter was representative of the type of meter commercially available and used in the field in these applications.

The meter evaluations were carried out in the NEL Abrasive Flow Test Facility and entailed simultaneous calibration of each group of meters, in series, against a reference electromagnetic (em) flowmeter installed upstream of the test meters. Prior to the start of the test programme the em meter was calibrated in-situ against a calibrated turbine meter traceable to the NEL Primary Standards.

Establishing and quantifying any change in the performance of the test meters is the objective of this test series. It must be noted that determination of flowrate errors from the test meters is not the objective of this test series. Hence, the initial clean water calibration of the meters is used as a datum from which all abrasive flow calibrations will be judged.

2 INTRODUCTION

Each group of meters was tested simultaneously (in series) during each section of the test programme, ie clean water calibration followed by various sand content tests. This allowed for direct comparison between meters of equal size as the test programme progressed. All sand percentages in this report are defined as percentage sand content by weight. Appendix I describes the sand specification. The sand used during this test series remained within specification for approximately 250 hours running time. After this, or sooner if sand samples indicated necessary, the test fluid and sand was replaced to ensure that the test condition remained constant.

3 SELECTION OF METERS

A functional specification for flowmeters in sandy flow service was sent out to manufacturers inviting them to tender for the supply of suitable flowmeters. Some manufacturers stated that they would not usually specify meters for this duty but would supply a meter typical of the meters used in the oil sector. For this reason the names of meter manufacturers detailed in this report were anonymised. The same meter manufacturers were used to provide 50 mm NB and 100 mm NB turbine meters, with the addition of one meter manufacturer (Manufacturer A) in the 50 mm NB tests. This was due to the test facility pipe lengths allowing for four 50 mm NB meters and only three 100 mm NB meters to be tested. Test meter results in this report are designated to Manufacturers A - D for 50 mm NB turbine meters, Manufacturers B - D for 100 mm NB turbine meters and Manufacturers E and F for wedge and Coriolis mass meters respectively. Details of test meter materials, turbine blade number, turbine blade shape, etc are shown in Tables 1a and 1b.

The meter types and the manufacturers for these tests were selected on the following criteria:

- Popularity of manufacturers meter in field use.
- Meter internal construction.
- Price and delivery.

It was obviously important to select meters that were being widely used to enable realistic data to be produced which would assist users. The differential pressure meter and one turbine meter were chosen as they were designed specifically for abrasive flow service. The remaining meter manufacturers have large numbers of meters in oil field use, although not specifically for abrasive flow applications they were selected as major meter manufacturers. Coriolis mass meters are now being used in many offshore applications therefore this type of meter was selected because of its increasing popularity in the oil industry and its 'non-intrusive' design.

4 METER INSTALLATION AND INSTRUMENTATION

The meters were tested in the abrasive flow test facility as described and shown schematically in Appendix II.

Each group of meters was installed in horizontal pipework, in series, in the facility to enable them to be tested and calibrated simultaneously. To ensure that meter performance was not influenced by the facility, or by another test meter, each meter was installed according to the manufacturers installation instructions with appropriate lengths of upstream and downstream straight pipe.

The test meter flowrate readings were logged simultaneously with the reference meter flowrate and velocity, temperature, line pressure and time of day. Sand samples were taken from the test line and measured at 250 hour, run time, intervals.

The test meter readings and meter flowrates were input into an EXCEL spreadsheet and the performance data calculated. Ten of these points were taken, from each meter, to obtain an averaged reading which represented one data point. Temperature, velocity (derived from the test meter nominal bore size and reference flowrate) and pressure drop were monitored in a similar manner to the reference meter and input into the spreadsheet for analysis. Test line pressure was also monitored to ensure cavitation did not take place.

5 TEST PROGRAMME

For each test series, dictated by meter size and type, the test programme was as follows:

- Run meters in clean water over a range of flowrates for a minimum of 24 hours. This acted as a "run-in" period for the test meters.
- Calibrate the meters in clean water, over a range of flowrates (within flow range of the meters or the facility), against the facilities reference electromagnetic flowmeter. Minimum test run period of 12 hours.
- Test each meter series at a minimum of two flowrates using three sand concentrations.
- Strip down test meters and complete an examination of meters for wear/damage.

6 TEST RESULTS

6.1 Clean Water Calibration of Reference Electromagnetic (em) Meter

The test facility reference em meter has been used for a number of years and therefore has a known history of stable calibration against calibrated turbine meters. The em meter was calibrated in-situ against a reference turbine meter immediately prior to the start of the test series and was subsequently used throughout the test period. A copy of the em meter calibration is shown in Fig. 1.

Error was calculated using:

$$\frac{\text{Reference meter - test meter}}{\text{Reference meter}} \times 100.$$

6.2 Clean Water Calibration of Turbine Flowmeters

All test meters were calibrated against the facilities reference electromagnetic flowmeter. This produced a "datum" (reference) clean water calibration from which future abrasive flow test results could be compared.

6.3 Evaluation of Test Meters at Optimum Performance Flowrate Using Three Sand Concentrations

Meter tests were completed at a flowrate that was considered to be representative of their optimum performance flowrate. For the turbine meters this represented a rate nominally mid-way in the manufacturers recommended flow range. The wedge meter was tested towards its upper flow limit because it has a very low turn down limit and would therefore perform best at a flowrate near its maximum. This flowrate corresponded to a flowrate approximately 50% of the Coriolis mass meter's maximum flowrate and therefore allowed these meters to be tested in series. The flowrates selected during this test were nominally 9 l/s for the 50 mm NB turbine meters, 35 l/s for the 100 mm NB turbine meter and 30 l/s for the Coriolis mass and differential pressure wedge meter.

6.3.1 Optimum flowrate abrasive flow tests on 50 mm NB turbine meters (Nominal 9 l/s)

This flowrate represents nominally 50% of the test meters maximum flowrate.

Fig. 2 shows the data obtained from the 50 mm NB turbine meter tests along with data taken from their original clean water calibrations at a similar flowrate. (Nominal 9 l/s.)

It should be noted that there is no sand test data for Manufacturer A. This meter seized after two hours running at 0.126% sand content and was removed from the test programme at this point.

During the abrasive flow tests Manufacturer B's test meter produced a similar result to the clean water calibration. The flowrate percentage error shows a slight improvement as the sand percentage and test period increased. It should be noted that this meter is recommended by the manufacturer specifically for abrasive flow duty.

Manufacturer C's, 50 mm NB turbine meter, initially produced an improved flowrate error compared to the initial clean water calibration, but this rapidly increased throughout the 0.126% sand tests where it peaked at nominally 3.4% after 172.5 hours abrasive flow duty. The flowrate error remained at this level until the end of the 0.364% sand content tests (256.5 hours abrasive flow duty) when this meters flowrate error increased to 81%. The meter was removed from the test facility to find that the meter's rotor blades had disappeared. This may have been due to erosion to the root or by the blades being torn away at the blade root.

The 50 mm NB turbine meter from Manufacturer D produced a similar flowrate error as the clean water calibration for the initial 20 hours of abrasive flow service at 0.126% sand content. The flowrate error gradually increased throughout the abrasive flow tests until it reached a peak of nominally 2.6% after 300 hours sand service. Following this the final data point at 324.5 hours, after 0.126%, 0.364% and 0.644% sand content runs showed an improvement compared to previous data.

6.3.2 Optimum flowrate abrasive flow tests on 100 mm NB turbine (Nominal 35 l/s)

This flowrate represents nominally 47% of the test meters maximum flowrate.

Fig. 3 shows the data obtained from the 100 mm NB turbine meter tests along with data taken from their respective clean water calibration at a similar flowrate. (Nominal 35 l/s.) As previously stated, only three 100 mm NB meters were tested due to facility pipe length restrictions. Manufacturer A was not requested to submit a test meter for this phase.

Manufacturer B's, 100 mm NB turbine meter, showed an immediate rise in flowrate percentage error of 0.25% when compared to the clean water calibration data at a nominal flowrate of 35 l/s. The flowrate percentage error remained at this level, approximately 2%, for the remainder of the test period encompassing 0.126%, 0.315% and 0.617% sand percentages over a 261.5 hour test period. It should be noted that this meter is recommended by the manufacturer specifically for abrasive flow duty.

Following the clean water calibration of Manufacture C's meter showed an immediate rise of 0.35% when 0.126% sand was added. The percentage error remained relatively constant at 1.50% throughout the following 57 hours at a sand content of 0.315%. After the sand content was increased to 0.617% the flowrate error remained relatively constant at 1.50% although the meter output was erratic towards the end of this sand percentage at this flowrate.

The initial 0.126% sand content test data from Manufacturer D's 100 mm NB turbine meter showed an improvement in flowrate percentage error from the clean water data, at a similar flowrate. This percentage error, 1.4%, continued for the 149 hour test period at 0.126% sand content. When the sand content was increased to 0.315% the flowrate percentage error immediately increased until after 26 hours the flowrate error was 1.75%. Over the following 31 hours, at this sand content, the flowrate error decreased back to the previous level, 1.4%. After the percentage sand was increased to 0.617% the flowrate error increased to a high of 2.1% but later returned to 1.6%, a similar figure to the initial clean water calibration, after a total of 261.5 hours in abrasive flow.

6.3.3 Optimum flowrate abrasive flow tests on 100 mm NB wedge meter and 75 mm NB mass meter (Nominal 30 l/s)

This flowrate represents nominally 67% of the test meters maximum flowrate.

Fig. 4 shows the data obtained from the 100 mm NB differential pressure wedge meter and the 75 mm NB Coriolis mass meter tests, Manufacturers E and F respectively, along with data taken from their original clean water calibrations at a similar flowrate.
(Nominal 30 l/s.)

During the 0.156% sand tests the differential pressure wedge meter from Manufacturer E, produced a rise of approximately 2.5% compared to the clean water calibration at 30 l/s. The flowrate percentage error remained at this level, 3%, throughout the 0.156% and 0.352% sand tests, a total abrasive flow period of 244.5 hours. It should be noted that the percentage error figures were erratic during this period showing large percentage spreads from the mean flowrate error.

The sand content was increased to 0.777% and following a further 129 hours at this level the flowrate error decreased slightly to 2% with an improvement in the spread of the error results.

During the 0.156% sand tests the Coriolis mass meter from Manufacturer F, produced a similar flowrate percentage error,(0.8%) to its clean water calibration. This continued throughout the 0.352% sand content tests for 244.5 hours, with the exception of two data points.

When the sand percentage was increased to 0.777% the flowrate percentage error reduced to 0.5% and remained there for 45.5 hours before rising over the following 20 hours and then reducing to 0.25% after 373.5 hours.

6.4 Evaluation of Test Meters at Low Flowrates Using Three Sand Concentrations

During this test the meters were run at a flowrate that was considered to be with-in the manufacturers recommended flow range. For the 50 mm NB turbine meters this represents a rate nominally 33 percent of their recommended maximum flowrate. The 100 mm NB turbine meter low flow data was collected at nominally 20 percent of the manufacturers recommended maximum flowrate. The mass and wedge meter low flow data was collected at approximately 20 percent of the manufacturers recommended maximum flowrate.

6.4.1 Low flowrate abrasive flow tests on 50 mm NB turbine meters (Nominal 6 l/s)

This flowrate represents nominally 33% of the test meters maximum flow range.

Low flowrate data points were taken towards the end of each sand content percentage test period.

After completing the sand content tests the test facility was run with clean water at low flowrate and data taken from the test meters to act as a comparison with the original clean water calibration.

Fig. 5 shows the data obtained for the 50 mm NB turbine meter tests along with data taken from the original and final clean water calibrations at a similar flowrate.
(Nominal 6 l/s.)

Data taken from Manufacturer B's 50 mm NB turbine meter, at the end of 172.5 hours of 0.126% sand content, showed an improvement on the original clean water data at a similar flowrate. The data taken after 84 hours at 0.364% showed a slight increase on the previous sand data but this represented a return to the percentage error shown in the original clean water calibration. Following the 0.644% sand tests the flowrate percentage error showed an increase of approximately 8.0% with poor repeatability.

The final clean water data showed a slight increase in the repeatability of the flowrate percentage error, compared to the original clean water calibration, but this may be due to more test data being recorded during the final clean water test.

Test data from Manufacturer C's, 50 mm NB turbine meter, at the end of 172.5 hours of 0.126% sand content tests showed a percentage error increase of approximately 1.5% compared to the original clean water calibration. During the 0.364% sand content tests the meter's flowrate percentage errors increased to unacceptable levels (82%) and the meter was removed from the test facility after 256.5 hours. After investigation it was discovered that this meter's rotor blades had been removed. This may have been due to persistent erosion or they could have been shorn off at the root.

Manufacturer D's 50 mm NB turbine meter low flow 0.126%, sand content flowrate percentage error test data showed an increase of approximately 0.4%, after 172.5 hours, compared to the original clean water calibration at a similar flowrate. Following a further 84 hours at 0.364% sand content the meters flowrate error had increased by a further 0.4%. After a further 68 hours at 0.644% sand content, a total abrasive run time of 324.5 hours, the meters flowrate error was approximately 9%. This represents a rise of approximately 8.5% from the original clean water test data. The final clean water test data shows a return to approximately 2% flowrate error. This represents a rise of approximately 1.5% compared to the original clean water data at this flowrate.

6.4.2 Low flowrate abrasive flow tests on 100 mm nb turbine meters (Nominal 15 l/s)

This flowrate represents nominally 20% of the test meters maximum flowrate.

Low flowrate data points were taken towards the end of each sand content period.

Fig. 6 shows the data obtained from the 100 mm NB turbine meter tests along with data taken from their original clean water calibrations at a similar flowrate. (Nominal 15 l/s.)

Data points taken at nominally 15 l/s for Manufacture B's 100 mm NB turbine meter, after 149 hours sand service at 0.126%, showed no change from the original clean water calibration. Following a further 57 hours at 0.315% sand concentration the flowrate percentage error increased by 0.25% and at the end of the 0.617% sand tests, a total abrasive flow test period of 250 hours, the flowrate error had increased a further 0.2%. This shows a combined increase of 0.45% after 261.5 hours abrasive flow service compared to the original clean water calibration.

Manufacturer C's, 100 mm NB turbine meter, showed similar results after 149 hours of 0.126% sand concentration tests as the original clean water calibration. Following a further 57 hours at 0.315% sand concentration the flowrate error had increased by 0.3% from the original clean water calibration. The sand concentration was further increased to 0.617% and after 53 hours the flowrate error increased by a further 0.5%. This showed an over all increase of 0.8% from the original clean water calibration after 258.5 hours sand service at various sand concentrations. Shortly after the final sand concentration test points the flowrate was increased and the meter seized.

The 100 mm NB turbine meter from Manufacturer D, following 149 hours service at 0.126% sand concentration, showed similar results to the clean water calibration. Data recorded after a further 57 hours service at 0.315% sand concentration showed a flowrate percentage error rise of 0.5% from the 0.126% sand concentration data. A further rise of 0.5% occurred following the next 55.5 hours service at 0.617% sand concentration. This gives a total flowrate percentage error increase of 1% after 261.5 hours abrasive flow service.

6.4.3 Low flowrate abrasive flow tests on 100 mm NB wedge meters and 75 mm NB mass meter (Nominal 9 l/s)

This flowrate (9 l/s) represents nominally 20% of the test meters maximum flowrate.

Low flowrate data points were taken towards the end of the 0.352% and 0.777% sand content test period.

It should be noted that this flowrate is below the 3:1 manufacturers recommended turndown ratio for the wedge meter. Therefore this meter could be expected to produce data out-with the manufacturers limits although the Coriolis mass meter is with-in its flow turn-down limits at this flowrate.

Fig. 7 shows the data obtained from the 100 mm NB wedge meter and 75 mm NB Coriolis mass meter tests also data taken from their original clean water calibrations at a similar flowrate. (Nominal 9 l/s.)

The 100 mm NB wedge meter, from Manufacturer E, showed a 15% increase in flowrate percentage error following 244.5 hours at 0.126% and 0.352% sand concentrations. A further rise of 5% was shown after 129 hours at 0.777% sand concentration. This shows a total increase in flowrate percentage error of 20% from the original clean water data at a similar flowrate.

The 75 mm NB Coriolis mass meter, Manufacturer F, showed an increase of 0.25% in flowrate percentage error after 244.5 hours at 0.126% and 0.352% sand concentrations. Following a further 129 hours at 0.777% sand concentration the flowrate percentage error had reduced to a level similar to the original clean water calibration at this flowrate.

6.5 Evaluation of Test Meters at High Flowrates Using Three Sand Concentrations

During this test the 50 mm NB turbine, 75 mm NB Coriolis mass and 100 mm NB wedge meters were run at a flowrate that was considered to be close to the maximum manufacturers recommended flow range. The test facility used had a maximum flowrate of 35 l/s. This flowrate had already been achieved during previous 100 mm NB meter tests. For the 50 mm NB turbine meters this flowrate represents a rate nominally 83% of their recommended maximum flowrate.

Flowrate data points were taken towards the end of each sand content test period.

Fig. 8 shows the data obtained from the 50 mm NB turbine meter tests along with data taken from their original clean water calibrations at a similar flowrate. (Nominal 15 l/s.)

Manufacturer B's, 50 mm NB turbine meter, data taken after 172.5 and 84 hours at 0.126% and 0.364% respective sand concentrations showed improvements of 0.56% and 0.8% respectively. The data collected at the end of the next 68 hours at 0.644% sand concentration tests, a total abrasive flow period of 324.5 hours, showed an increase of 1% from the previous sand data. This represents a total increase of 0.28% from the original clean water calibration at a similar flowrate.

Manufacturer C's, 50 mm NB turbine meter, showed an immediate increase of 2% after 172.5 hours at 0.126% sand content. The sand content was increased to 0.364% but the flowrate error reached unacceptable limits and the meter was removed from the facility to find that all the meter's rotor blades had been removed.

Data from the 0.126% sand content tests on the 50 mm NB turbine meter, Manufacturer D, after a 172.5 hour period showed a percentage error of approximately 2.5%. This represents a flowrate error shift of 3% from the original clean water calibration. Following the next 84 hours at 0.364% sand content the calculated error was1.8%, a rise of 1.1% from the clean water calibration. Following a further 68 hours at 0.644% sand concentration, a total abrasive flow test period of 324.5 hours, a further increase of 0.56% was shown compared to the previous sand content data. This represents an increase of 1.7% when compared to the original clean water calibration at a similar flowrate.

6.6 Intermediate Flowrate Abrasive Flow Tests on 75 mm NB Mass Meter and 100 mm NB Wedge Meters (Nominal 15 l/s)

This flowrate represents nominally 33% of the test meters maximum flow range.

Flowrate data points were taken towards the end of the 0.126% and 0.777% sand content periods.

Fig. 9. shows the data obtained from the 100 mm NB wedge meter and 75 mm NB mass meter tests, Manufacturers E and F respectively, along with data taken from their original clean water calibrations at a similar flowrate. (Nominal 15 l/s.)

A 15 l/s flowrate is within Manufacturer E's recommended 3:1 turn-down ratio for the wedge meter. Test meter accuracy levels, within the manufacturers error limits, should have been achievable.

Following 139.5 hours at 0.126% sand concentration Manufacturer E's test meter shows a rise in flowrate error of nominally 8% compared to the original clean water calibration. Following a further 105 and 129 hours at 0.352% and 0.777% sand content respectively, totalling 373.5 hours of abrasive flow service, the meters flowrate error showed a further increase of 5% compared to the previous sand content data. This represents a rise of 13% compared to the original clean water calibration at a similar flowrate.

Manufacturer F, the Coriolis mass meter, showed an increase of 0.6% between the original clean water calibration and the 0.126% sand content data after 139.5 hours. Following a further 105 and 129 hours at 0.352% and 0.777% respective sand contents, totalling 373.5 hours of abrasive flow service, the flowrate error showed an improvement of 0.15% from the original clean water calibration at a similar flowrate.

7 CONCLUSIONS

The entire test series entailed testing nine meters. Four 50 mm NB turbine meters, three 100 mm NB turbine meters, one 100 mm NB wedge meter and one 75 mm NB Coriolis mass meter. Test meter details are summarised in Tables 1 and 2.

7.1 Performance, Size

7.1.1 50 mm NB turbine meters (all data) compared to reference flowmeter

Fig. 10 shows the 50 mm NB turbine meter test data, Manufacturers A, B, C, and D, compared to the reference electromagnetic flowmeter.

Manufacturer A's 50 mm NB turbine meter seized following 2 hours of abrasive flow testing at 0.126% sand concentration and was removed from the test schedule.

Manufacturer B's 50 mm NB turbine meter results show that this meter consistently performed within ±1.0% of the reference flowmeter with the exception of the 0.644% sand concentration points at 6 l/s. Here the percentage error increased from nominally 0.5% to 10%. This meter was specifically designed for abrasive flow duty. The wear on the upstream edge of this meter's rotor blades is shown in Fig. 11.

For Manufacturer C's 50 mm NB turbine meter, this shows that during the clean water calibration the meter was more accurate at lower flowrates with an average error of 1.09%. During the 0.126% sand concentration tests, over the flow range, the average error was nominally 2.5% (with the exclusion of a few data points at 9 l/s with errors between -1% and 3.1%). The 0.364% sand tests initially show the flowrate error increased to 3.5%. After approximately 250 hours abrasive flow the error had risen to 23% and after 256.5 the error had further increased to 82%. The meter was removed from the test facility where inspection revealed that the rotor blades had disappeared. Fig. 12 shows the wear on the rotor blade assembly and Fig. 13 the erosion on the inlet flow straightener.

Manufacturer D's, 50 mm NB turbine, clean water results show that this meter consistently performed within 1% of the reference flowmeter. The 0.126% sand content data shows an increase in error to nominally 1.5%, with the exception of data at 15 l/s which showed errors of 2.8%. The 0.364% sand content tests show a rise in error across the flow range to nominally 2%. The error increases again during the 0.644% sand tests to nominally 2.5% with the exception of low flowrates (6 l/s) when the percentage error increases to 12%. The wear on this meter's rotor is shown in Fig. 14.

7.1.2 100 mm NB turbine meters (all data) compared to reference flowmeter

Fig. 15 shows the 100 mm NB turbine meter test data, Manufacturers B, C and D, compared to the reference electromagnetic flowmeter.

Manufacturers B's 100 mm NB turbine meter clean water calibration shows an average 1.56% error over the flow range with the 0.126% sand content test results showing a similar error at low flowrates and a 0.39% increase at the optimum flowrate. The 0.315% sand test results show a shift of 0.25% across the flow range compared to the previous sand content data. The 0.671% sand tests show a further increase of nominally 0.5% across the flow range compared to the 0.315% sand tests. Fig. 16 shows the wear on this manufacturer's rotor. Fig. 17 shows the rotor shaft wear on this manufacturer's meter.

Increases in sand concentration appear to have a direct effect on the meter performance, particularly with respect to repeatability results. It should be noted that the overall increase in flowrate error between the clean water calibration and the last sand concentration tests is within 1%. This manufacturer's meter was specifically designed for abrasive flow service.

Manufacturer C, 100 mm NB turbine meter, produced the most accurate clean water calibration with a nominal flowrate error of 1% across the flow range. The 0.126% sand concentration tests showed little deviation from this figure particularly at low flowrates. Data from the 0.315% sand tests showed an increase of 0.39% across the flow range compared to the clean water data. The 0.671% sand tests produced similar results as the 0.315% sand data at the optimum flowrate. The low flowrate data showed an initial flowrate increase of 0.5% with the meter output becoming erratic until at 258.5 hours sand service when the meter seized. This meter was removed from the test series. Visual inspection showed that the rotor shroud had seized onto the meter bore as demonstrated in Figs 18 and 19.

The 100 mm NB turbine meter, Manufacturer D, clean water calibration showed a gradual increase in flowrate error towards the higher flowrates. The 0.126% sand data showed a slight improvement in flowrate percentage error across the flow range. During the 0.315% sand test the error increased to 2% at the low flowrates (15 l/s) with the optimum flowrate data remaining similar to the clean water and 0.126% data. This pattern was repeated for the 0.671% sand test data, giving a 0.89% increase at low flowrates compared to the clean water calibration; the optimum flowrate error remained virtually unchanged.

Manufacturer D's 100 mm NB turbine meter's accuracy was obviously affected (2%) by sand service at low flowrates (15 l/s) with only marginal increase at higher flows. The meter bore showed severe abrasion in the area of the rotor blades as well as slight rounding of the rotor blade leading edge.

7.1.3 75 mm NB wedge meter and 100 mm NB Coriolis mass meter (all data) compared to reference flowmeter

Fig. 20 shows the 75 mm NB mass meter and 100 mm NB wedge meter test data compared to the reference flow meter. Both meters were designed for use in abrasive flow service.

The 100 mm NB differential pressure wedge meter, Manufacturer E, clean water calibration showed an average flowrate error of 0.33% across the flow range. The optimum flowrate data at 0.156% sand showed an increase of 1.75% compared to the clean water calibration with the low flowrate data producing a 7.71% increase from the clean water data. The 0.352% sand tests showed a similar pattern to the 0.156% sand tests with the meters optimum flowrate figures equalling the previous sand data, but the low flowrate figures producing a further large shift of 8% from the previous sand test. The final 0.777% sand data again showed no difference from previous data at the meters optimum flowrate but the low flowrate error (even with-in the specified 3:1 turndown ratio) continued to rise to 20%.

The Coriolis mass meter, Manufacturer F, clean water calibration produced an average flowrate error of 0.68% across the flow range. The 0.156% sand test showed a negligible increase at the optimum flowrates with a 0.4% increase at low flowrates. The 0.352% sand tests showed no change from the clean water calibration with the 0.777% sand test producing no change at low flowrates and an improvement of 0.5% at the optimum flowrates compared to the clean water calibration at a similar flowrate.

Overall this meter's accuracy was not affected by abrasive flow with only slight polishing of the surface material at the meter's inlet manifold. The internal flow tubes could not be inspected.

7.2 Manufacturer, Type of Meter

The turbine meters performed with varying degrees of success. On the whole the 100 mm nominal bore meters performed better than the 50 mm nominal bore meters.

Two 50 mm turbine meters failed with one (Manufacturer C) being completely stripped of its rotor blades and Manufacturer A's meter seizing immediately after the introduction of sand into the test fluid. The 50 mm nominal bore, Manufacturer D, had 60% of its rotor blades worn and would probably not have survived for much longer at this rate of wear.

Manufacturer B did out-perform the other meters in the 50 mm nominal bore size, although it did show large errors at low flowrates with the highest sand percentages. It should be noted that this meter is specifically designed for abrasive flow use.

Only one (Manufacturer C) of the three 100 mm turbine meters failed to complete the test series and that was only by three hours. The 100 mm NB turbine meters showed similar results as the 50 mm NB turbine meter tests, although as previously noted this size of turbine meter did prove more reliable than the smaller size. Manufacturer B, in the 100 mm NB size, meter gave slightly better results across the flow range than Manufacturer C, until Manufacturer C's meter seized with Manufacturer D's being less accurate particularly at the lower flowrates. Once again Manufacturer B was the only meter in the 100 mm NB range to be recommended specifically for abrasive flow duty although Manufacturer D's meter did provide comparable results though suffered increased wear.

The differential pressure wedge meter (Manufacturer E), the second most expensive meter in the test series, produced comparable results to the mass meter at high flowrates but became significantly inaccurate, although remaining quite repeatable, at low flowrates close to and below the manufacturer's 3:1 flowrate turn-down ratio. Although this meter is of robust construction and showed little sign of wear during the test series there were indications that corrosive build up on the bore of the pressure tappings could become a problem during long term operation. This would obviously be dependant on the metered fluid and its compatibility with the meter's construction material.

The Coriolis mass meter, Manufacturer F, produced the most consistent results through out the test series with the abrasive flow test data showing little deviation from the original clean water calibration. This meter also had the advantage of a large flowrate turn-down ratio and alternative outputs, ie temperature, derived volume flowrate etc. The meter was more expensive than the other test meters therefore consideration would have to be given regarding cost against accuracy, reliability and convenience. This meter would be particularly suited to high performance, long term, maintenance free utilisation. The meter showed very little sign of abrasion/wear during the test series with only slight material polishing at the inlet manifold.

7.3 Material, Construction Details

Where a manufacturer supplied two sizes of meter these were both of the same model and design. All of the turbine meters tested were constructed with stainless steel rotor blades and meter bodies. Various grades of stainless steel were utilised ranging from austenitic stainless steel blades on Manufacturer B's turbine meters, to 430 grade stainless steel in Manufacturer C's blade construction.

Of the three manufacturers that provided meters of both 100 mm and 50 mm NB sizes only Manufacturer C's meters failed to complete the tests for each size. This manufacturer's blade thickness was also relatively thin in comparison to other meters in their respective bore size. The other meter to fail during the sand tests was Manufacturer A's 50 mm NB meter. This meter along with the 50 mm and 100 mm NB meters supplied by Manufacturer C's were constructed with flat profiled rotor blades, as opposed to the other meters' helical type blade profile.

For these tests the number of blades alone appears to have no significance on the outcome of the abrasive flow tests. However, the combination of rotor blade profile and thickness are likely to have some effect on a meters' overall performance in abrasive flow. It was also noted that turbine meters fitted with rotor blade shrouds did not perform well, with both shrouded meters failing during testing.

As expected the Coriolis mass and wedge meters were not, as dramatically, affected by sand abrasion and wear as the turbine meters. This was mainly due to both meters having no moving parts in the test fluid. Slight polishing was witnessed on both meters but this was considered minimal and was unlikely to affect the meters' performance. The wedge meter did show considerable material build up on the pressure tapping internal bores. This was after careful material selection by the manufacturer.

The mass meter model used in these tests was selected mainly due to its user popularity and was provided with hastelloy measurement tubes. In theory, this material should perform better than stainless steel in most abrasive flow duties.

8 THE WAY FORWARD

Points for consideration:

NEL would welcome the opportunity to discuss the results of these tests further and to identify other potential projects involving dirty service activities for UK industry.

A number of points that merit for future consideration and examination have been highlighted during this test series and are briefly outlined below.

- Testing meters over longer test periods. The test periods used in this series of tests are short and not fully representative of in-field operating times because the tests were 'accelerated' by using relatively high sand content levels.

- Test other alternative meter types that are available, to get a benchmark on the capabilities of all meter types in sandy service fluids, eg Venturi, Vee-cone and positive-displacement and Ultrasonic meters.

- Look at the effects of different particle sizes (eg - fine, coarse) and types on meter performance.

- For turbine meters, the effects of different turbine meter blade combinations and geometries, bearing design, running clearances and materials.

ACKNOWLEDGEMENT

NEL acknowledges the sponsorship of Department of Trade and Industry and the National Measurement System Policy Unit Flow Programme for the work. Guidance notes and full reports of all Flow Programme Projects are available from NEL.

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3 100 mm NB turbine meter data. Nominal flowrate 35 l/s. Manufacturers B - D

4 Coriolis mass and wedge meter data; Nominal flowrate 30 l/s. Manufacturers E and F

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6 100 mm NB turbine meter data. Nominal flowrate 15 l/s. Manufacturers B - D

7 Coriolis mass and wedge meter data. Nominal flowrate 9 l/s. Manufacturers E and F

8 50 mm NB turbine meter data. Nominal flowrate 15 l/s. Manufacturers A - D

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12 Manufacturer C. 50 mm diameter meter, rotor shaft wear

13 Manufacturer C. 50 mm diameter meter, flow straightener wear

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15 100 mm NB turbine meter data compared to reference flowmeter; Manufacturers B - D

16 Manufacturer B. 100 mm diameter meter, rotor blade wear

17 Manufacturer B. 100 mm diameter meter, rotor shaft wear

18 Manufacturer C. 100 mm diameter meter, rotor ring wear

19 Manufacturer C. 100 mm diameter meter, meter bore wear

20 Coriolis mass and wedge meter data compared to reference flowmeter. Manufacturers E and F

TABLE 1a

TURBINE METERS (50 mm NOMINAL BORE)

Test Meter	**Manufacturer A (50 mm)**	**Manufacturer B (50 mm)**	**Manufacturer C (50 mm)**	**Manufacturer D (50 mm)**
Nominal bore	50 mm	50 mm	50 mm	50 mm
No of blades	8	4	8	8
Blade shape	Flat	Helical	Flat	Helical
Blade thickness (@ mid point)	0.685 mm	2.0 mm	0.43 mm	0.90 mm
Blades on outer ring	No	No	No	No
Blade material	410 SS	Austenitic SS	430 SS	Stainless steel
Meter body material	Stainless steel	Stainless steel	304 SS	Stainless steel
Upstream flow straightener	Yes	Yes	Yes	Yes
Downstream flow straightener	No	Yes	Yes	No
Manufacturers quoted flow range	1.87 - 18.70 l/s	2.5 - 23.3 l/s	1.4 - 14.3 l/s	1.9 - 18.9 l/s
Manufacturers quoted accuracy (over flow range)	±0.25%	±0.20%	±0.25%	±0.15%
Manufacturers quoted repeatability	±0.02%	±0.01%	±0.02%	±0.02%
Test hours duration (clean water)	88.5	88.5	88.5	88.5
Test hours, 0.126% sand	2	172.5	172.5	172.5
Test hours, 0.156% sand	-	-	-	-
Test hours, 0.315% sand	-	-	-	-
Test hours, 0.352% sand	-	-	-	-
Test hours, 0.364% sand	-	84	84	84
Test hours, 0.644% sand	-	68	-	68
Test hours, 0.671% sand	-	-	-	-
Test hours, 0.777% sand	-	-	-	-
Total hours in sand service	2	324.5	256.5	324.5
Degree of wear	Rotor blades seized onto meter bore. This was caused by sand entrapped between blade tip and bore. Wear high spots on meter bearing.	Wear on upstream edge of rotor blades.	All rotor blades removed at root.	Approx. 60% of rotor blades eroded from upstream edge. Slight wear path around rotor area of meter bore.

TABLE 1b

TURBINE METERS (100 mm NOMINAL BORE), WEDGE AND CORIOLIS MASS METERS

Manufacturer B (100 mm)	Manufacturer C (100 mm)	Manufacturer D (100 mm)	Manufacturer E Wedge meter (100 mm)	Manufacturer F Coriolis meter (75 mm)
100 mm	100 mm	100 mm	100 mm	75 mm
8	6	12	Not applicable	Not applicable
Helical	Flat	Helical	Not applicable	Not applicable
2.2 mm	0.76 mm	1.3 mm	Not applicable	Not applicable
No	Yes	No	Not applicable	Not applicable
Austenitic SS	430 SS	Stainless steel	Not applicable	Not applicable
316 SS	304 SS	Stainless steel	Carbon steel (wetted parts)	Hastelloy (wette parts)
Yes	Yes	Yes	No	No
Yes	Yes	No	No	No
6.25 - 74.97 l/s	8.16 - 81.65 l/s	8.16 - 81.65 l/s	13.8 - 41.4 l/s	1.0 - 47 l/s
±0.20%	±0.25%	±0.15%	±0.5	±0.1
±0.02%	±0.02%	±0.02%	±0.2	±0.02
22.25	22.25	22.25	75	75
149	149	149	- 139.5	- 139.5
57	57 - -	57 - -	- 105 -	- 105 -
- 55.5 -	- 52.5 -	- 55.5 -	- 129	- 129
261.5	258.5	261.5	373.5	373.5
Slight wear on upstream edge of rotor.	Extensive scoring on rotor outer ring. Wear on meter bore at rotor ring/bore interface. Wear high spots on rotor bush. Meter seized after 258.5 hours sand service.	Severe sand abrasion on meter bore at rotor area. Slight rounding of rotor blades.	Slight polishing of wedge apex. Corrosion on upstream and downstream pressure tappings. Heaviest on upstream tapping.	Polishing of inlet manifold apex.

TABLE 2a

TURBINE METERS (50 mm NOMINAL BORE)

	Manufacturer A (50 mm) % Error	Manufacturer B (50 mm) % Error	Manufacturer C (50 mm) % Error	Manufacturer D (50 mm) % Error
	Flowrate: 5 l/s	**Velocity: 2.7 m/s**		
Clean water	0.26	0.52	0.73	0.65
0.14% sand	Meter removed	0.27	2.5	0.3
0.34% sand	Meter removed	0.55	81	2.3
0.70% sand	Meter removed	-9.1	Meter removed	11.63
	Flowrate: 9 l/s	**Velocity: 4.7 m/s**		
Clean water	0.33	0.53	0.91	0.61
0.14% sand	Meter removed	0.52	1.67	1.38
0.34% sand	Meter removed	0.12	10	2
0.70% sand	Meter removed	0.4	Meter removed	2.4
	Flowrate: 15 l/s	**Velocity: 7.5 m/s**		
Clean water	0.8	0.85	1.42	0.64
0.14% sand	Meter removed	0.22	3.2	-2.8
0.34% sand	Meter removed	- 0.06	76	1.9
0.70% sand	Meter removed	0.94	Meter removed	2.2

TABLE 2b

TURBINE AND WEDGE FLOW METERS (100 mm NOMINAL BORE), CORIOLIS METER 75 mm NOMINAL BORE

	Manufacturer B (100 mm) % Error	Manufacturer C (100 mm) % Error	Manufacture r D (100 mm) % Error	Manufacturer E Wedge Meter % Error	Manufacturer F Coriolis Meter % Error
	Flowrate: 10 l/s	**Velocity: 1.3 m/s**			**Velocity: 2.3 m/s**
Clean water				-0.08	0.55
0.14% sand				Not available	Not available
0.34% sand				16.14	0.64
0.70% sand				20	0.5
	Flowrate: 15 l/s	**Velocity: 1.9 m/s**			**Velocity: 3.4 m/s**
Clean water	1.47	0.94	1.47	0.34	0.57
0.14% sand	1.45	0.88	1.5	8.1	1.2
0.34% sand	1.78	1.33	1.86	Not available	Not available
0.70% sand	2.06	1.72	2.23	Not available	Not available
	Flowrate: 30 l/s	**Velocity: 3.8 m/s**			**Velocity: 6.8 m/s**
Clean water				0.47	0.81
0.14% sand				3	0.97
0.34% sand				2.6	0.71
0.70% sand				3	0.5
	Flowrate: 35 l/s	**Velocity: 4.5 m/s**			**Velocity: 7.9 m/s**
Clean water	1.61	1.07	1.6	0.47	0.81
0.14% sand	2	1.27	1.36	0.88	0.67
0.34% sand	2	1.46	1.71	1.3	1
0.70% sand	2.1	1.41	1.68	Not available	Not available

Note: All error, flowrate, velocity and sand percentage values are nominal figures
Not available indicated that flowrate and velocity were not undertaken

APPENDIX I

SAND SPECIFICATION

The quarry sand used throughout this test series had a sub-rounded/rounded particle shape and was graded between 500 microns and 125 microns via an aperture sized mesh. The average particle size was 275 ± 25 microns.

Using BS 410 grading technique, the sizing distribution of the sand particles was similar to that shown below:

ANALYSIS OF SAND PARTICLE SIZE.

Particle size Aperture/Mesh size microns	% Retained by Weight to BS410
710	0.7
500	3.9
355	16.2
250	44.8
180	28.4
125	5.5
<125	0.5

APPENDIX II

THE NEL ABRASIVE FLOW TEST FACILITY

Description of Facility

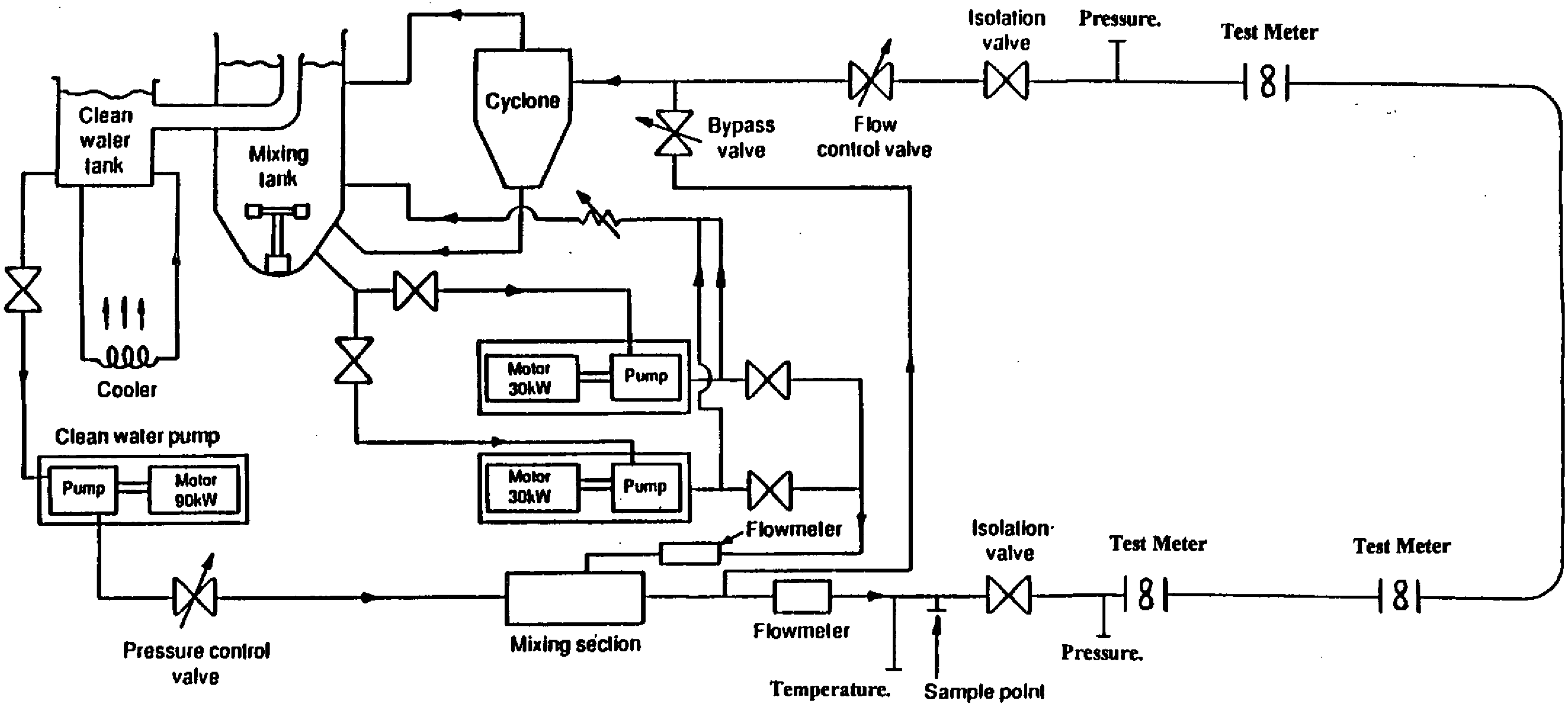
A diagram of the facility is shown in Figure II.1 of this Appendix. Clean water is taken from a storage tank by a pump and discharged into pipework where concentrated sandy water is injected by a positive displacement pump into the flow stream in a mixing section. The concentrated sandy water is supplied from a mixer tank which is constantly agitated.

The turbulent flow of the fluid, in conjunction with a number of right angle bends in series, ensure that the sand is fully mixed in the pipe before it enters the test facility test section where the test meters were mounted in series.

For 50 mm NB meter four can be installed at the one time but this was reduced to three for 100 mm NB meters due to facility pipe length restrictions with respect to appropriate up and down stream pipe lengths between test meters. After the test section the fluid passes through the flow control valve and returns to the mixing tank through cyclone separators. The cleaned water returns to the mixing tank and passes through filters before overflowing back to the clean water tank. The concentrated sandy water falls to the bottom of the mixing tank and the whole process repeats. The pipework and mixing tank were carbon steel and were not painted or coated internally. The clean water tank was painted internally with a corrosion resistant paint.

For test purposes the required flowrate and line pressure in the test section are set by adjusting the flow control valve, together with the bypass and pressure control valve. An electromagnetic flowmeter measured the flow through the test section with a similar, but smaller nominal bore, meter measuring the flow of concentrated sandy water in the injection line.

By varying the speed of the injection pumps and the concentration of the sand in the mixing tank the sand concentration in the test section can be altered as required. Test fluid samples are taken from the test section at regular intervals. An air blast cooler enables the test fluid to be temperature controlled between 40 and 70°C.



Appendix II. Schematic of NEL abrasive Flow Test Facility.

Fig. 1: CALIBRATION OF REFERENCE EM METER. FLOWRATE % ERROR vs REFERENCE FLOWRATE

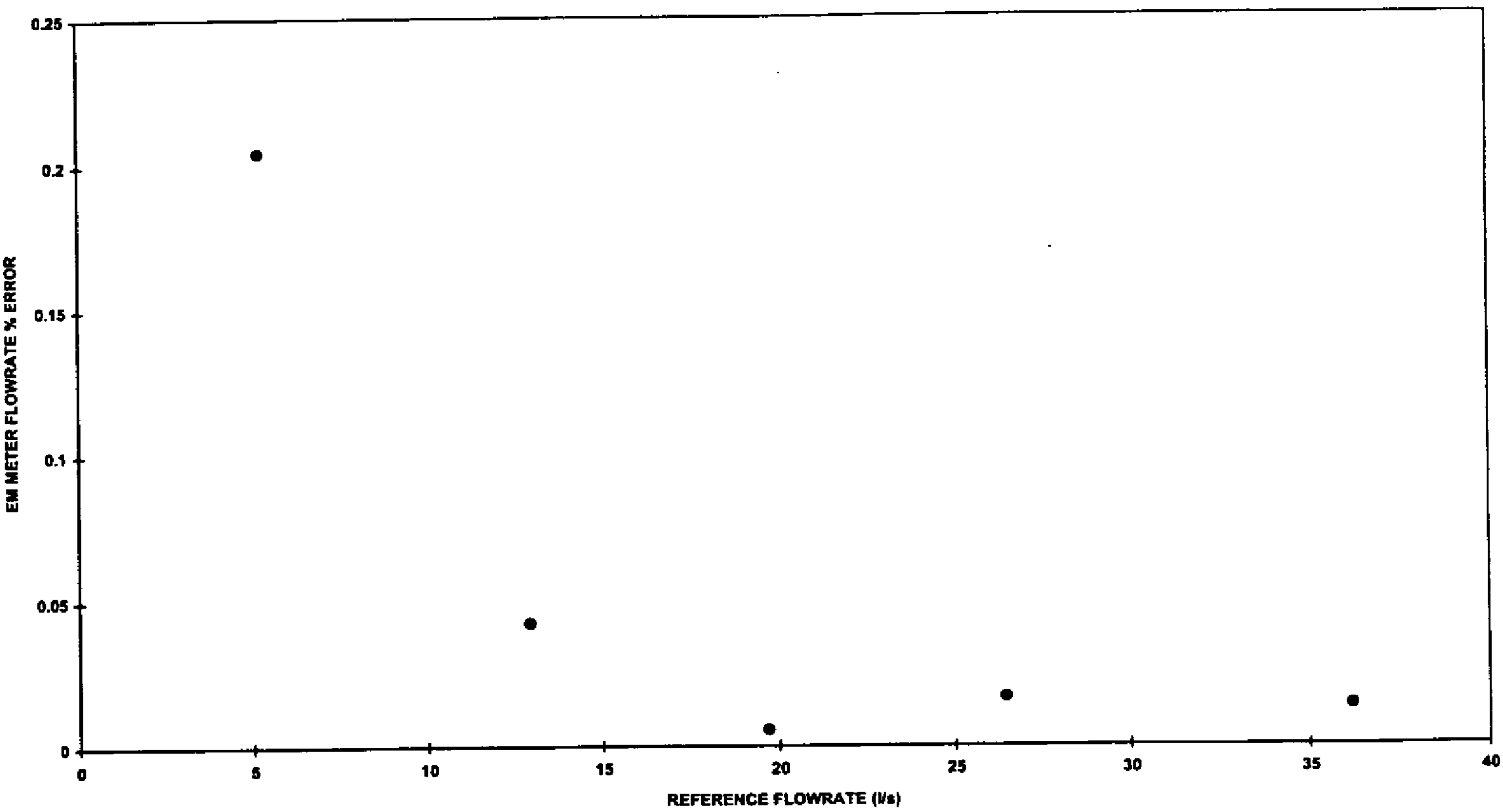


Fig. 2: 50 mm NB. TURBINE METER DATA - NOMINAL FLOWRATE 9 l/s

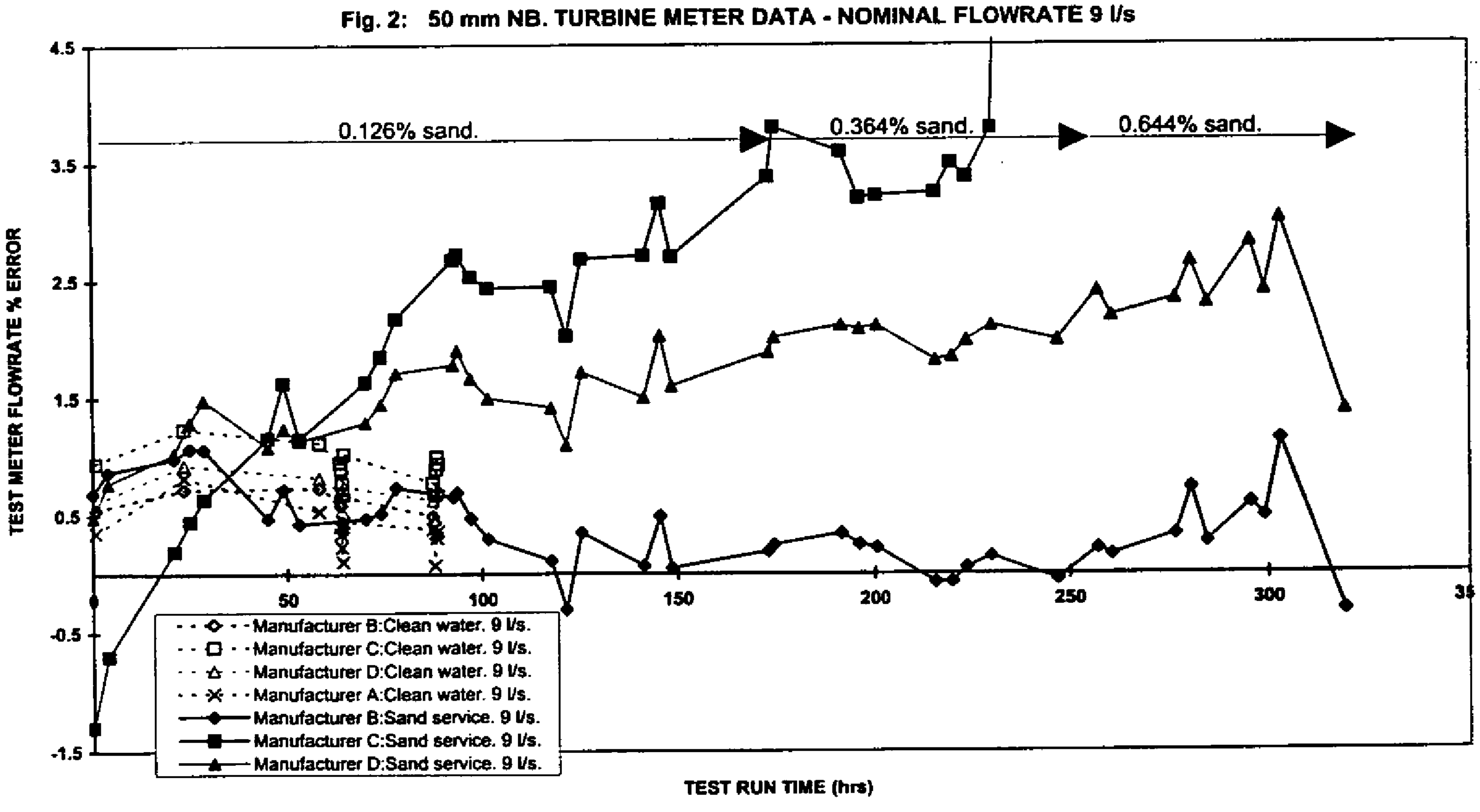


Fig. 3: 100mm NB. TURBINE METER DATA
NOMINAL FLOWRATE 35 l/s

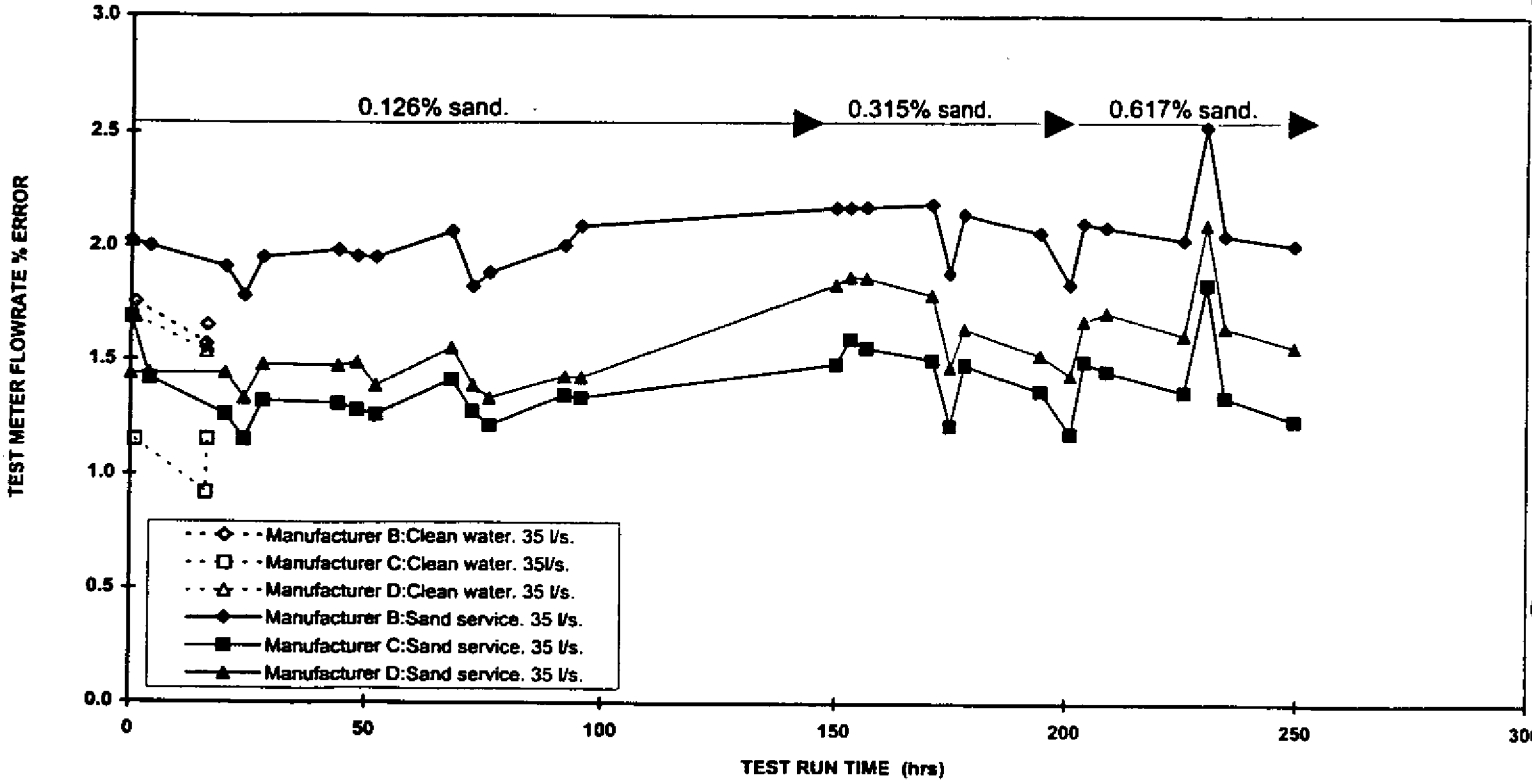
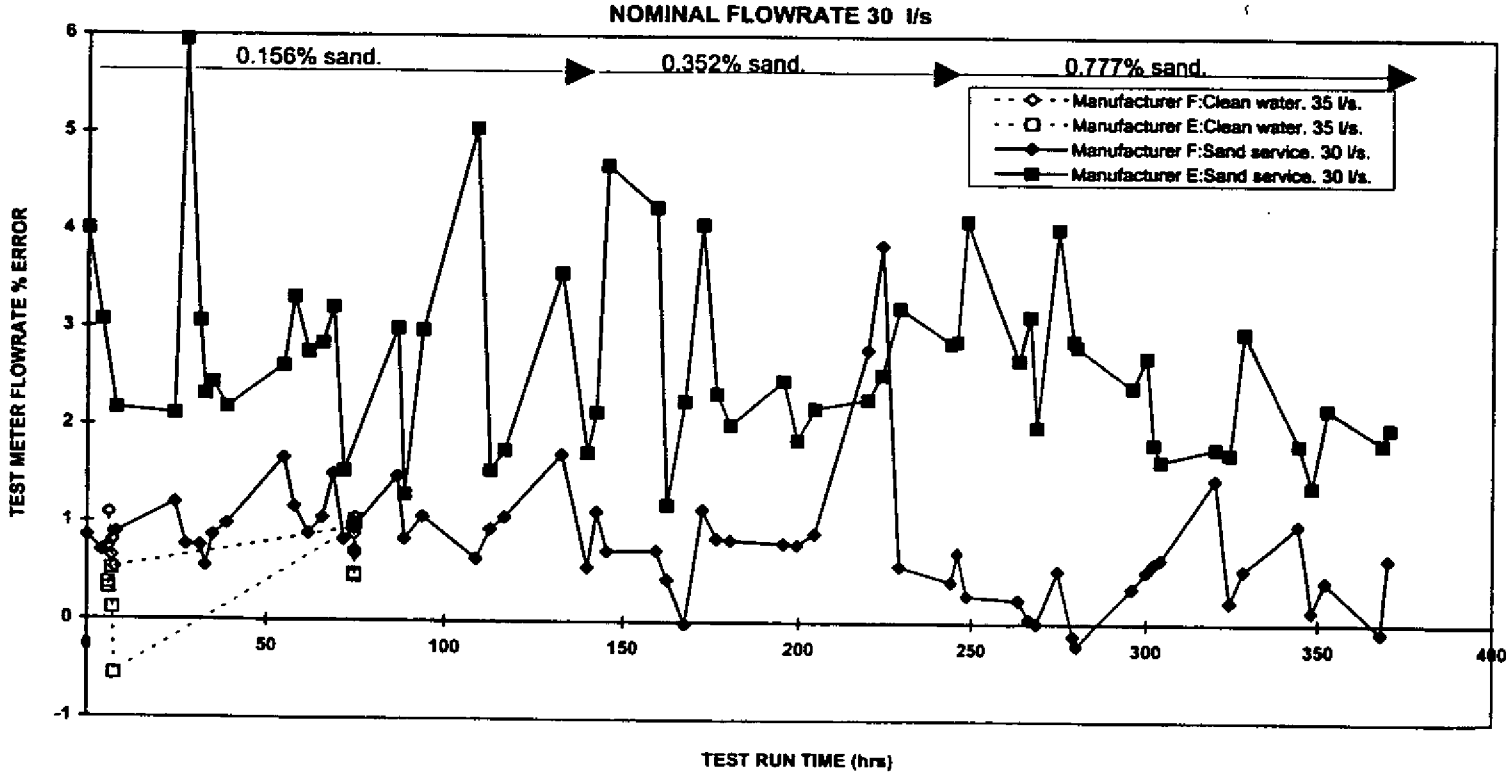


Fig. 4: CORIOLIS MASS AND WEDGE METER DATA
NOMINAL FLOWRATE 30 l/s



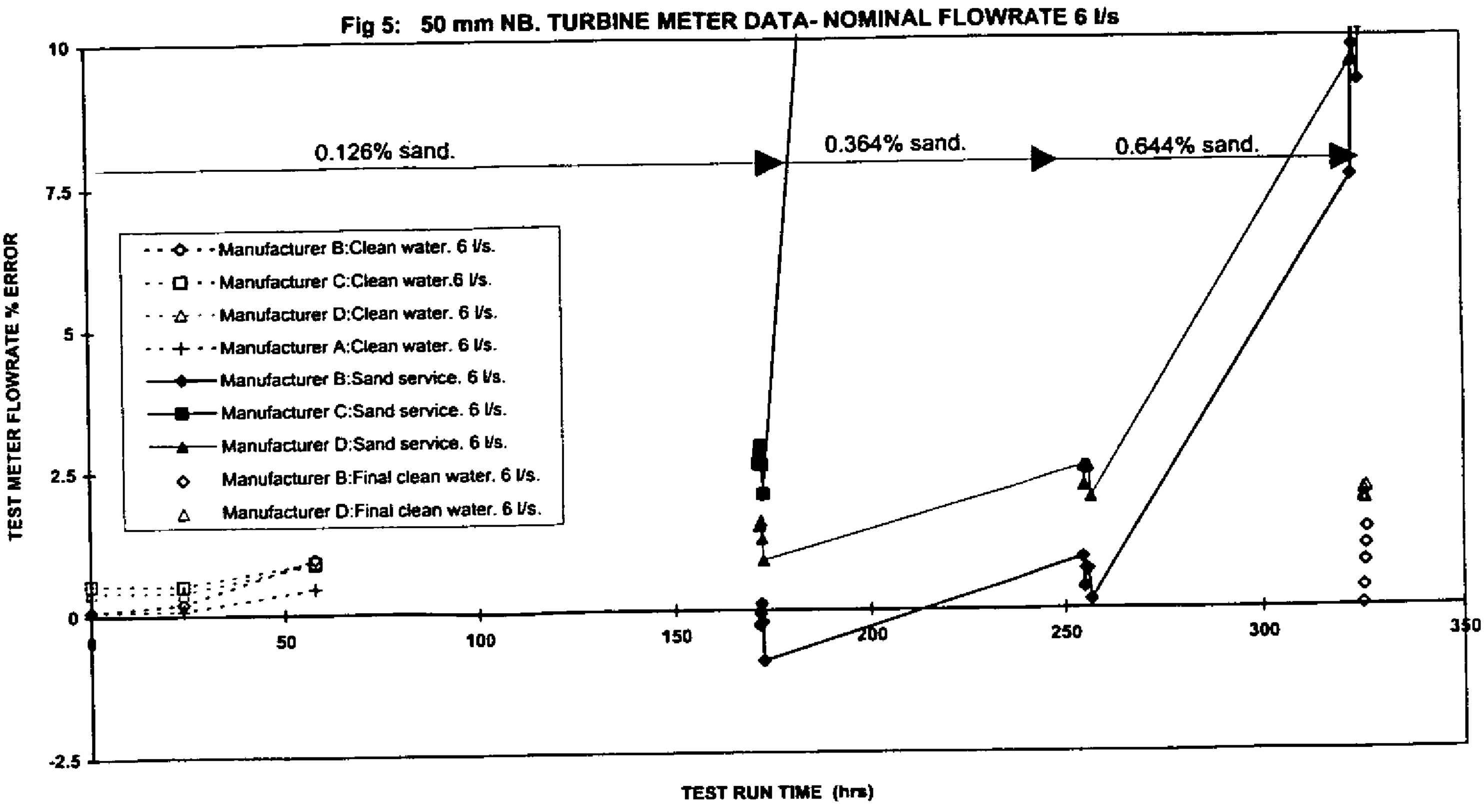


Fig 5: 50 mm NB. TURBINE METER DATA- NOMINAL FLOWRATE 6 l/s
0.126% sand.
0.364% sand.
0.644% sand.
Manufacturer B:Clean water. 6 l/s.
Manufacturer C:Clean water.6 l/s.
Manufacturer D:Clean water. 6 l/s.
Manufacturer A:Clean water. 6 l/s.
Manufacturer B:Sand service. 6 l/s.
Manufacturer C:Sand service. 6 l/s.
Manufacturer D:Sand service. 6 l/s.
Manufacturer B:Final clean water. 6 l/s.
Manufacturer D:Final clean water. 6 l/s.
TEST METER FLOWRATE % ERROR
TEST RUN TIME (hrs)
10
7.5
5
2.5
0
-2.5
50
100
150
200
250
300
350

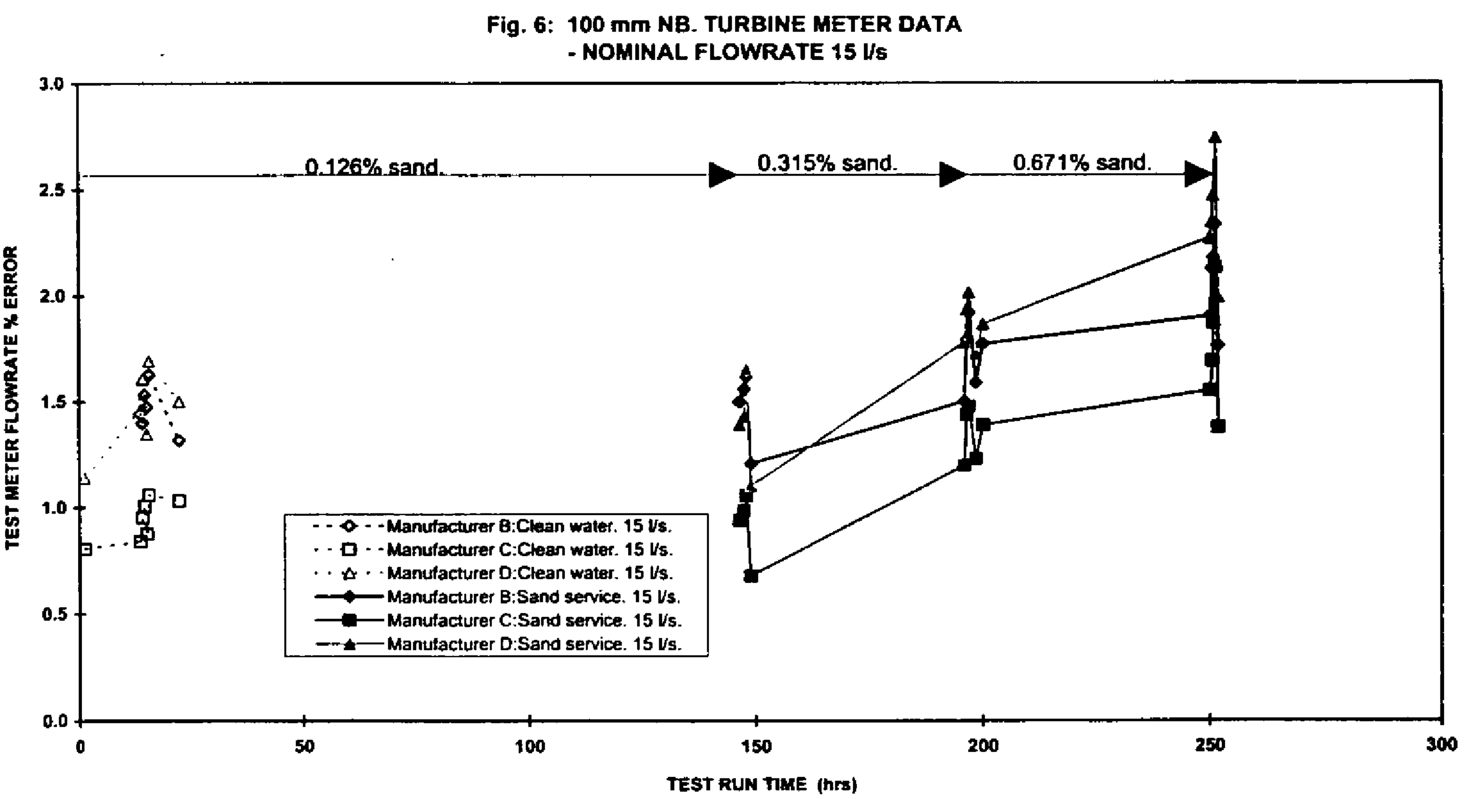


Fig. 6: 100 mm NB. TURBINE METER DATA
- NOMINAL FLOWRATE 15 l/s
0.126% sand.
0.315% sand.
0.671% sand.
Manufacturer B:Clean water. 15 l/s.
Manufacturer C:Clean water. 15 l/s.
Manufacturer D:Clean water. 15 l/s.
Manufacturer B:Sand service. 15 l/s.
Manufacturer C:Sand service. 15 l/s.
Manufacturer D:Sand service. 15 l/s.
TEST METER FLOWRATE % ERROR
TEST RUN TIME (hrs)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300

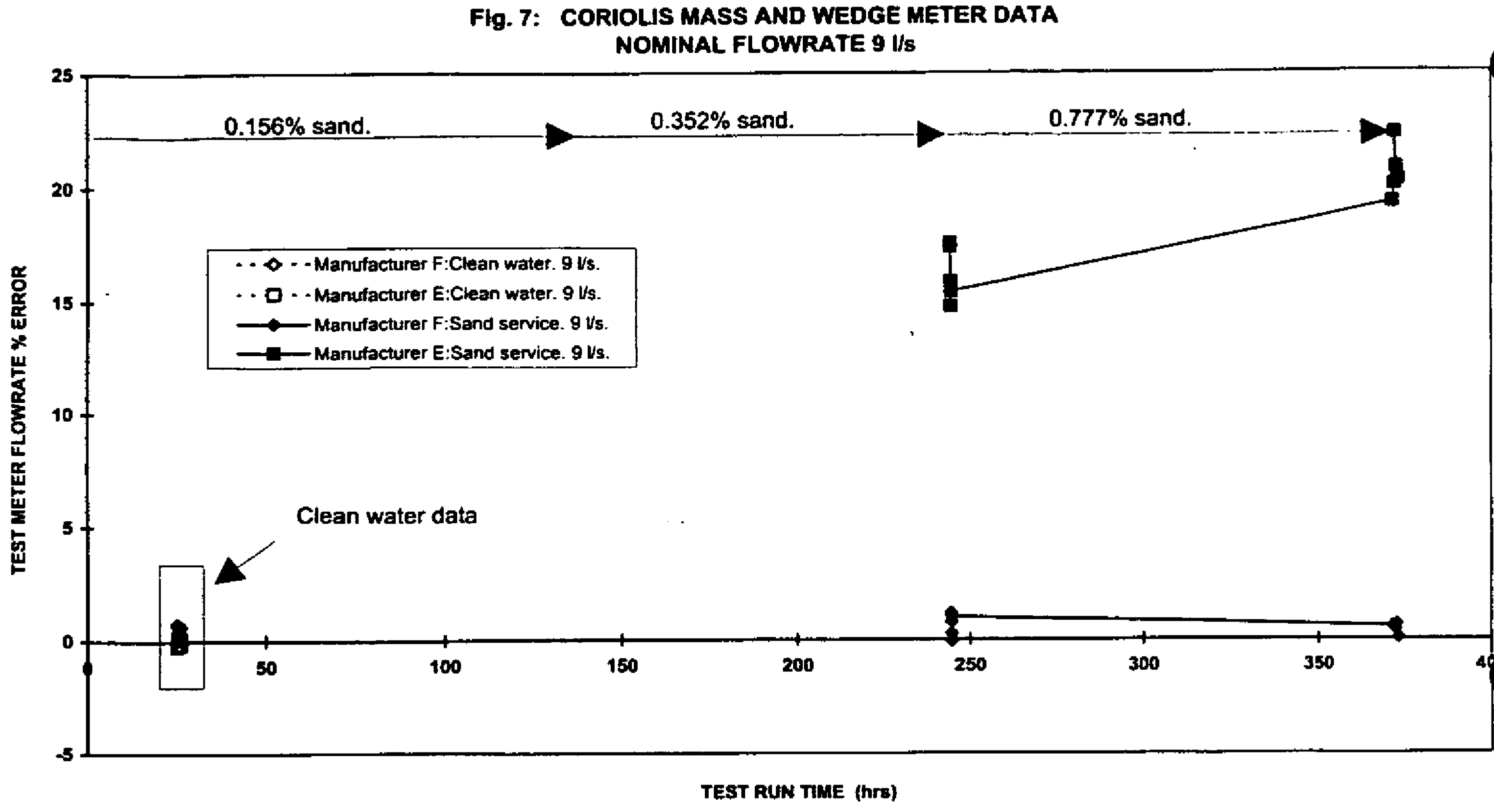


Fig. 7: CORIOLIS MASS AND WEDGE METER DATA
NOMINAL FLOWRATE 9 l/s
0.156% sand.
0.352% sand.
0.777% sand.
Manufacturer F:Clean water. 9 l/s.
Manufacturer E:Clean water. 9 l/s.
Manufacturer F:Sand service. 9 l/s.
Manufacturer E:Sand service. 9 l/s.
Clean water data
TEST METER FLOWRATE % ERROR
TEST RUN TIME (hrs)

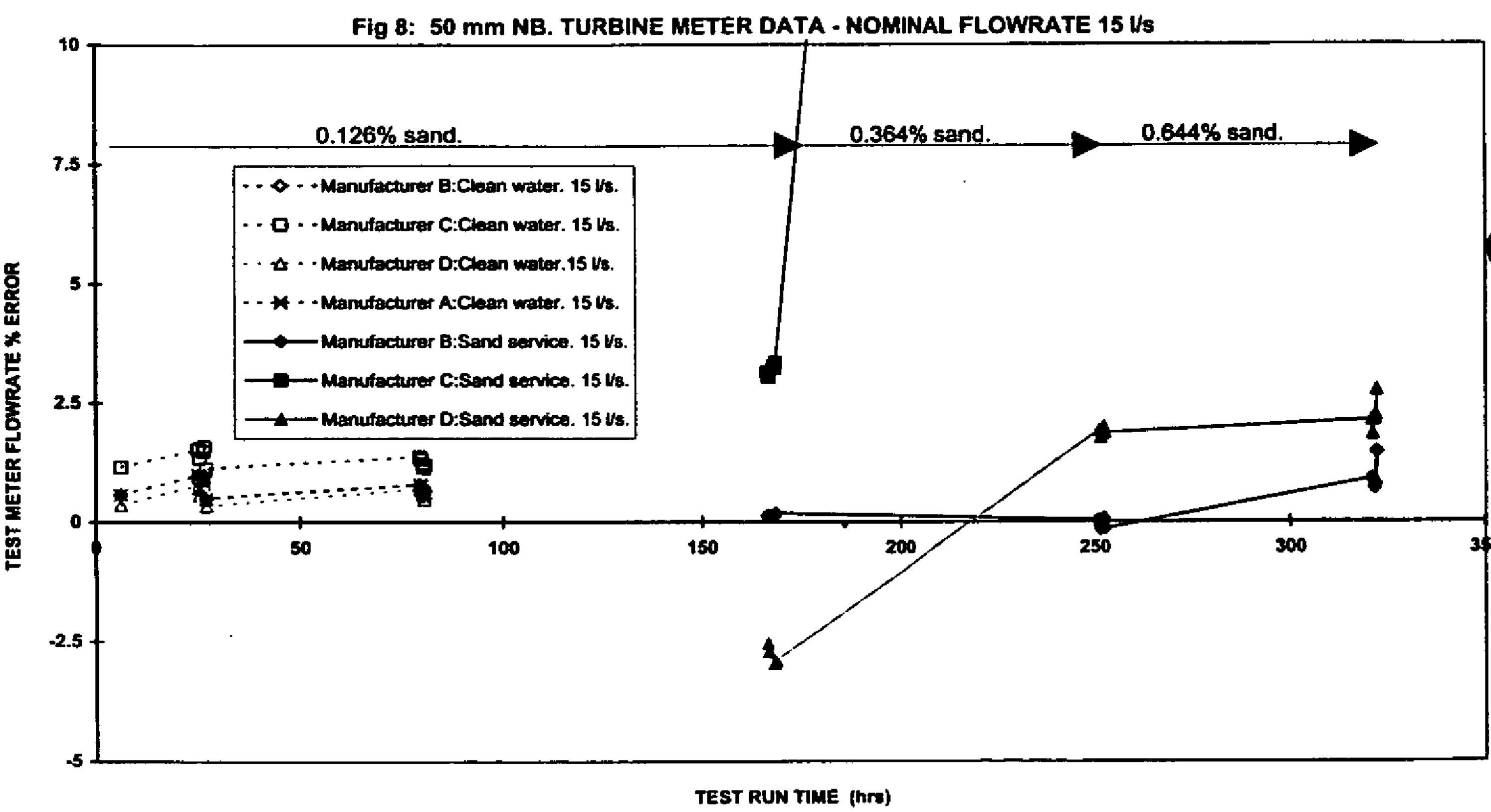


Fig 8: 50 mm NB. TURBINE METER DATA - NOMINAL FLOWRATE 15 l/s
0.126% sand.
0.364% sand.
0.644% sand.
Manufacturer B:Clean water. 15 l/s.
Manufacturer C:Clean water. 15 l/s.
Manufacturer D:Clean water.15 l/s.
Manufacturer A:Clean water. 15 l/s.
Manufacturer B:Sand service. 15 l/s.
Manufacturer C:Sand service. 15 l/s.
Manufacturer D:Sand service. 15 l/s.
TEST METER FLOWRATE % ERROR
TEST RUN TIME (hrs)

Fig. 9: CORIOLIS MASS AND WEDGE METER DATA
NOMINAL FLOWRATE 15 l/s

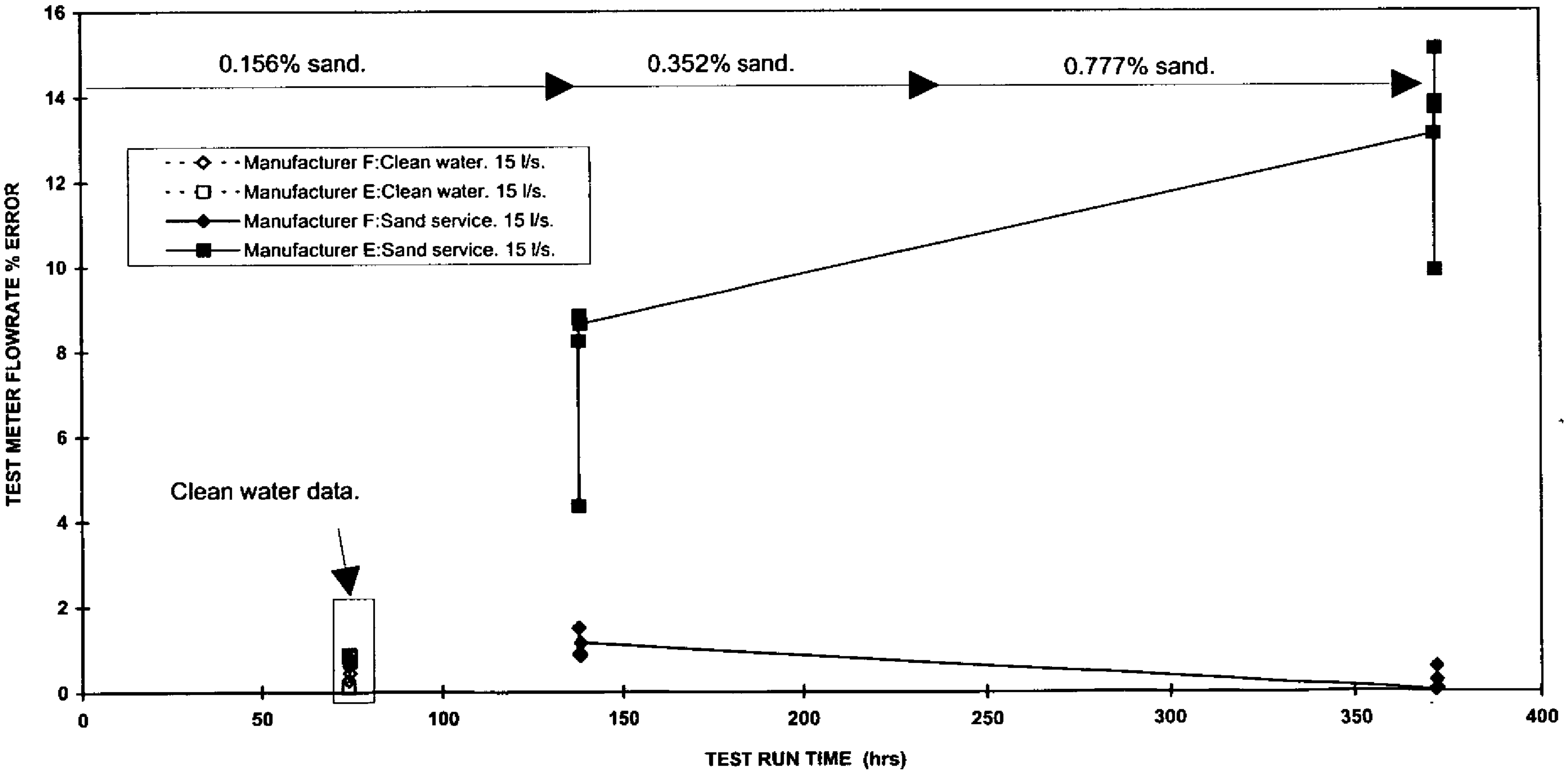


Fig. 10: 50 mm NB. TURBINE METER DATA COMPARED TO REFERENCE FLOWMETER.

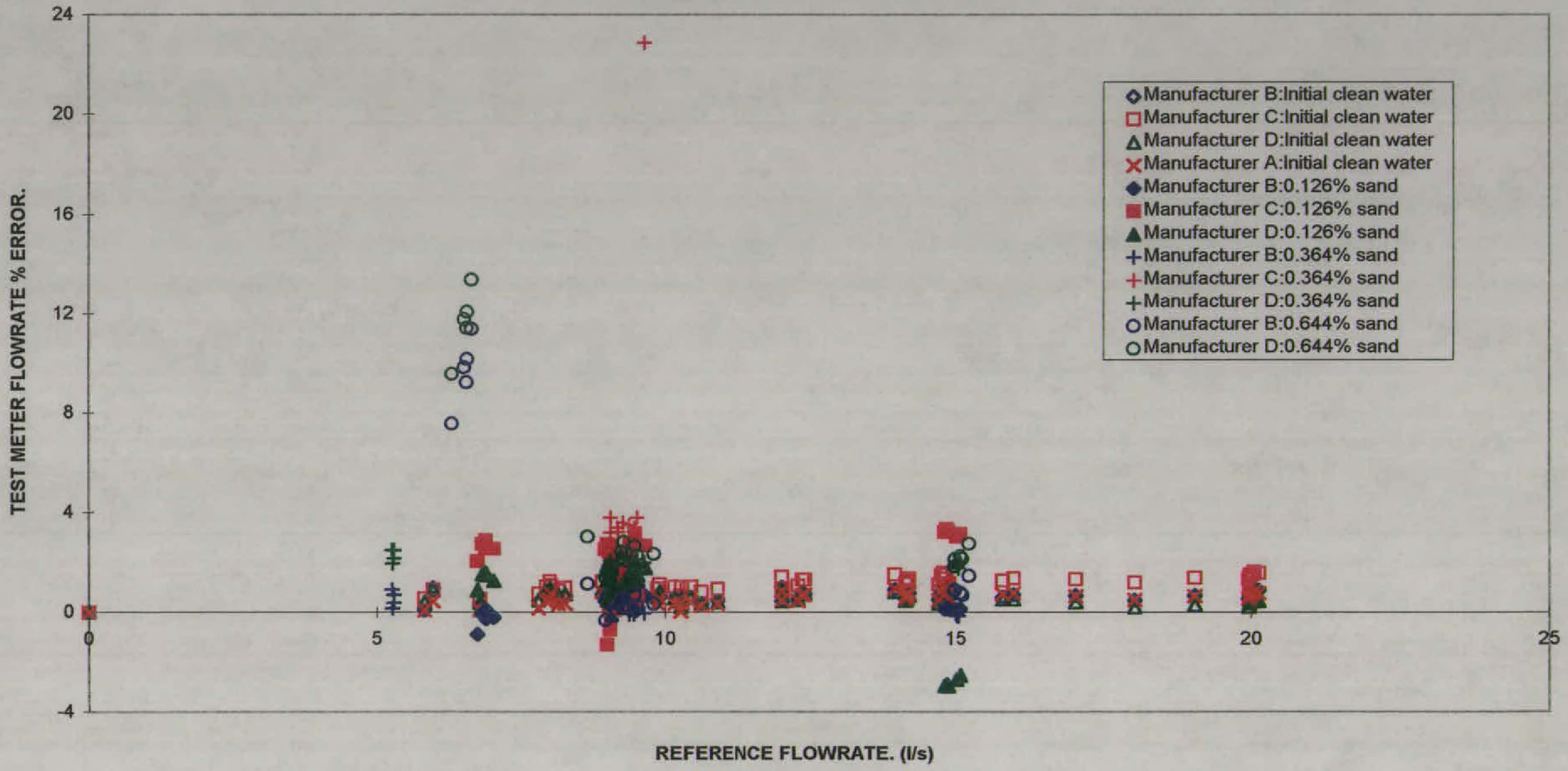


Fig 11 MANUFACTURER B. 50 mm DIAMETER METER, ROTOR BLADE WEAR

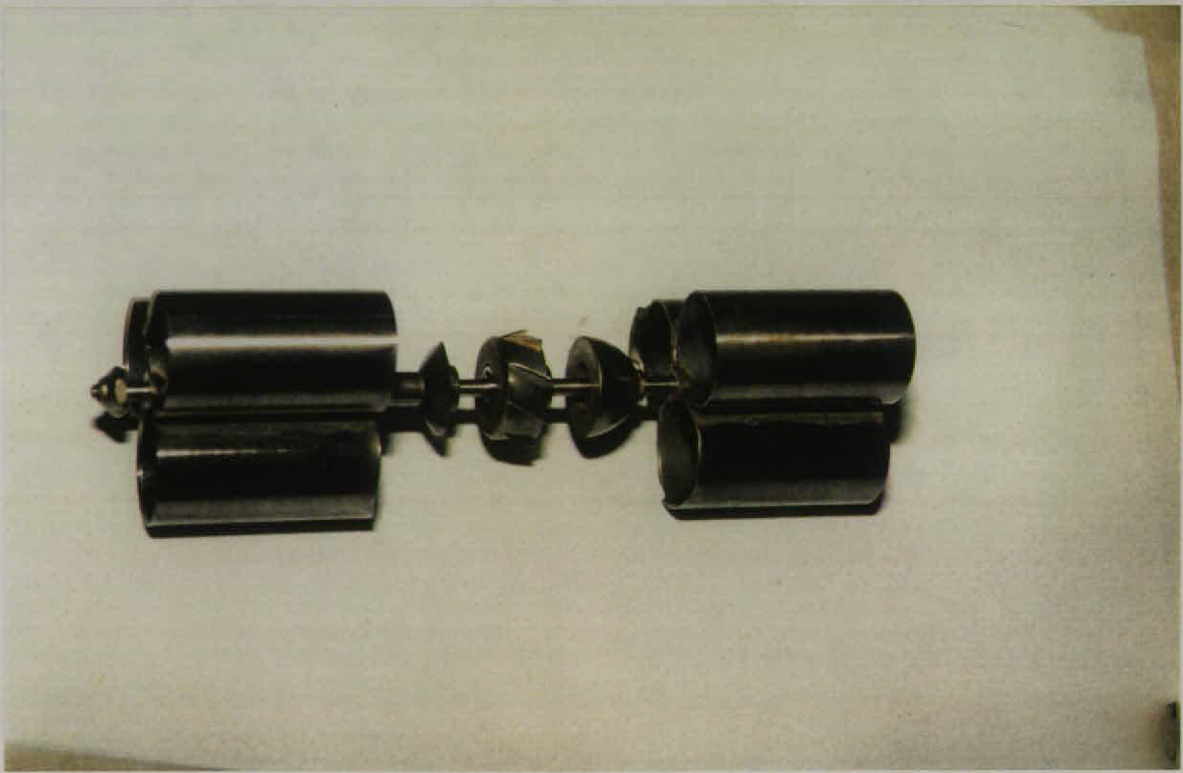


Fig 12 MANUFACTURER C. 50 mm DIAMETER METER, ROTOR SHAFT WEAR

Fig 13 MANUFACTURER C. 50 mm DIAMETER METER, FLOW STRAIGHTENER WEAR

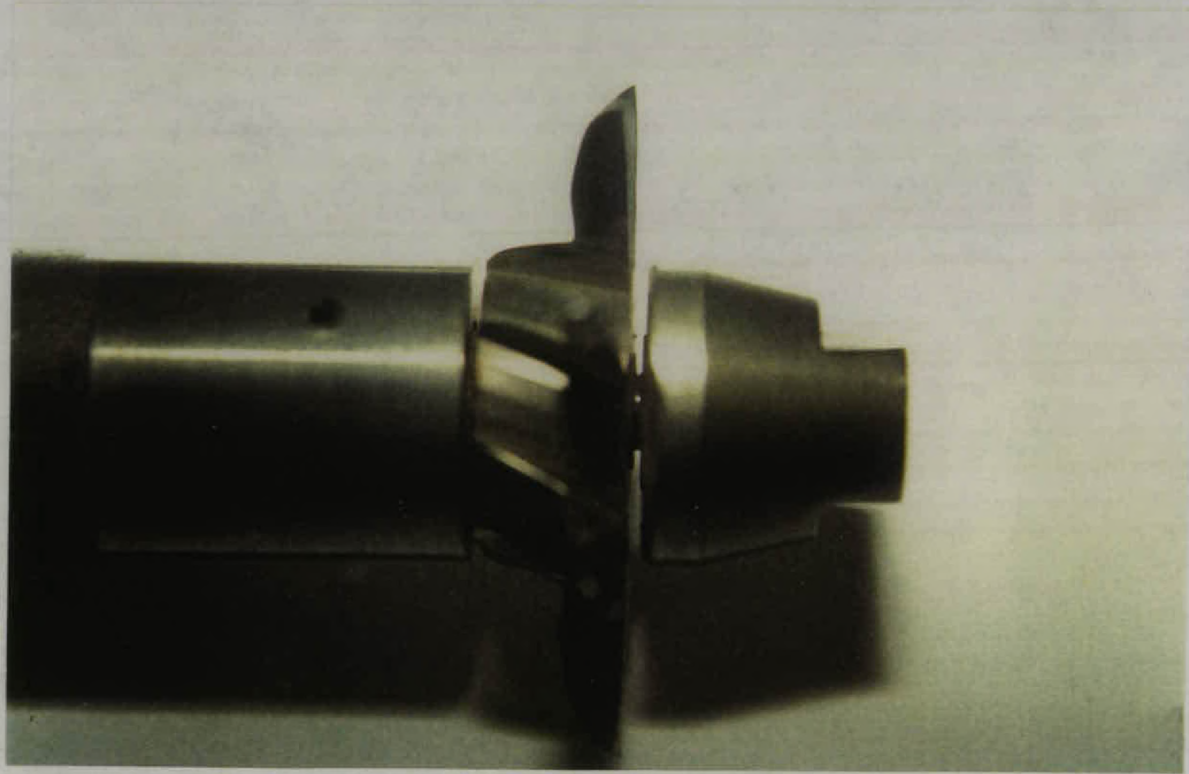
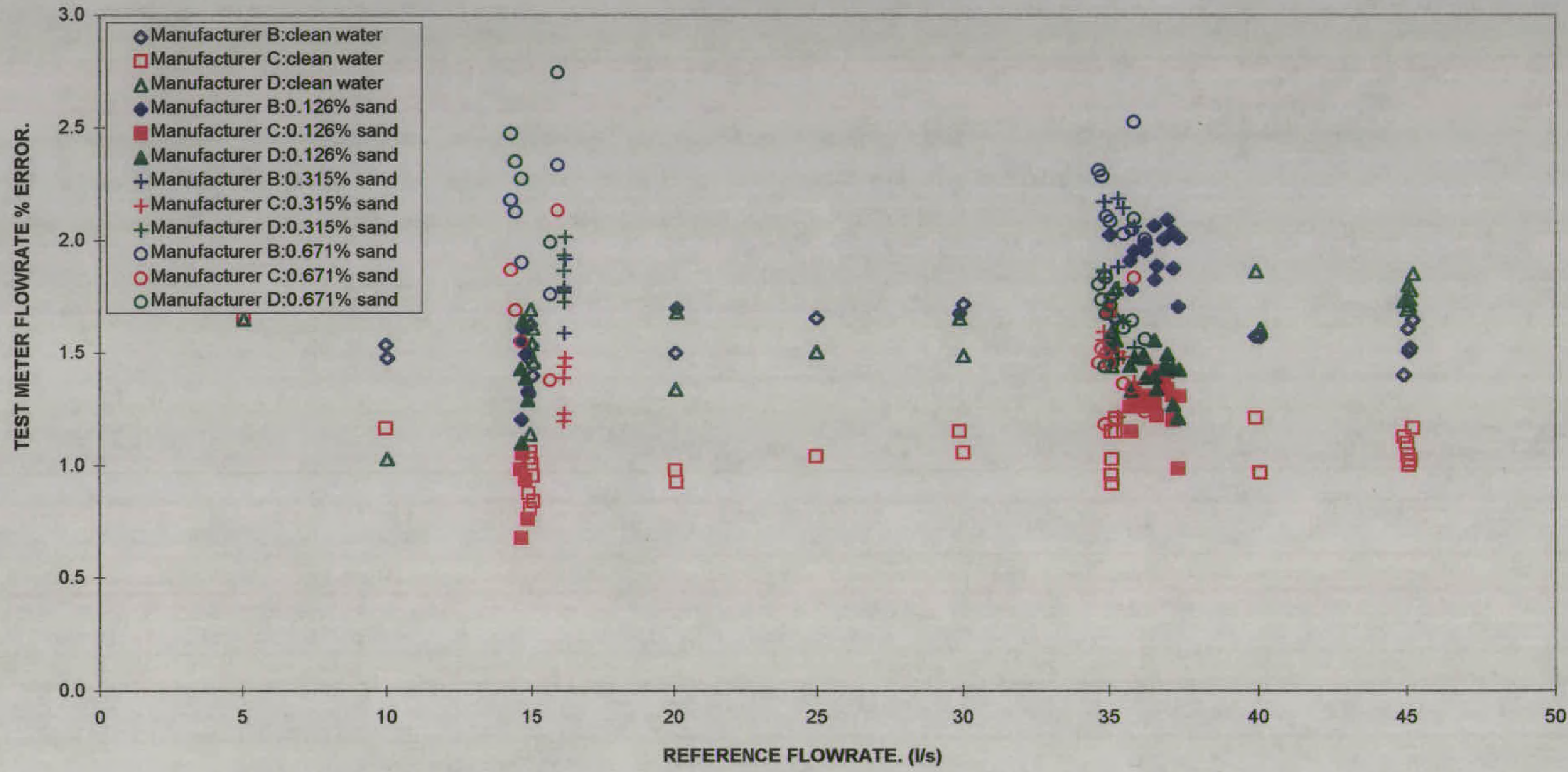


Fig 14 MANUFACTURER D. 50 mm DIAMETER METER, ROTOR BLADE WEAR

Fig.15: 100 mm NB. TURBINE METER DATA COMPARED TO REFERENCE FLOWMETER.



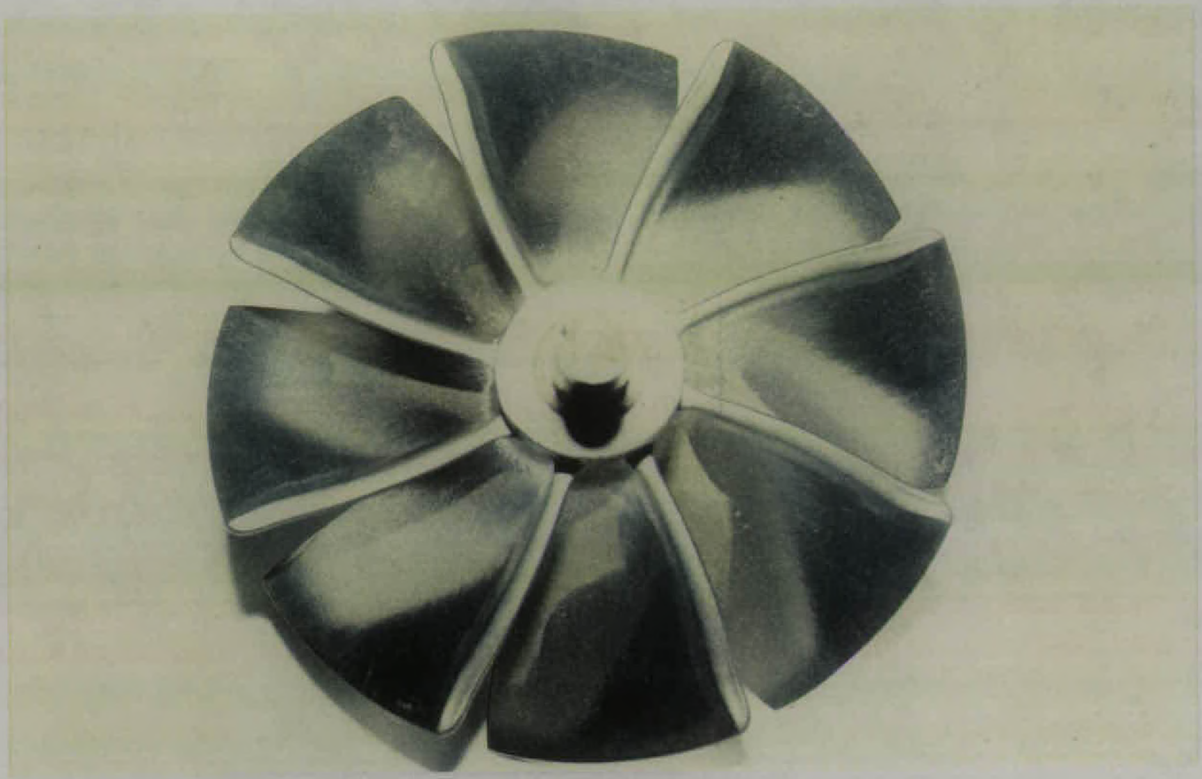


Fig 16 MANUFACTURER B. 100 mm DIAMETER METER, ROTOR BLADE WEAR

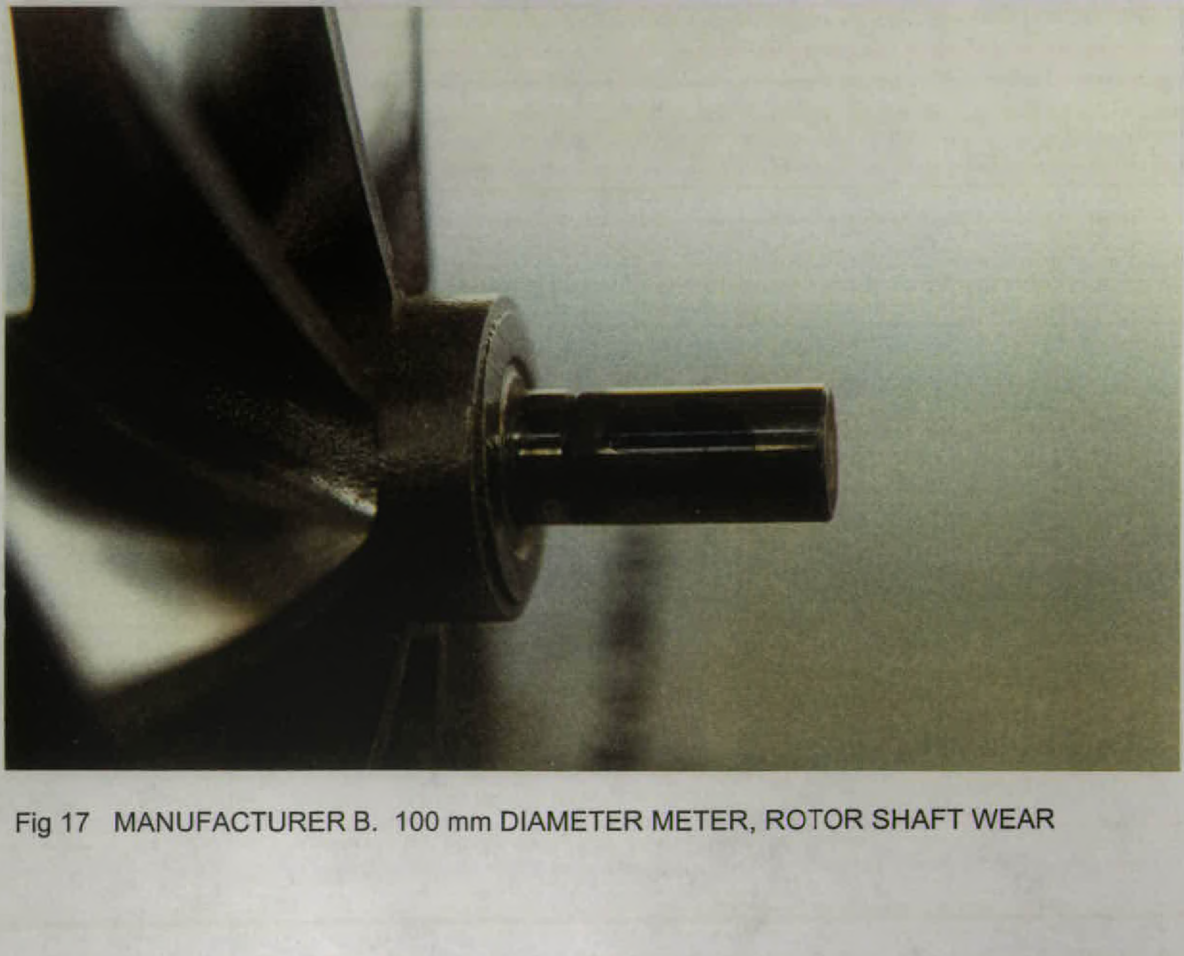


Fig 17 MANUFACTURER B. 100 mm DIAMETER METER, ROTOR SHAFT WEAR

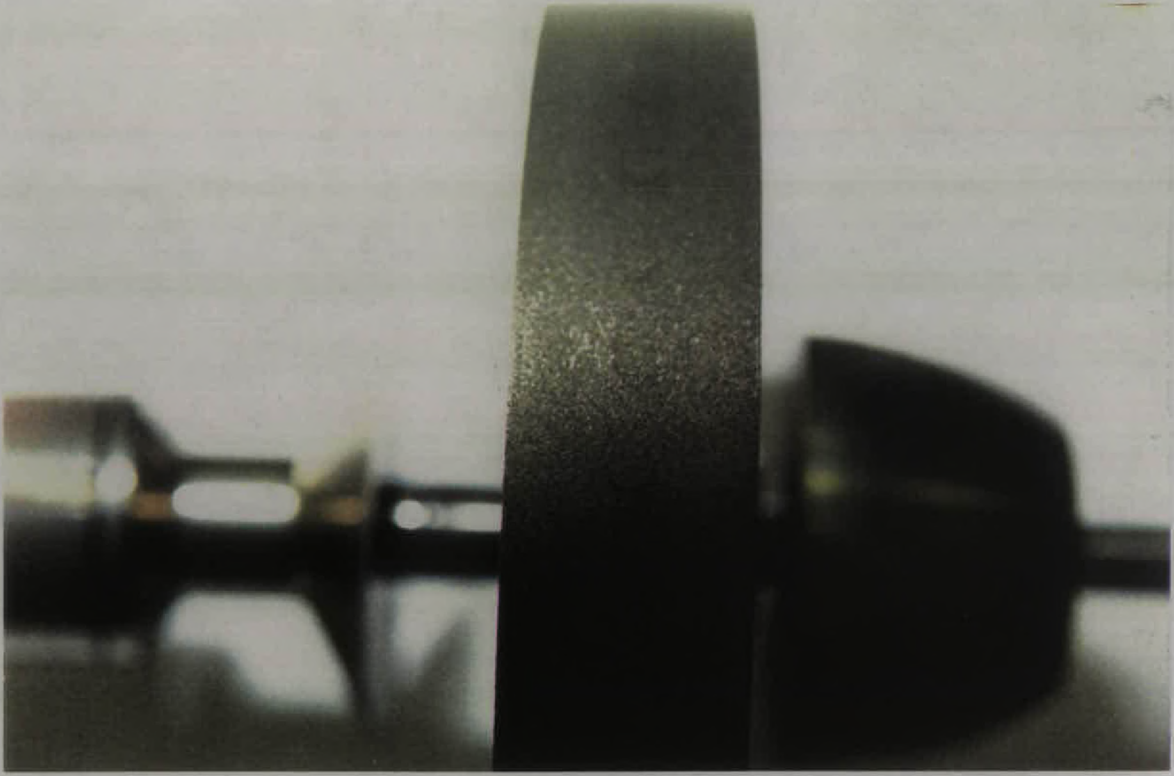
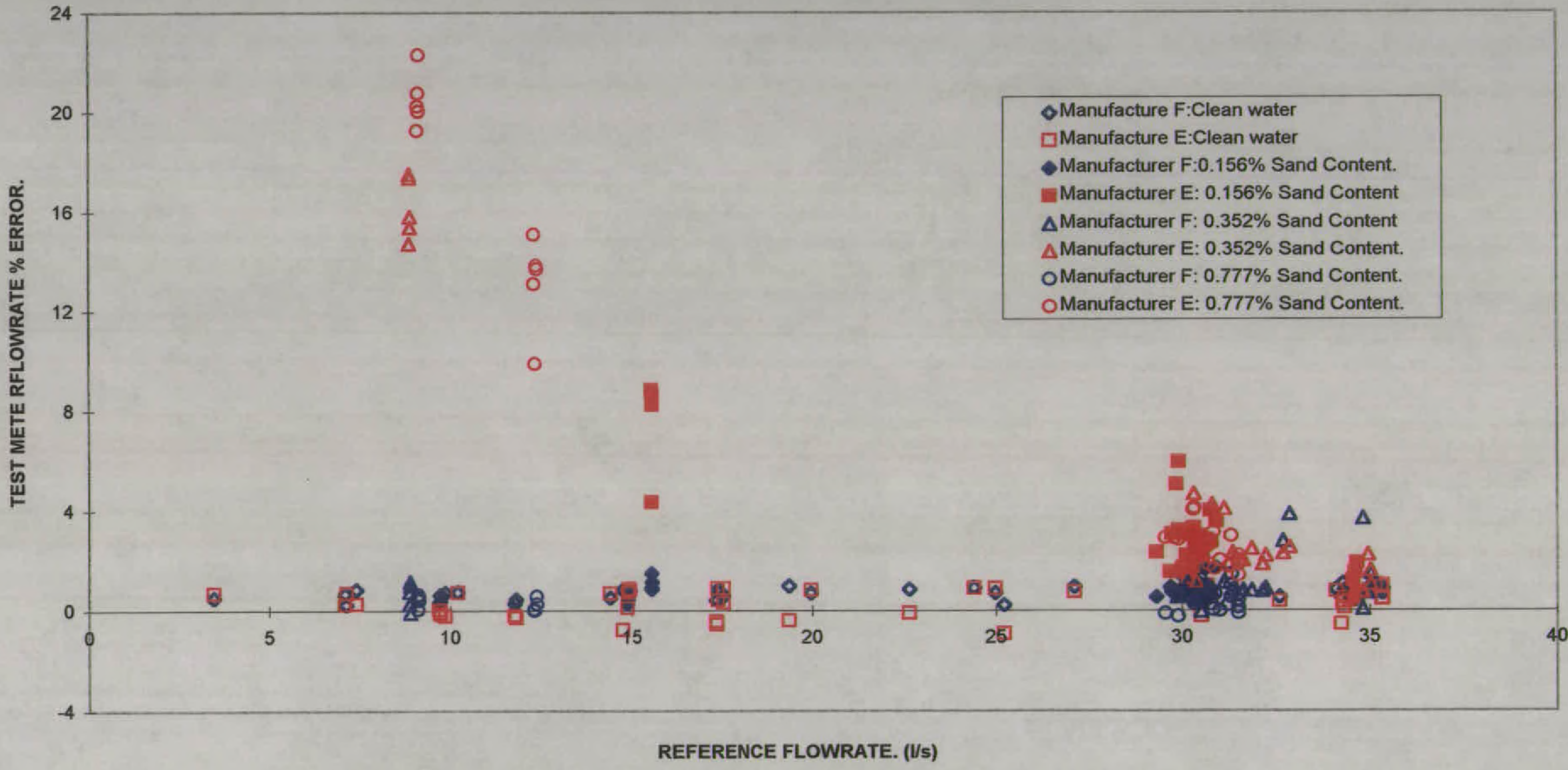


Fig 18 MANUFACTURER C. 100 mm DIAMETER METER, ROTOR RING WEAR

Fig 19 MANUFACTURER C. 100 mm DIAMETER METER, METER BORE WEAR

Fig. 20: CORIOLIS MASS AND WEDGE METER DATA
COMPARED TO REFERENCE FLOWMETER.



References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.