OPTIMAL FLOW CONDITIONER

by

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C O N T E N T S

1 INTRODUCTION

The Central Area Transmission System (CATS) is a North Sea pipelin development scheduled for operation in April 1993. The pipeline i 400 kilometers long and 36 inches in diameter capable of transporting up to 1.4 billion standard cubic feet of gas per day The gas is delivered to Teesside, England to fuel a new combinec cycle heat and power station being constructed by Teesside Power Limited. Amoco-operated gas fields (Everest and Lomond) will flc 300 million SCFD which is only 21 per cent of the total pipeline capacity.

This excess capacity along with the connectors that have been built into the pipeline will allow other gas fields to tie into the line and act as a common transportation system for any newly developed gas fields.

Amoco is committed to accurate natural gas measurement throughout the CATS system both onshore and offshore as it is essential for an equitable financial allocation. Accurate and consistent orifice metering relies on a fully developed velocity profile, free of swirl at the upstream plane of the orifice plate. In order to achieve this objective of accurate gas measurement, Amoco intends to install (and also intends to require all third party pipeline entrants to install) flow conditioner devices upstream of all meters critical to sales and allocation, both onshore and offshore.

2 CATS METERING DESIGN

In an effort to meet the appropriate metering standards and guidelines set forth for Licensees and Operators in the UK Continental Shelf and provide the safest possible equipment and operating procedures consistent with the Cullen Report, Amoco CATS project group has designed each offshore gas metering system with three (3), single chambered type orifice fittings sized so that any single meter may be serviced during any expected flowing conditions. This design philosophy incorporates an 18 inch header with 10 inch branch connections (1.7 to 1 reduction in diameter) for each meter run.

ISO 5167: 1980, Section 6 'Installation Requirements' requires that an orifice flow measuring device be installed in the pipe-line at a position such that the flow conditions immediately upstream approach those of a fully developed profile and are free from swirl as described in Section 6.4. These conditions are deemed to exist when straight pipe of a certain length separate the orifice plate from the nearest upstream and downstream flow disturbances. Section 6.2 provides the minimum straight lengths of pipe required between the orifice plate and various fittings such as single bends, combination of bends, reducers and expanders, fully open globe and gate valves and abrupt reductions from large vessels. Although it is extremely common to design meter stations with multi-tube header arrangements, due to operating conditions and economics of design, there is no mention of this configuration in this section leaving the Licensee with the task of trying to 'interpret' the standard, subject to government bodies approval, when installing any header arrangement. Section 6.3 of the Standards recommends that particular types of flow straightening devices can be used to permit the installation of a flow measuring device downstream of fittings not listed above. However it also specifies a minimum overall length of 42 diameters shall be used for all straightening devices unless the conditions stated in Section 6.4 are met. This generally discourages the use of conditioners as it invariably requires longer (rather than shorter as expected) upstream run lengths or an expensive and time consuming test to demonstrate compliance with Section 6.4.

After considerable research into recent developments in the field of flow straighteners and conditioners for orifice meters, Amoco proposed an optimum installation design for the upstream meter tube length and straightener location as shown in the meter layout in Fig. 1 (29 diameters (D) overall upstream with the straightening device at 10D from the closest disturbance). The metering design has an upstream configuration consisting of a 12-inch vertical (down) inlet into a 18-inch horizontal header with three 10-inch meter tubes off branch type connections. Each meter tube is constructed with two matched bore valves (10D total), a flanged type flow straightening or conditioning device, a straight section of 17-19 pipe diameters (depending on the straightening device length) and a flange neck single chambered orifice fitting.

3 TEST PIPE ARRANGEMENT

A drawing of the test pipe is shown in Fig. 2 and a photograph of the pipe in Fig. 3. The test pipe was designed for maximum flexibility in testing by using several doweled flanges for precise alignment. The design allows the flow conditions to be measured at up to seven pitot locations (6D, 7D, 9D, 10D, 13D, 16D and 19D) downstream of the flanges holding the conditioner (from the upstream end of the respective conditioner to the centreline of the pitot/ orifice plate). The 19D location corresponded to Amoco's proposed metering system design.

The traversing pitot companion flanges were modified orifice flange unions designed so that the pitot ring holder was centred in the pipe without any gap, step or offset from the pipe wall and the pitot was perpendicular to the flow. Each set of test flanges was designed for precise alignment with or without the pitot installed. The test pipe was designed to meet the pressure requirements (70 bar) at the Bishop Auckland facility and the 12-inch inlet and outlet flanges are in the same plane and elevation.

The test pipe was carefully selected so that is was as concentric as commercially available with consistent roughness to meet normal ISO 5167 requirements. The flanges and ring were machined to best fit the pipe. The companion orifice flange unions were machined and dowelled for near perfect alignment regardless of the arrangement of the conditioners or pitot. Spacers (12 mm thick by 10.060 ID) with standard 'O-ring' seals were placed between all flanges not holding the pitot or conditioner so that there was a smooth transition, free of gaps or intrusions, throughout the entire pipe section.

For determination of the unrecovered pressure drop across the straightener or conditioner, taps were provided at 1D upstream and 7D downstream of the upstream face of the device. For the determination of density, a 1/2-inch BSP connection was provided 7D downstream of the 19D flange location (for temperature measurement) and a static pressure tapping was provided on each of the flanges.

Pipe Measurements. NEL Metrology Section inspected and measured[1] the test pipe and pitot carrier ring internal diameters and the relative roughness of the pipe bore. A total of 75 roughness and 132 diameter measurements were taken throughout the test pipe section. The pitot ring internal diameter was measured with the same instrument at four diameters with an average of 10.060-inch. The test pipe was found to be consistently round and adjacent flanges within 0.002-inch of the pitot diameter.

The pipe relative roughness was measured using a portable surface texture measuring instrument after a calibration check using the 'calibrated scratch pad' (239 microinch per inch). These measurements were taken at three radial positions in 25 different planes for a total of 75 readings along the pipe at one diameter (10-inch) increments from 2 1/2 diameters upstream of the conditioner to 2 1/2 diameters downstream of the last pitot device. The average of the relative roughness measurements was 150, and the mean, 123.5 microinch per inch with only four readings above 300 (two of which were in a hand-ground region).

The pipe internal diameter was measured over the same region of pipe with one additional radial reading (four per plane) plus additional planes, one inch into the flanges between pipe spools, for a total of 33 planes or 132 diameters. The mean of the diameter readings was 10.0626-inch with a single standard deviation of 0.0100-inch. When only measurements in the flanges were considered (adjacent to pitot ring), the average was 10.0572-inch. The pitot ring was machined for 10.060-inch pipe relating to an average step change at the pitot ring of 0.0014-inch or about 1/10000 of the pipe diameter.

In order to protect the pipe from corrosion during shipment, a rust inhibitor was applied to the internal surfaces. All internal measurements were taken prior to the application of rust inhibitor. The inhibitor was removed with white spirit prior to testing at NEL and the process again repeated before transit to and from the British Gas test site.

Flow Conditioners. The following four flow straighteners or conditioners (all designed to be held between 10-inch 600# ANSI Raised Face flanges) were tested.

a Conventional 19 tube 2D long Short Tube Bundle (Fig. 4).

b Zanker (1D long) constructed to ISO 5167 requirements (Fig. 5).

c Laws Conditioning Plate (University of Salford) (Fig. 6). A perforated plate flow conditioner with an open area or porosity of about 51.5 per cent.

d K-Lab Mark 5 Conditioning Plate (Confidential).

Pitot Tube. The single traverse assembly unit (Fig. 7), designed by Gasunie for the EEC orifice discharge coefficient tests, incorporated a constant blockage swirl angle and impact ressure probe. Pitot side pressure sensors were located ±40° from the centre impact pressure sensor. The device was installed between modified orifice flange unions designed to enable it to be centred in the pipe, without any gap, step or offset from the pipe wall, and perpendicular to the flow. Before each new installation the pitot ring was centred on the outer diameter of the companion flanges using adjustable matched 'tee blocks', such that no internal offset could be detected visually or by touch.

4 NEL TESTS

The main objective of the tests was to determine the optimum location of various flow conditioning and straightening devices within the upstream orifice meter tube and to verify that the velocity profile and swirl components of the installation were within the specified limits set out in ISO 5167, Paragraph 6.4. In order to establish the amount of swirl generated by the header configuration and the effectiveness of the conditioners, flow profiles were measured at OD and 19D without any flow conditioner installed. After the profile tests were completed the discharge coefficient of a nominal 0.6 diameter ratio orifice plate was measured with the Laws and Tube bundle conditioners in the test line. Selection of the various test configurations, by Amoco, were based on data from the conditioner plates designers, published papers and Amoco's own research and design expertise.

The face of the flange located 10D from the header to branch connection was chosen as the datum from which the positions of the flow conditioners were measured. Since the overall length of the various flow conditioners varied from 0.12D to 2D the distance between the conditioner and pitot was measured from the face of the conditioner flange. The majority of the tests were conducted with a flow conditioner (with its flange upstream) installed at the datum pipe flange; exceptions to this were the K-Lab device at 6D and the tube bundle at 13D as mentioned below. For each test, the pitot device was moved to a position representing a possible orifice plate location.

Pitot traverses were conducted in the vertical and horizontal planes; with negative radius ratios corresponding to the bottom or left-hand pipe wall (looking downstream) respectively. The swirl angle was measured by rotating the pitot tube until the differential pressure, across the side pressure sensors, was zero; the angular rotation of the tube representing the swirl angle. The impact pressure was then measured at that angle with the central pitot orifice since it represented the peak impact pressure. Any offset (bias) of indicated swirl angle at the centreline was subtracted from the other readings as the actual swirl angle was assumed to be zero at the centreline of the pipe.

For the profile tests the mass flow through the test rig was held constant during each traverse. The first flow conditioner to be tested was the tube bundle and the flowrate was set to give the maximum possible Reynolds number; the K-Lab and Zanker devices, having greater pressure losses, had to be tested at lower flowrates, the Laws device was tested at the same flowrate as the K-Lab. During the orifice plate tests the flow was varied between the minimum and maximum rate attainable.

The reference flowrate was measured by a venturi meter. Air temperature at the outlet of the flowmeter and test section were measured by platinum resistance thermometers together with a precision thermometer digital readout. The static and differential pressures at the flowmeter and pitot were measured by Rosemount pressure transmitters and the barometric pressure by a precision quartz pressure gauge. The calibration of the reference flowmeter and all recorded measurements are traceable to national standards.

Data from the pressure transmitters and resistance thermometers was collected by a data logging system controlled by a PC. Pressure readings were integrated over a ten second period, the average of five periods were used for each test point: single temperature readings were recorded within the same time period.

5 NEL TEST RESULTS

The results of the NEL profile tests are given in Figs 8 to 19. Each figure shows the traverse results compared with the theoretical flow profile (using $n = 9.9$, see Appendix), with ±5 per cent error bands; the corrected swirl angle is also shown. The overall accuracy of the pitot determination of swirl angle is estimated to be less than ±0.75 degree including dead band and mechanical hysteresis.

The velocity calculated from the pitot differential pressure was corrected for compressibility using:

$$V_c = V\left[\left(\frac{\gamma}{1-\gamma}\right)\frac{P_1}{\delta p}\left(\left[\frac{\delta p}{P_1}+1\right]^{\frac{(\gamma-1)}{\gamma}}-1\right)\right]^{\frac{1}{2}}$$

where V is pitot velocity, δp and P_1 are the pitot differential and inlet pressures and γ is the isentropic component for air.

The velocity ratio, V_R, (point velocity, V_c, to centreline velocity, V_{CL}) was rationalised with respect to the volume flow associated with the centreline velocity, ie

$$V_R = \frac{Q_{CL}}{Q} \times \frac{V_C}{V_{CL}}$$

No Flow Conditioner. Figs 8 and 9 shows that the velocity profiles at both positions were significantly inverted. The maximum swirl angle at the 0D position was found to be 24 degrees with 20 degrees of swirl remaining at the 19D position. The initial test (0D) demonstrated flowing conditions at the flow conditioner inlet. The second test (19D) approximates flowing conditions for a common North Sea installation without a flow conditioner, that is, in general accord with ISO 5167 design criteria of 30 diameters downstream of a 2 to 1 header to branch connection.

Zanker Flow Conditioner. The velocity profile from the Zanker was examined only at the 19D position (Fig. 10). Although it produced a reasonable velocity profile it did not remove enough of the swirl, a total of approximately five degree remained in both the horizontal and vertical planes. The profile produced was a bit flat and somewhat asymmetric.

K-Lab Flow Conditioner. The K-Lab flow conditioner was tested with the pitot at 6D and 19D from the datum pipe flange (Figs 11 and 12). At 6D the device was installed in reverse with it's datum face downstream allowing a full 6D between the end of the device and the traverse plane. The measured profile was flat compared to the theoretical profile and slightly more than one degree of swirl remained. At 19D, the remaining swirl was similar but the flow profile was nearer the theoretical prediction but slightly asymmetric in the vertical plane such that the end points were outwith the five per cent limit.

E. Laws Flow Conditioner. The flow profile was examined at three positions: 6, 9, and 19 diameters downstream of the conditioner (Figs 13 to 15). Since the length of this device was so short it was not reversed as was the K-Lab conditioner. The profile at 6D was rather flat and slightly asymmetric with a maximum swirl angle of about one degree. The asymmetry caused the profile to be greater than five per cent above the theoretical profile near the wall of the pipe. At 9D, the overall swirl angle was similar and the flow profile was slightly improved so that it was just on the five per cent limit. The swirl angle remained practically unchanged at 19D, and the flow profile was well within five per cent of the theoretical profile.

Tube Bundle. The flow profile was examined at four positions measured from the datum flange of the conditioner: 9D, 13D, 13D-Reversed (13DR) and 19D (Figs 16 to 19). In the 13D-Reversed position the tube bundle was installed in reverse in a 3D pipespool so that the inlet of the conditioner was 1D downstream of the datum pipe flange and the pitot 13D downstream of the datum face of the conditioner. Thus for these four configurations the pitot was 7D, 11D, 13 D and 17D respectively, from the downstream end of the bundle. At all of the locations the maximum swirl angle was less than one degree.

At 9D the flow profile deviated significantly from the theoretical profile and the outer annular portion exceeded the mid 25 per cent to produce an inverted or collapsed profile.

The 13D velocity profile exhibited slight inversion and moderate asymmetry, but exceeded the profile limits. This configuration had the least swirl of any of the flow conditioners evaluated. At 13DR (26D overall), the asymmetry was significantly less than at 13D but the profile still departed from the theoretical, but to a lesser degree. In this configuration the swirl angle increased only slightly.

At 19D the profile was nearer the theoretical than at the other locations but still exceeded the five per cent criteria at radius ratios between 0.5-0.8. The swirl angle near the edge of the pipe began to increase but did not exceed two degrees.

Pressure Drop. The pressure drop for each device, recorded during the test, is shown in Fig. 20. The tube bundle displayed the lowest loss of less than one velocity head and the Laws was next with less than two.

Coefficient of Discharge (C_d) Tests. Orifice discharge coefficient tests, using a 0.597 beta ratio orifice plate in two positions, were conducted with the Laws and tube bundle conditioners. The plate was manufactured to ISO 5167 specifications, and the edge sharpness and internal diameter measurements were checked by the Metrology Section of NEL. Each test consisted of a Cd at five flow rates; the results, compared with the NEL standard Cd equation[2], are shown in Figs 21 to 24.

The Laws conditioner was tested with the orifice plate 9 and 19 diameters downstream (19D and 29D overall length). As expected, the test Cd results, Figs 21 and 22, are nearer the standard at the higher flow rates and larger Reynolds numbers. The results at 9D are slightly better than those at I9D.

The tube bundle was tested with the plate in the 13D and 13D-Reversed positions downstream (23D and 24D overall). The 13D position, Fig. 23, produced the Cd results most near the NEL standard (within 0.25 per cent). Overall, the 13D tube bundle Cd was closer to the NEL prediction than the Laws at I9D. The Laws at 9D and tube bundle at 13D produced similar results at the larger Reynolds numbers.

6 HIGH PRESSURE NATURAL GAS TEST

Based on the NEL low pressure air results, a short list of optimum conditioners were chosen for the high pressure (850 psi) natural gas test at British Gas' Bishop Auckland facility. The flow conditioners and their respective locations chosen for the second phase of testing at Bishop Auckland were: E. Laws at 9D and 19D and the tube bundle at 13D and 19D.

Note: For these tests, the pitot device was fixed at the 29D flange location so that the length upstream of the conditioner device changed (increased) instead of the overall length.

At NEL, the different test locations were achieved by moving the pitot closer to the conditioner with the conditioner fixed at the 10D location except for the tube bundle at the 13D Reversed position).

__Profile Tests__ Tests were conducted at three flow rates with approximate pipe Reynolds Numbers of 5,000,000, 10,000,000 and 12,500,000 (CATS Everest and Lomond normal maximum is about 10,000,000. Gas samples were taken after each test for an average composition.

In general, the velocity profile data obtained from the HP natural gas tests did not vary significantly from the NEL LP air tests. The tube bundle profile data remained relatively flat while removing swirl to about 1 degree or less. The E Laws device at 19D (Figure 26) yielded the velocity profile closest to the theoretical.

__Discharge Coefficient Tests.__ Using the same plate tested at NEL (beta = 0.597), discharge coefficient tests were conducted with the E. Laws device at 9D and 19D and the tube bundle at 13D and comparisons made to the ISO or Stoltz equation. Each coefficient test consisted of three points at four flow rates between 5,000,000 and 10,000,000 Reynolds Number.

Although the precision of the individual coefficient tests is estimated to be no better than 0.3 per cent due to variations in natural gas composition found in the grid system, the data have been included in order to validate the profile tests. In order to minimise the effects of natural gas composition resulting in a density variation, three points are averaged at each flow rate for a single comparison point.

The Laws at 19D was within 0.2 per cent of the ISO equation at all four test points and within 0.1 per cent (Figure 27) in the Reynolds Number range of expected flowing conditions of CATS offshore meter systems. The discharge coefficient test with the E. Laws conditioner at the 9D location also yielded data within 0.1 per cent of the ISO equation (Figure 28).

7 CONCLUSIONS

- The header arrangement with vertical inlet and branch connections which is commonly used in North Sea gas metering stations is a significant swirl generator.

- The length of 10 inch commercially smooth, straight pipe installed downstream of the conventional header that would be required to reduce swirl to 2 degrees or less (per the intent of the standard) would far exceed the 30 diameters required in the standard.

- The tube bundle eliminates swirl almost completely but produces a much flatter velocity profile than that predicted by the theoretical power law equation.

- There is no appreciable Reynolds Number affect on the velocity profile or swirl angle as shown by the close correlation between the NEL Low Pressure air and British Gas High Pressure natural gas data.

- All of the conditioners tested eliminated the swirl to within the 2 degree criteria except for the Zanker.
- In general, the velocity profiles produced by all of the conditioners were more flat than the fully developed theoretical flow profile.

- The relationship between actual velocity profile and coefficient of discharge is not fully understood as shown by the tube bundle results which give a very flat profile (with deviation up to 10 per cent from the theoretical) at 13 diameters but produce orifice coefficients very close to predicted values in tests at NEL for a beta ratio of 0.6.

- The orifice coefficient tests at British Gas, although informative, have limitations due to the natural gas composition variations and other uncontrollable factors such as ambient conditions. It would seem appropriate to ascribe an uncertainty of 0.3 percent (for an individual test point) to the coefficient results. Averaging the points before comparison may reduce the effects significantly. This uncertainty does not apply to the velocity profile and swirl data as the results of these measurements are presented in relative terms.

- When installing orifice meters downstream of headers, the predicted orifice coefficients may be used with greater confidence if a flow conditioner is installed at the proper location.

- The installation requirements for flow conditioners set forth in ISO 5167 Section 6.3.1 exceed the actual requirements for custody transfer meters with a diameter ratio maximum of 0.6 when such orifice meters are downstream of common headers with branch connections.

- The minimal upstream installation piping required for conditioners downstream of headers for the tube bundle or perforated plate may be much shorter than tested herein as the inlet section (upstream of conditioner) could probably be reduced to three diameters (perforated plate) or five diameters (tube bundle) without affecting results.

  When additional data on the relationship between fully developed flow profiles and orifice discharge coefficients become available, the minimum length between the conditioner and the orifice plate may be further reduced such that the overall upstream meter tube section is no greater than 12 to 16 diameters when using conditioner plates or tube bundles.

- The Laws type flow conditioner performed best overall as it met the profile and swirl criteria set forth in ISO 5167 Section 6.4 and exhibited the lowest pressure drop of the perforated plates.

  The results of the discharge coefficient tests in high pressure natural gas with a 0.6 beta ratio installed 19D downstream of the Laws conditioner show good agreement with the ISO equation (within 0.1% at operating Reynolds number values) and provide significant additional evidence that the requirements of ISO 5167 can be met fully, using this conditioner configuration.

APPENDIX

Velocity Profile in Fully Developed Pipe Flow

In order to meet the requirements of Clause 6.4 of ISO 5167 it is necessary to determine what velocity profile would be obtained in swirl-free flow after a long straight length of pipe similar to that used in the tests. Schlichting[3] describes work of Nikuradse[4] who collected extensive data on velocity profiles in smooth pipes. His data can be represented by the empirical equation

$$\frac{u}{U} = \left(1 - \frac{r}{R}\right)^{\frac{1}{n}} \qquad (1)$$

where U is the pipe maximum axial velocity, R the pipe radius and u is the axial velocity at a point where the radial distance is r. This gives a good fit to experimental data, but there is no accurate theoretical way of determining n. In Nikuradse's data n ranged from 6.0 where the pipe Reynolds number, Re_D was 4000, to 10.0 where Re_D was 2.0×10^6 or 3.2×10^6.

The best method of determining n is to calculate it by fitting data whose Reynolds number is similar to that in the installation being tested for acceptability. Data collected in air at NEL[5] with $Re_D = 9 \times 10^5$, pipe diameter = 102 mm and 140D of straight pipe upstream were available: fitting these data using a least-squares fit gave n a 9.9.

One problem with the velocity profile in equation (1) is that it does not have a zero derivative on the pipe axis. To solve this problem the following was tried:

$$\frac{u}{U} = \begin{cases} a\left(1 - \frac{r}{R}\right)^{\frac{1}{n}}, & \frac{r}{R} > c \\ 1 - b\left(\frac{r}{R}\right)^2, & \frac{r}{R} \le c \end{cases} \qquad (2)$$

where a and b are chosen so that the equation both is continuous and has a continuous derivative at r/R = c. This equation has a zero derivative on the pipe axis and has a very similar behaviour to equation (1) in the neighbourhood of the wall. However, when the NEL air data in Ref. 5 were fitted there was almost no improvement in quality of fit from that obtained with equation (1); moreover n was almost unchanged.

Data, collected by British Gas, with a least 100D of upstream pipe in 250 mm pipe at $Re_D = 1.4 \times 10^7$ and in 600 mm pipe at $Re_D = 2.2 \times 10^7$, were included in reports to the EEC[6,7], but only in graphical form. The data, in tabular form, for the 600 mm pipe were obtained from British Gas.

Three sets of data were agailable, on two planes at $Re_D = 2.2 \times 10^7$, and on one plane at $Re_D = 8 \times 10^6$. Only the data at the higher Reynolds number have been analysed, since those at the lower have a maximum velocity two per cent higher than the centre-line velocity. The exponent n in equation (1) was obtained by using a least-squares fit to the data on each plane: on the 45 degree plane n = 9.7; on the 30 degree plane n = 10.1. This supports the use of the power law profile in equation (1) with n = 9.9 as a good representation of what the velocity profile would be after a long length of pipe at the Reynolds numbers encountered in both the air and gas tests. The 600 mm data have been plotted in Fig. 25 for comparison with equation (1) with n = 9.9 and it can be seen that there is good agreement.

Gasunie have also collected data downstream of 80D of 600 mm pipe[8] (including a full-bore ball valve 50D upstream of the measuring point) for Re_D from 2.5×10^6 to 5×10^7 and found that the profile can be described quite well with a power law and that n appeared to be around 10. The value of n is a little larger for higher Re_D than for lower.

From the data analysed the power low profile in equation (1) with n = 9.9 gives a good representation of what the velocity profile would be after a very long straight length of pipe at the Reynolds numbers encountered in both the air and the gas tests.

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LIST OF FIGURES

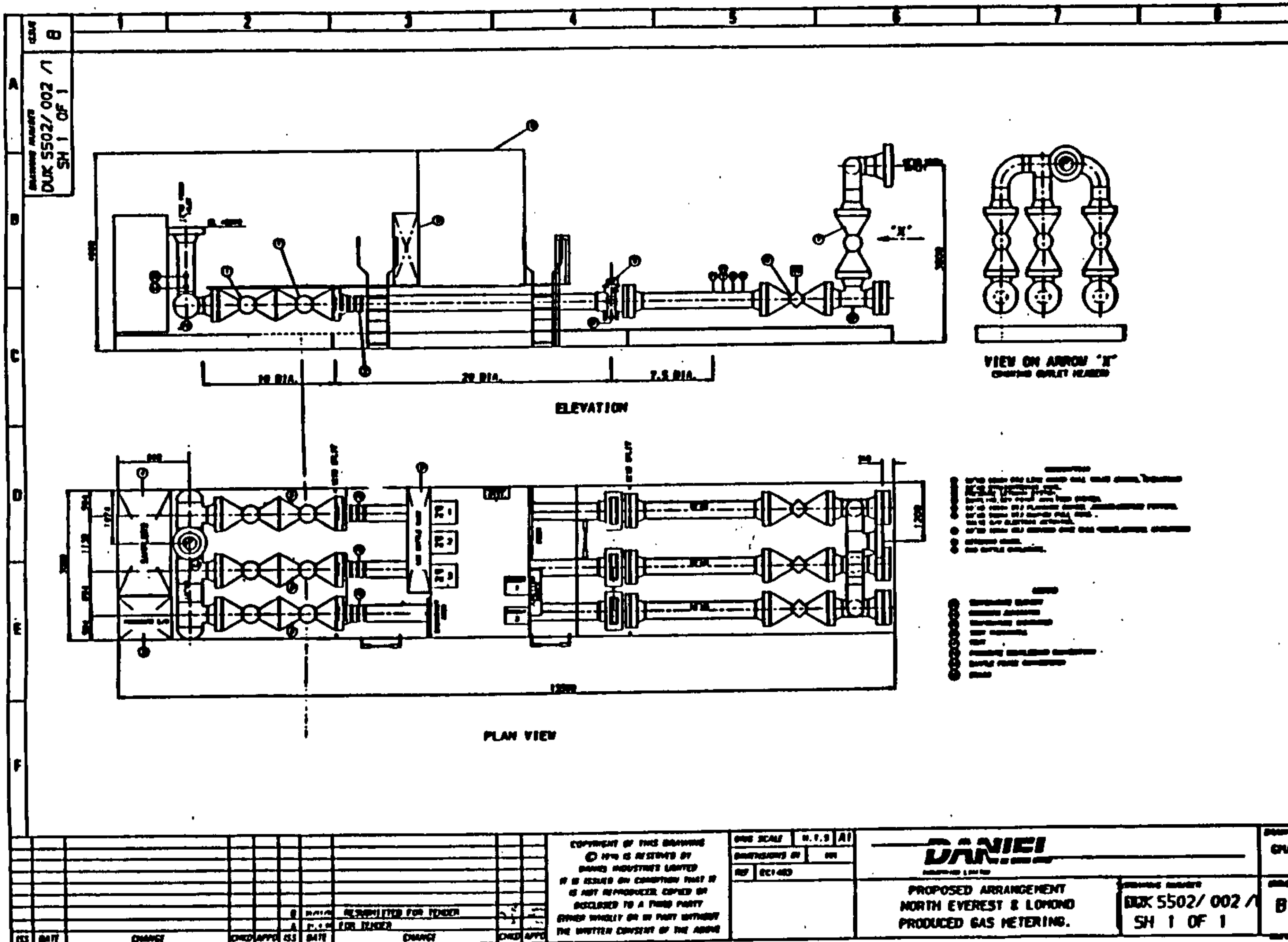


Fig. 1 Proposed Metering Station

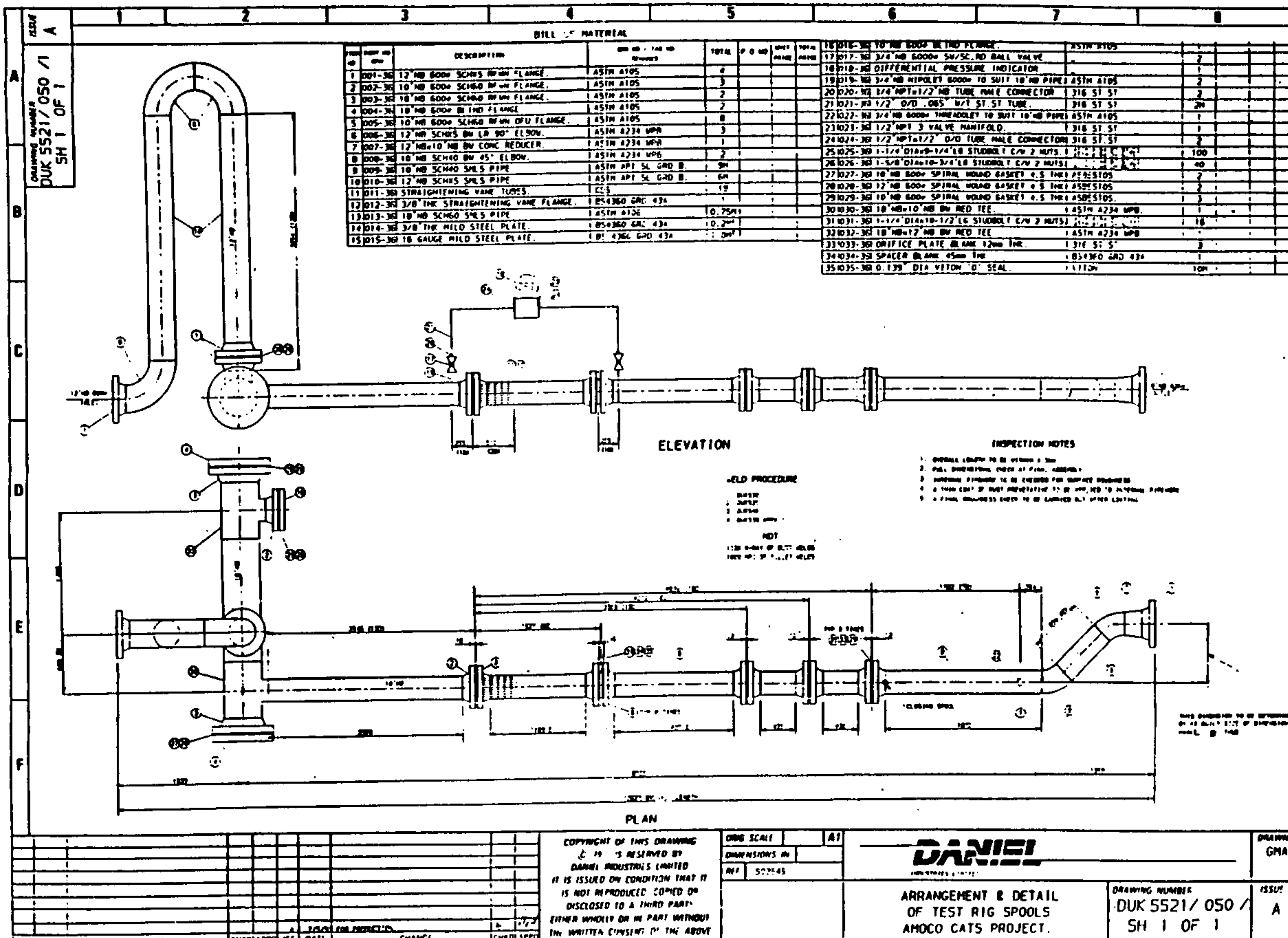


Fig. 2 Drawing of Test Pipe Arrangement

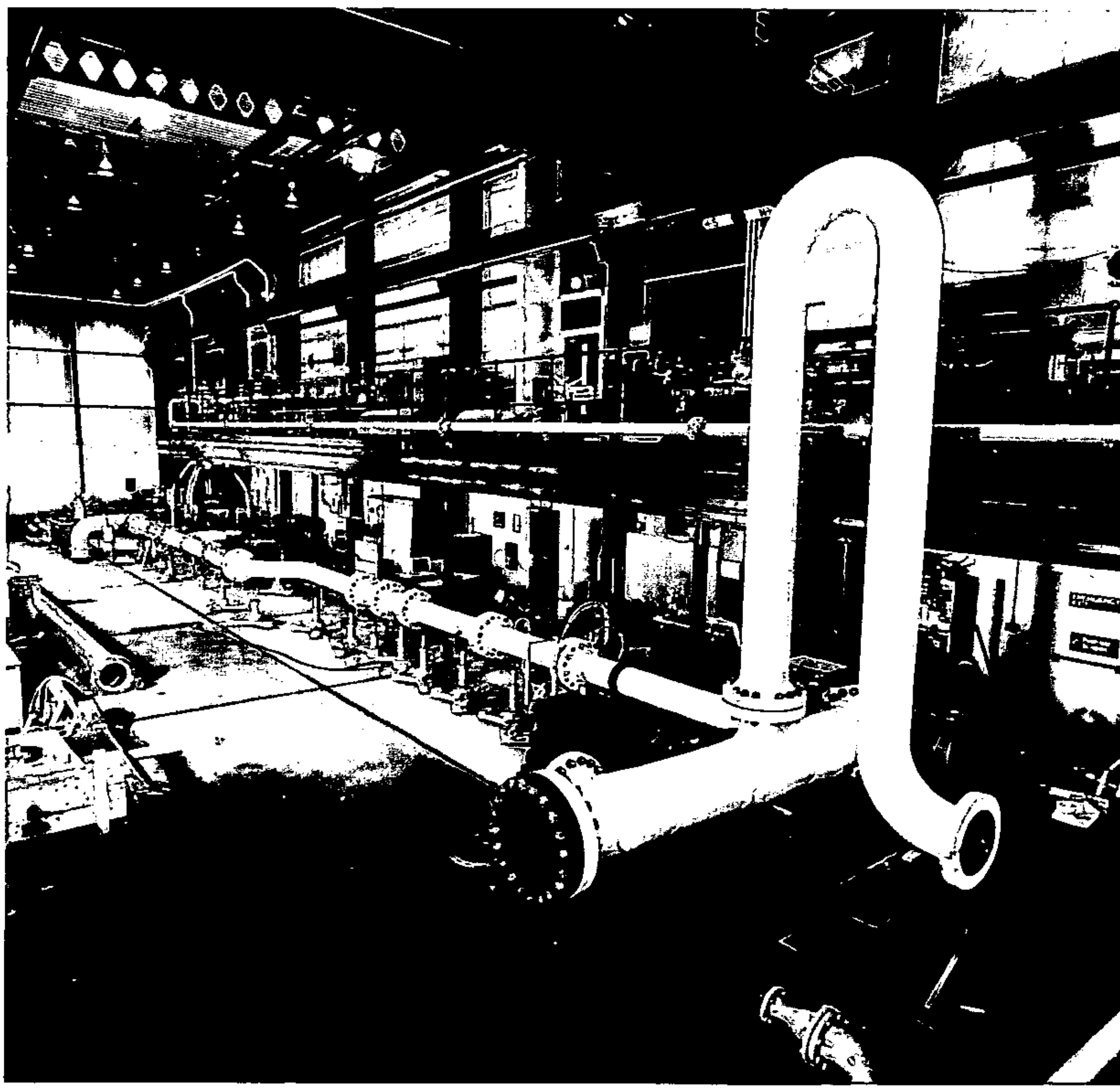


Fig. 3 Test Pipe

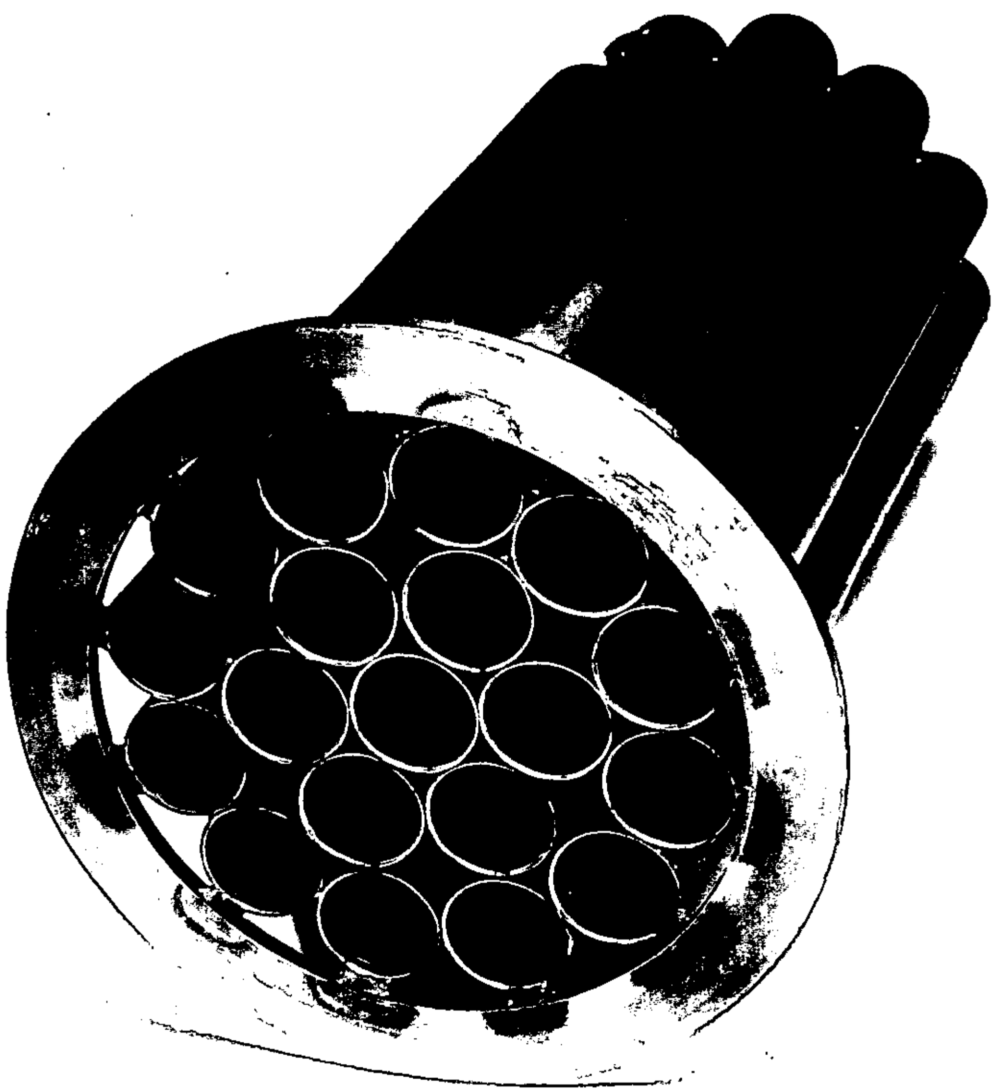


Fig. 4 Tube Bundle

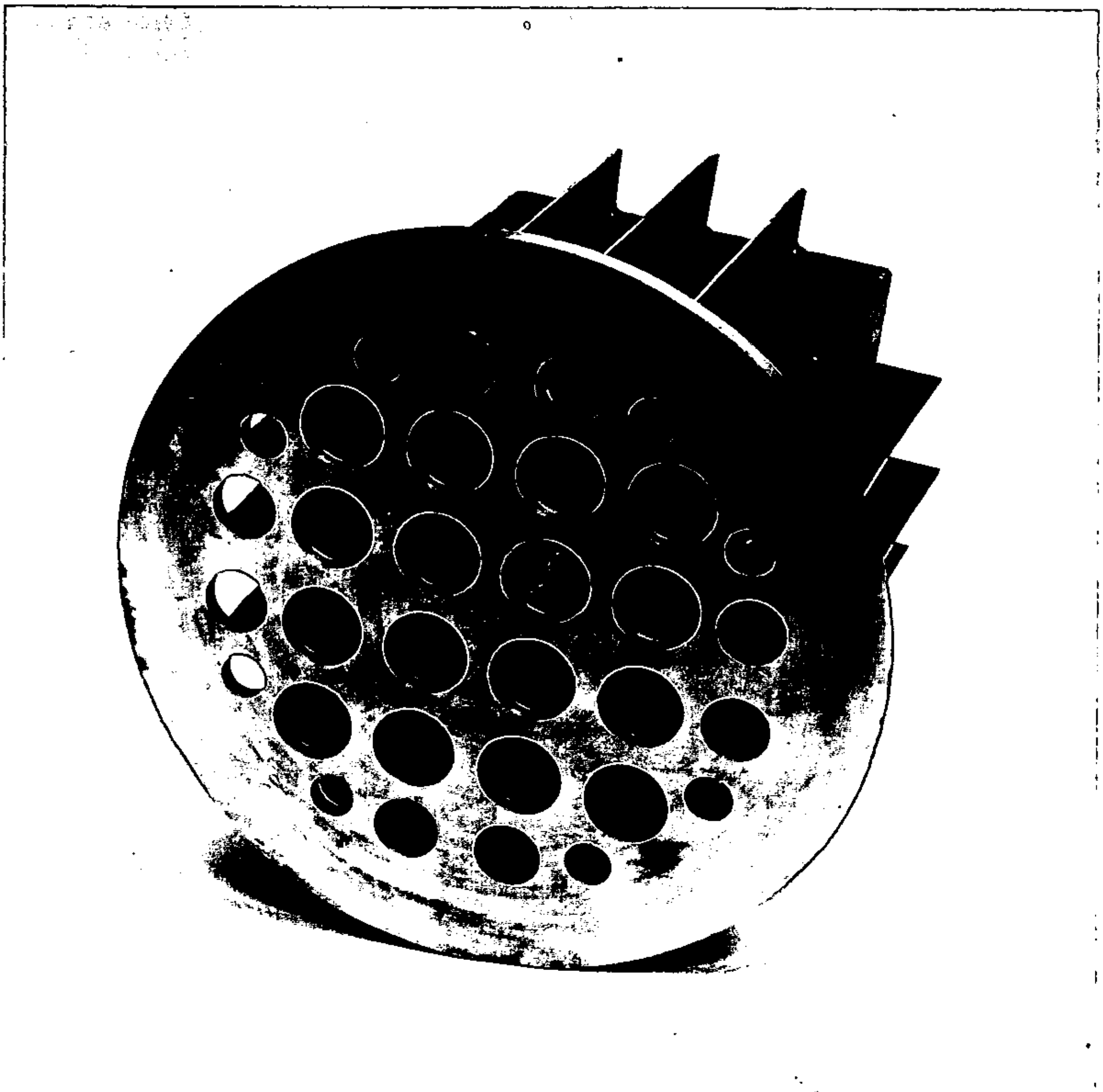


Fig. 5   Zanker Flow Straightener

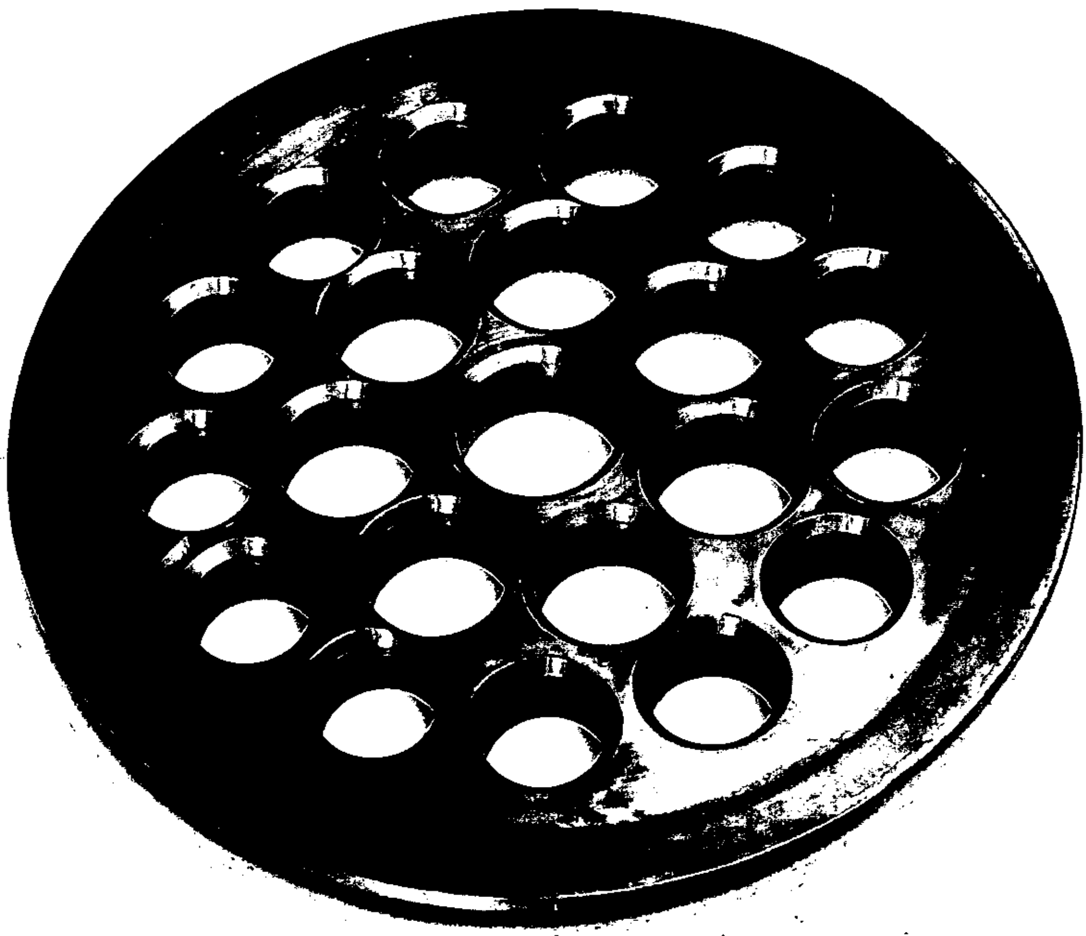


Fig. 6   Law Conditioner

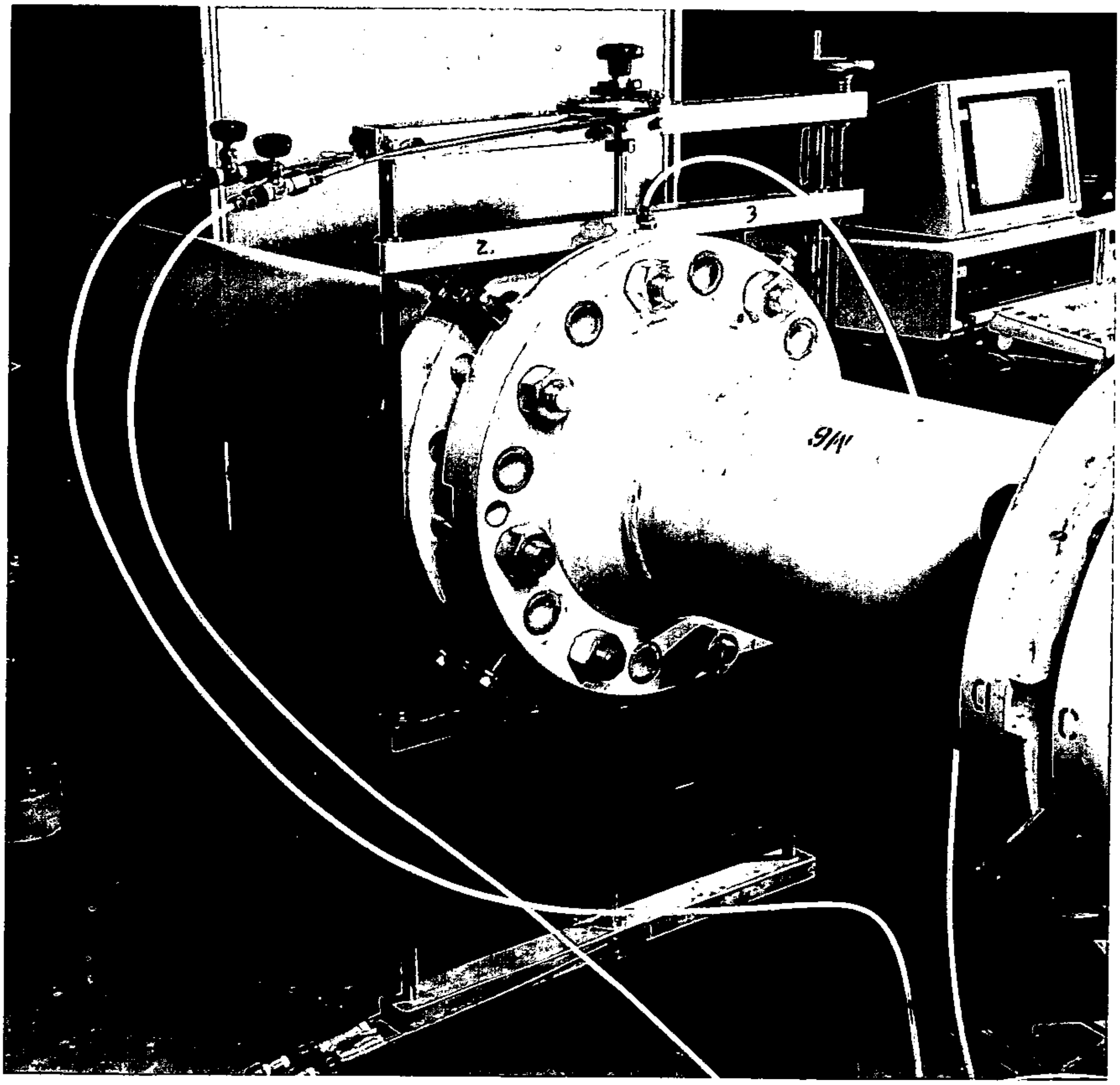


Fig. 7   Pitot Traverse Unit

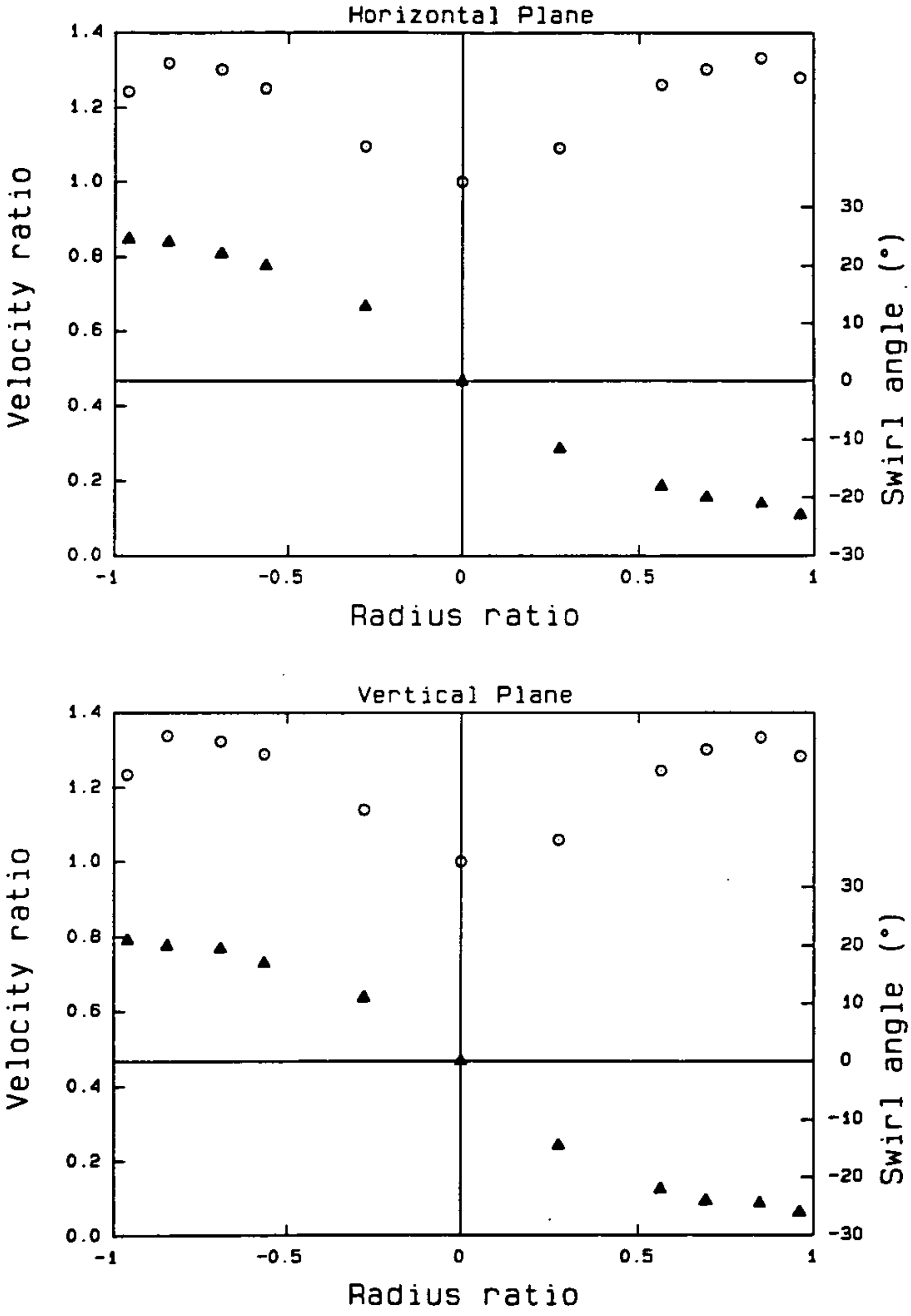
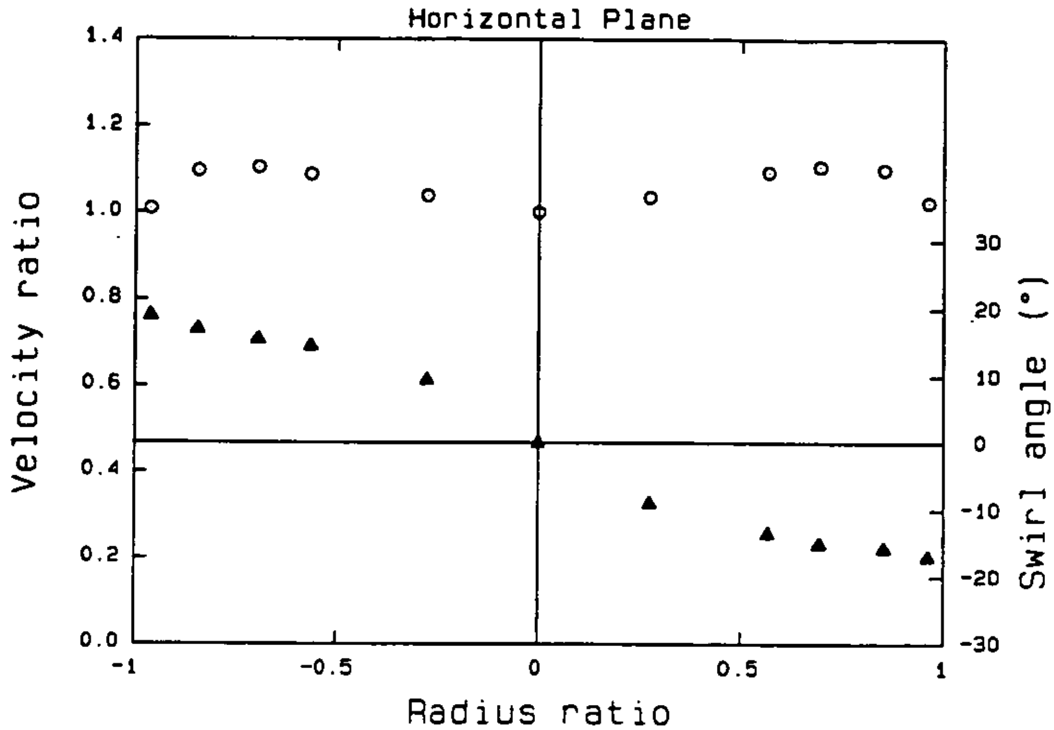


Fig 8 Profile at OD - No flow straightener



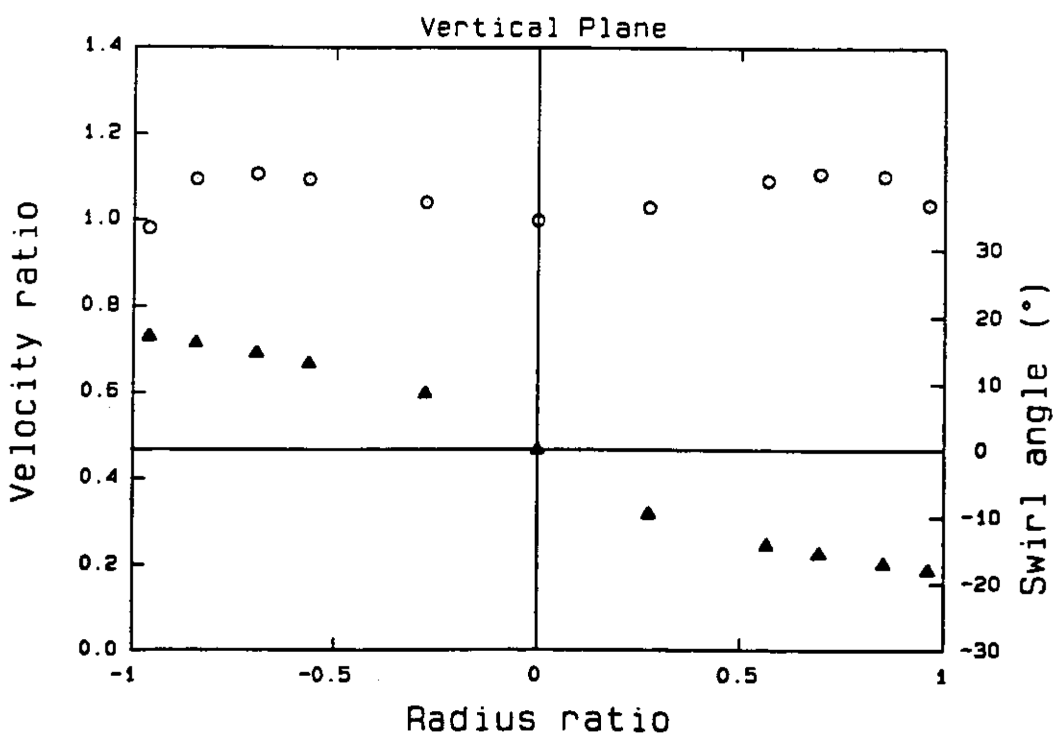


Fig 9 Profile at 19D - No flow straightener

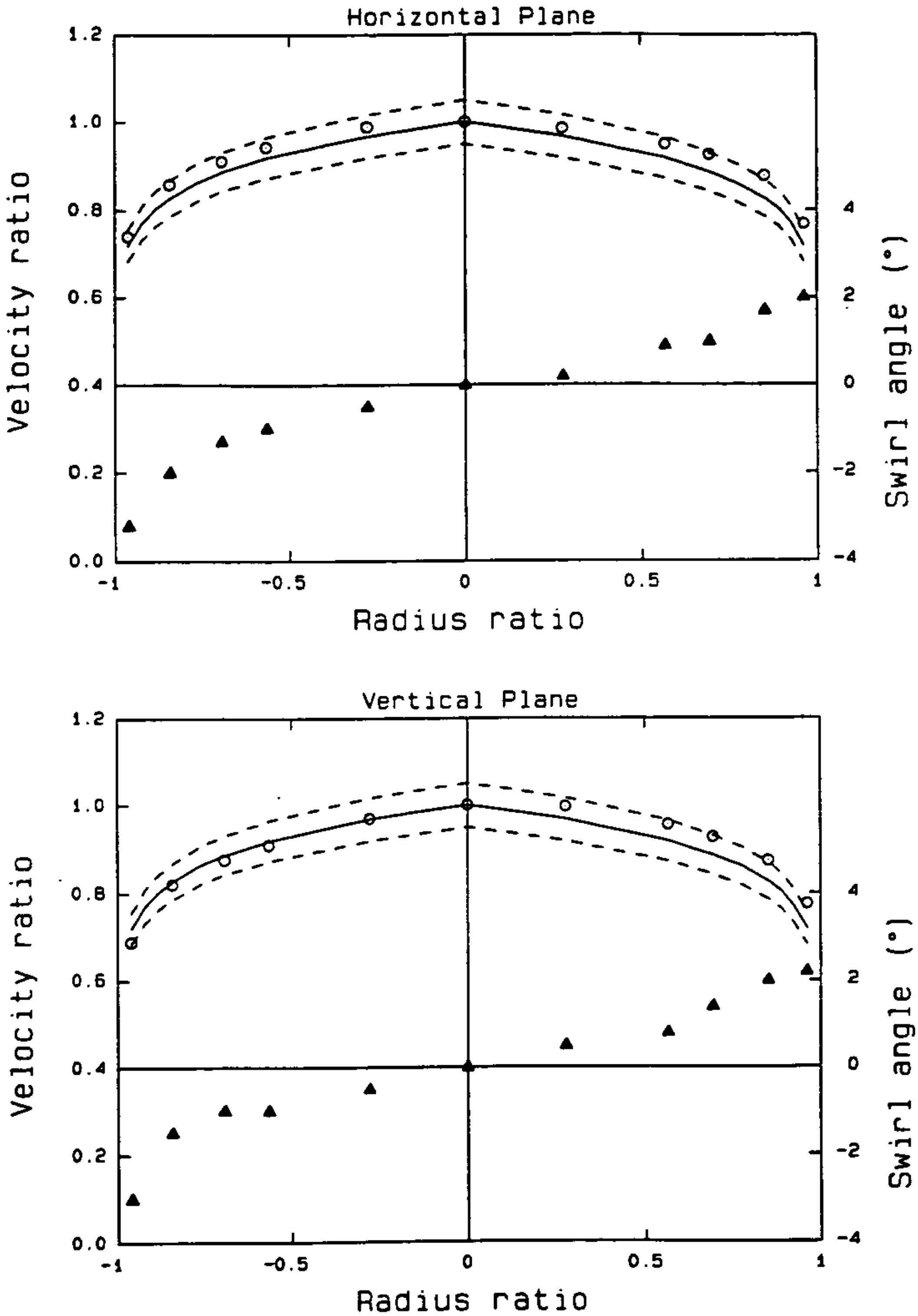


Fig 10 Zanker - Profile at 19D

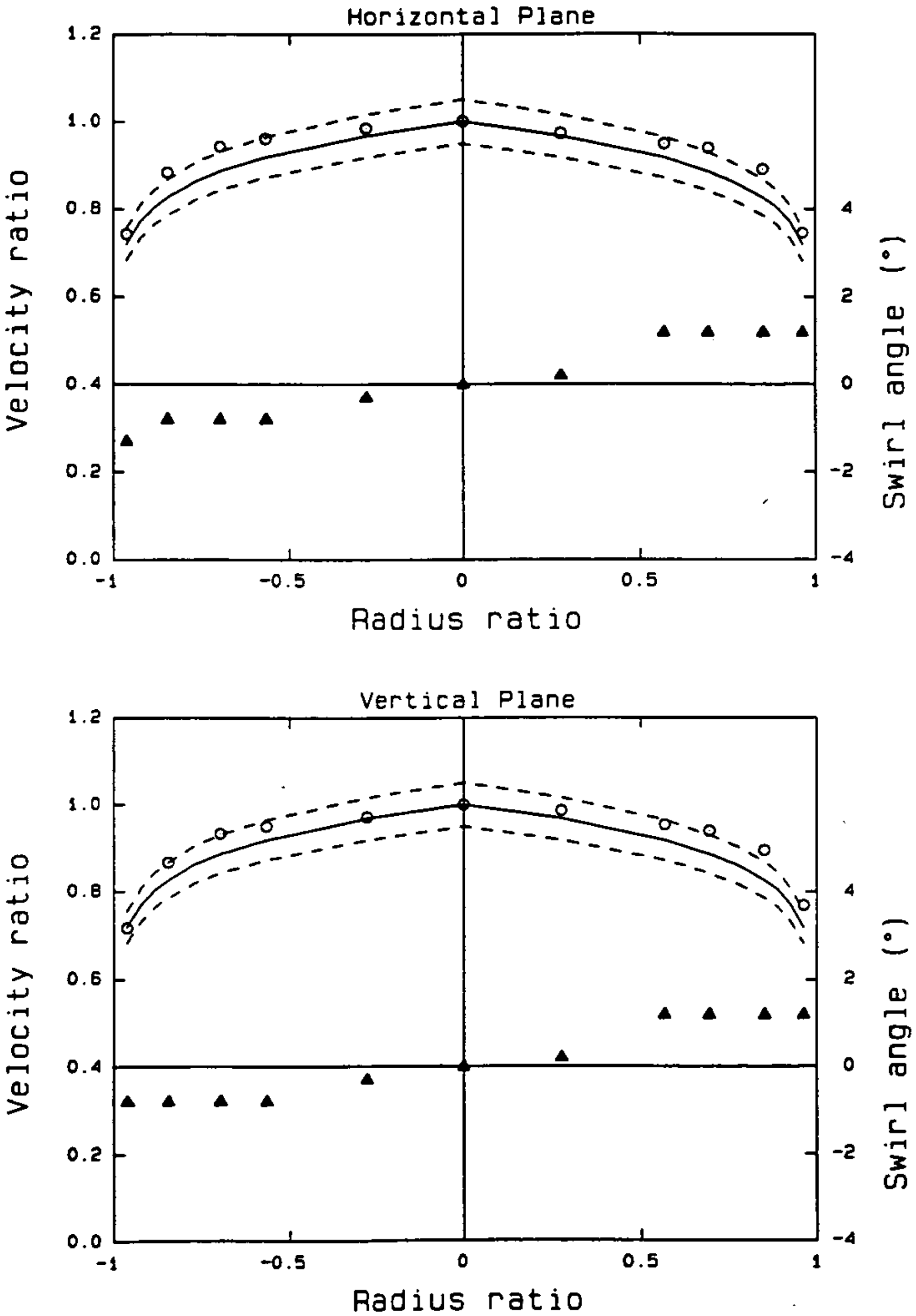


Fig 11   K-Lab - Profile at 6D

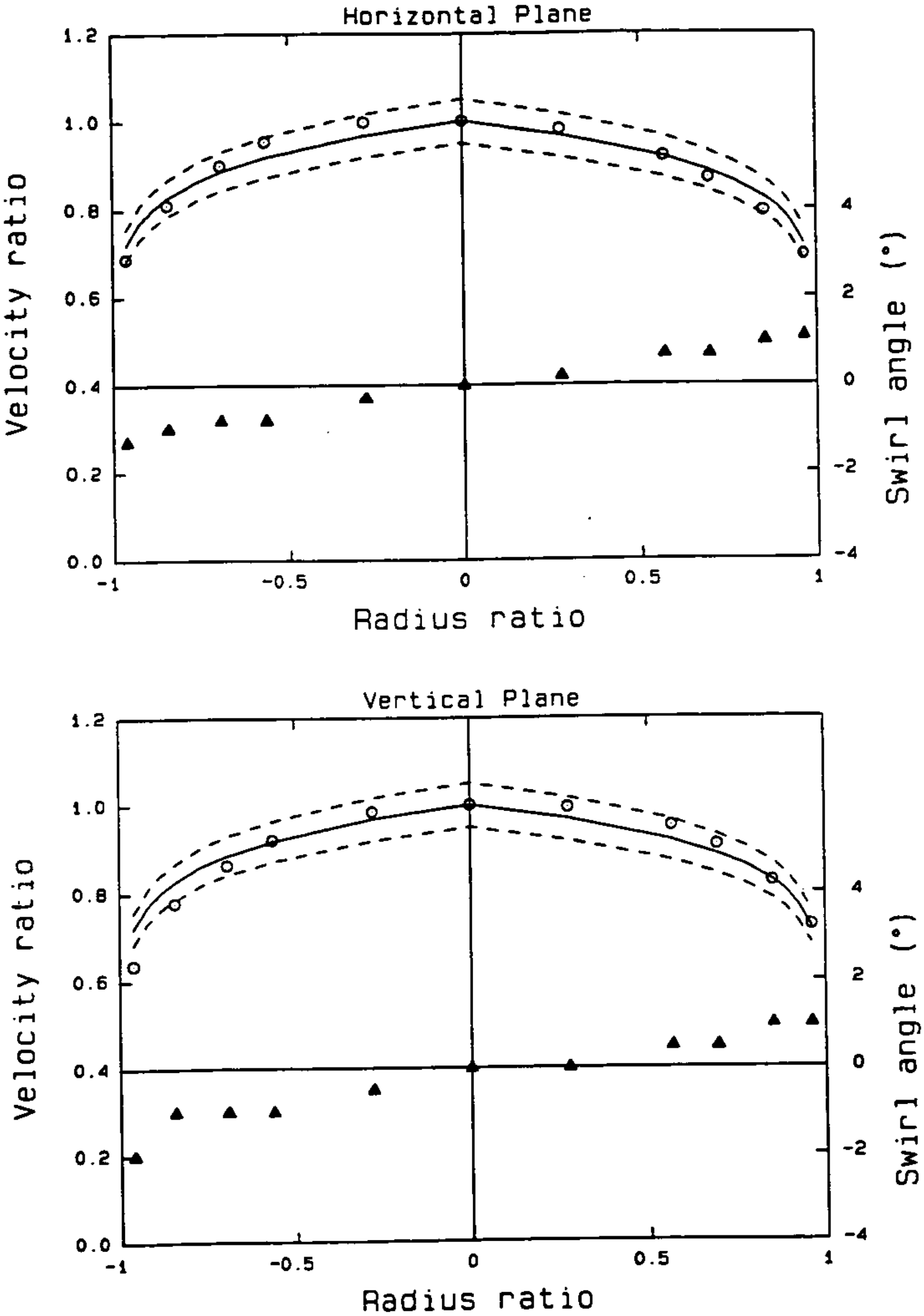


Fig 12 K-Lab - Profile at 19D

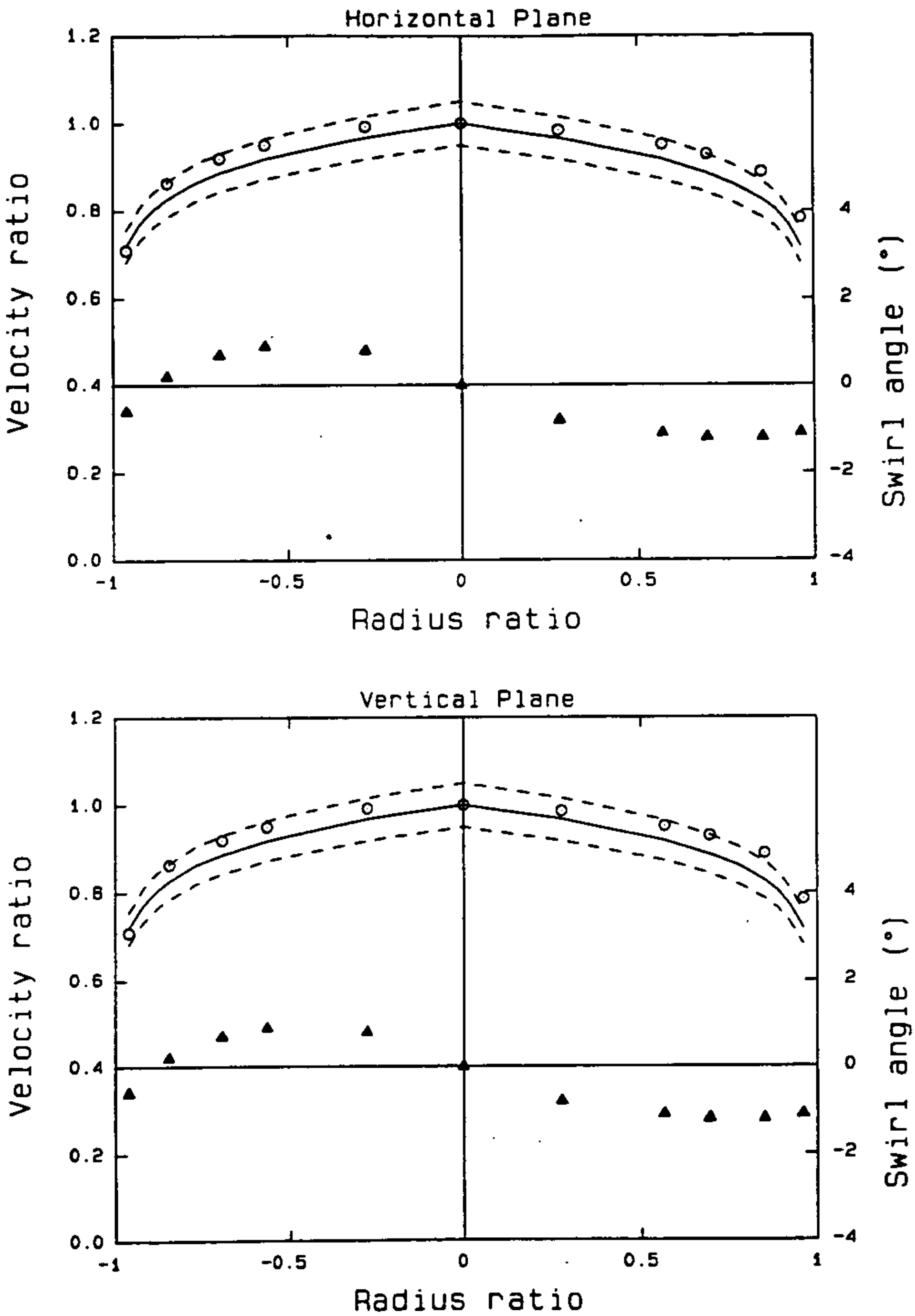


Fig 13 Laws - Profile at 6D

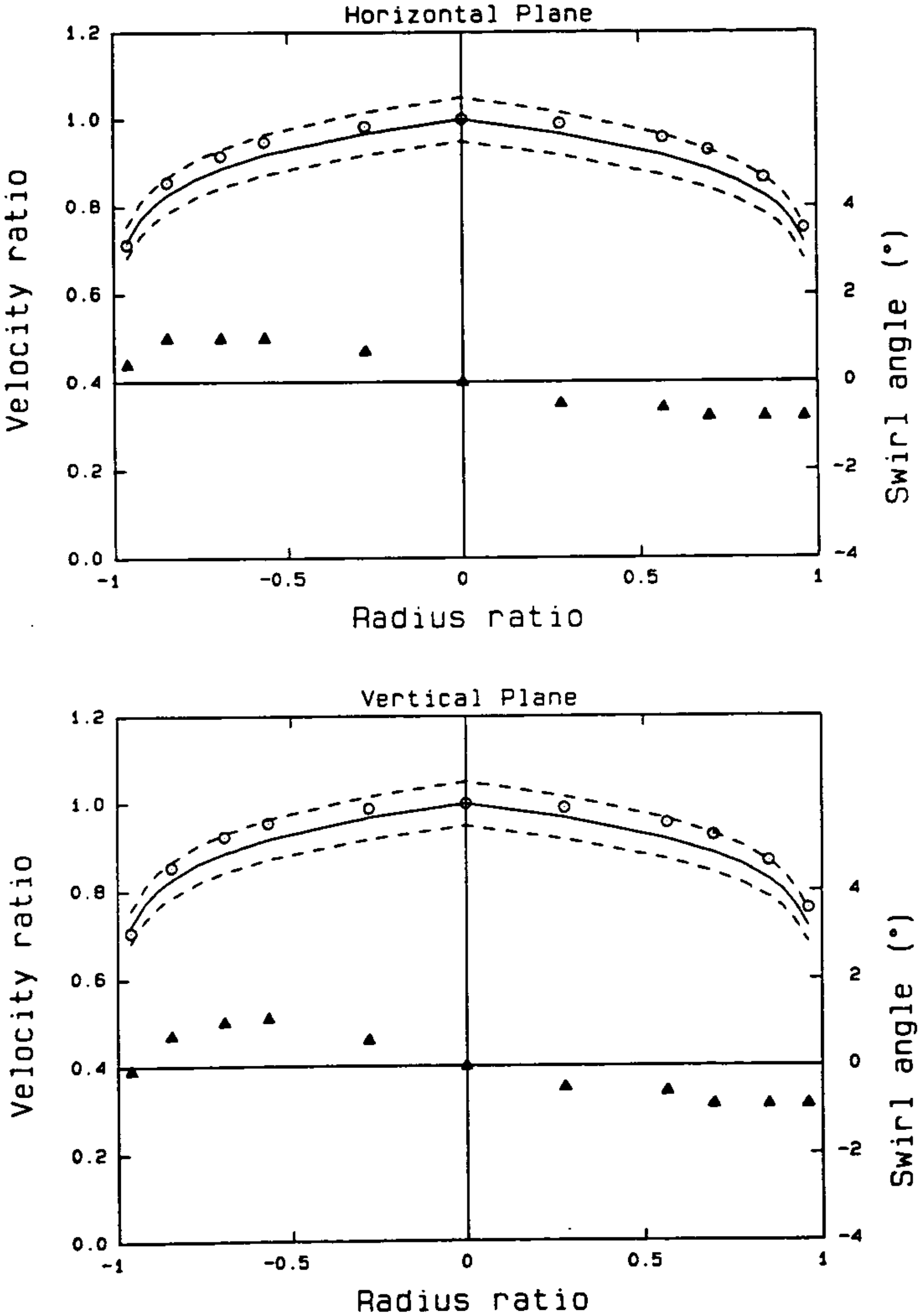


Fig 14 Laws - Profile at 9D

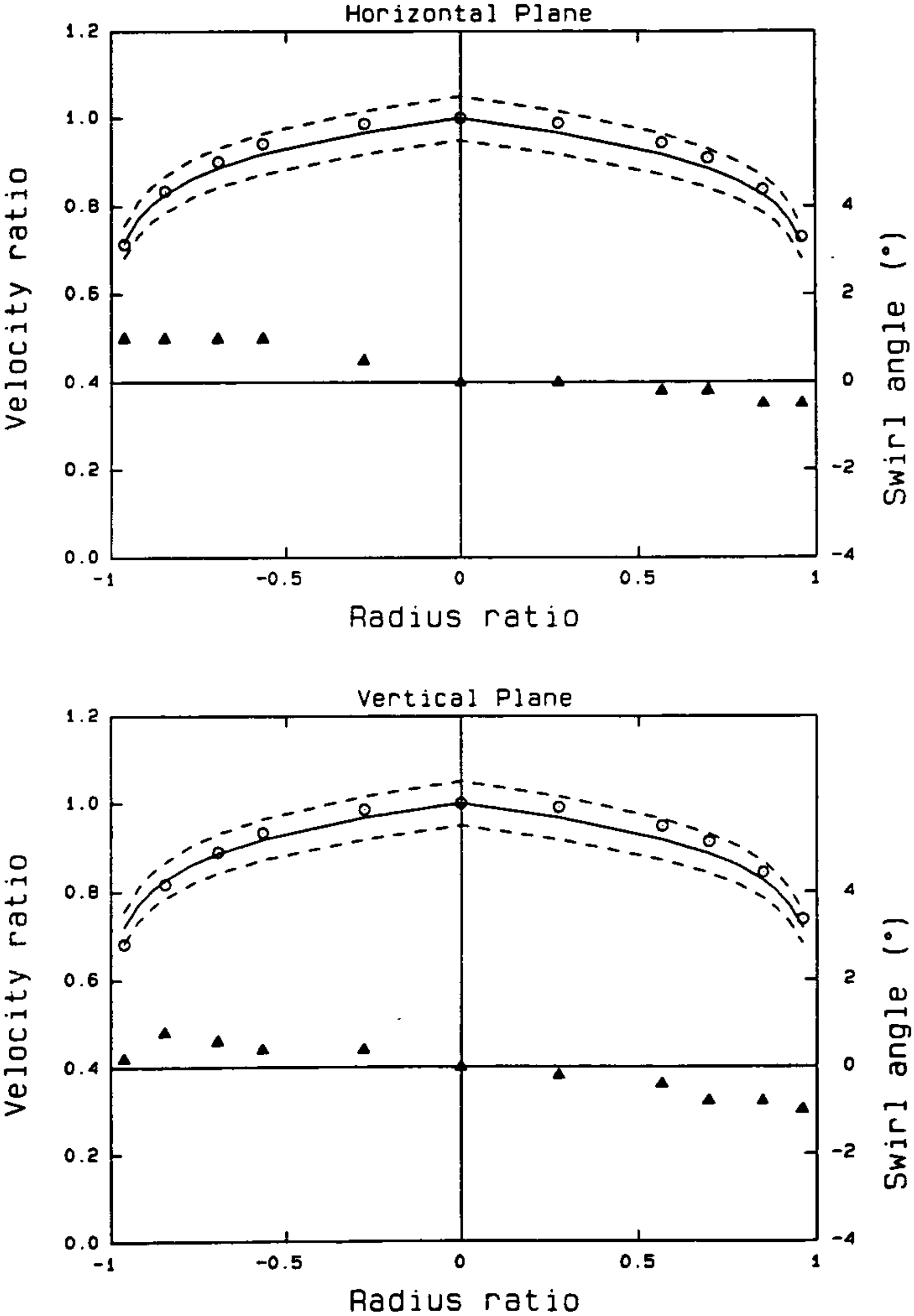


Fig 15 Laws - Profile at 19D

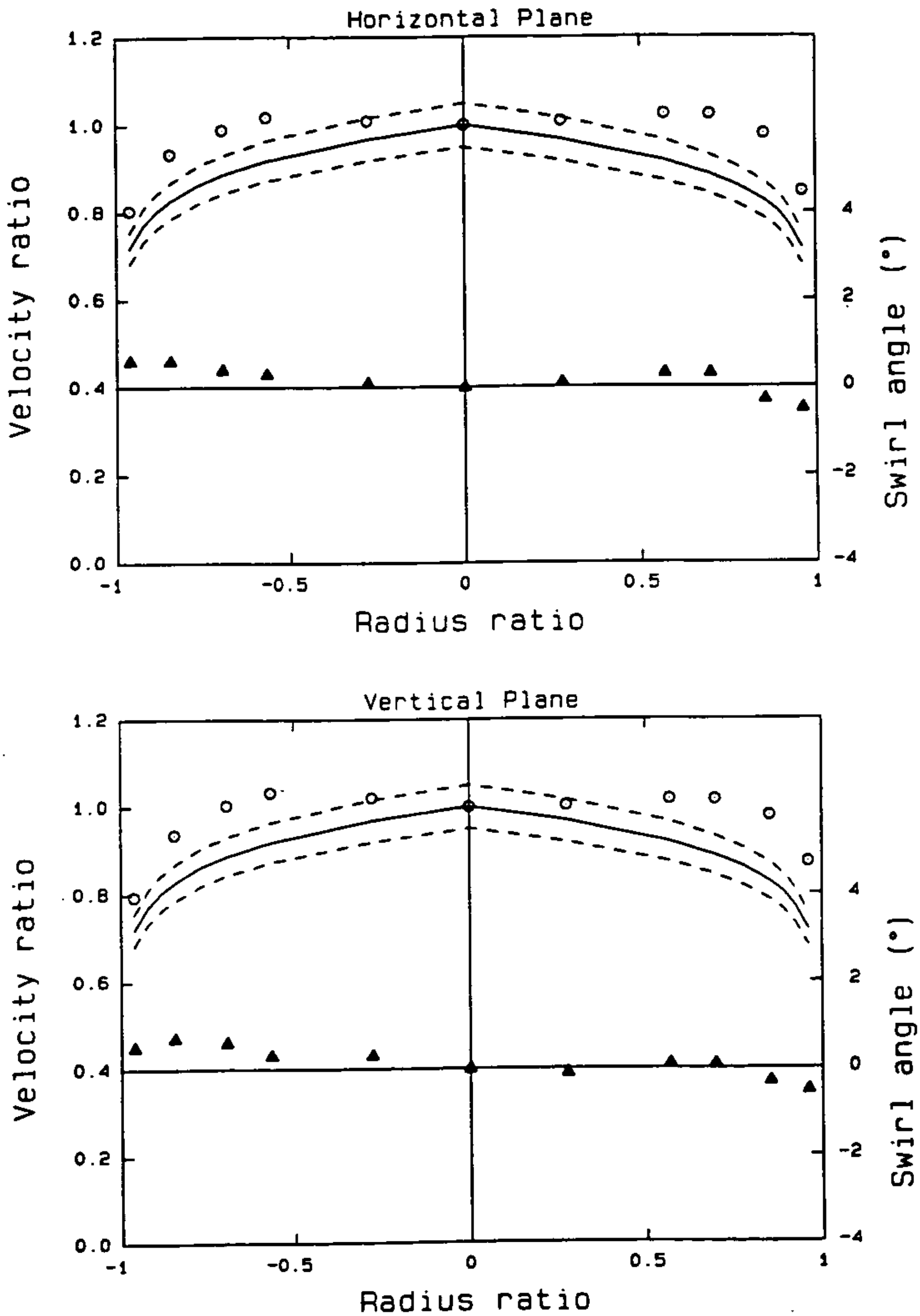


Fig 16 Tube bundle - Profile at 9D

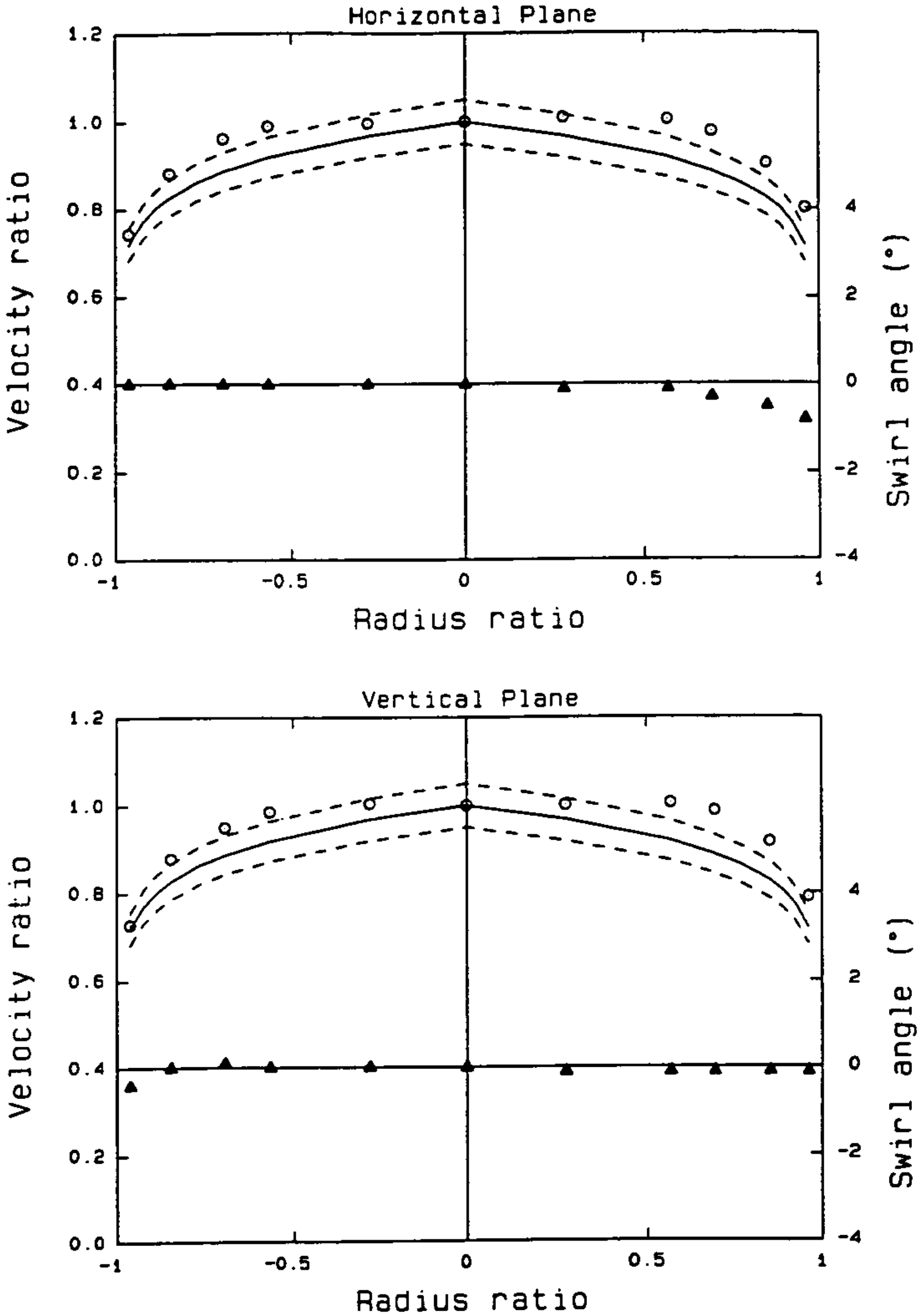


Fig 17 Tube bundle - Profile at 13D

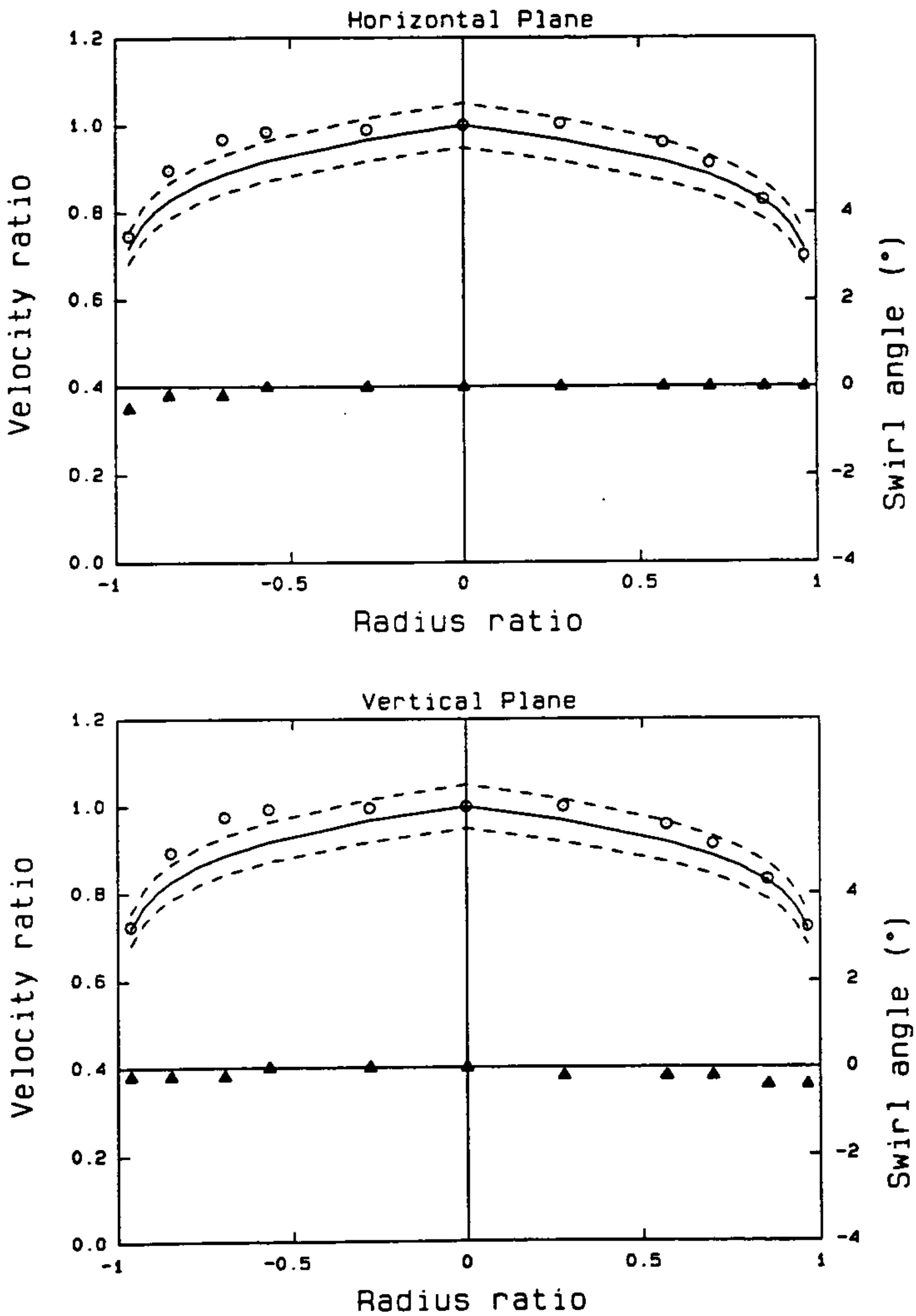


Fig 18 Tube bundle - Profile at 13DR

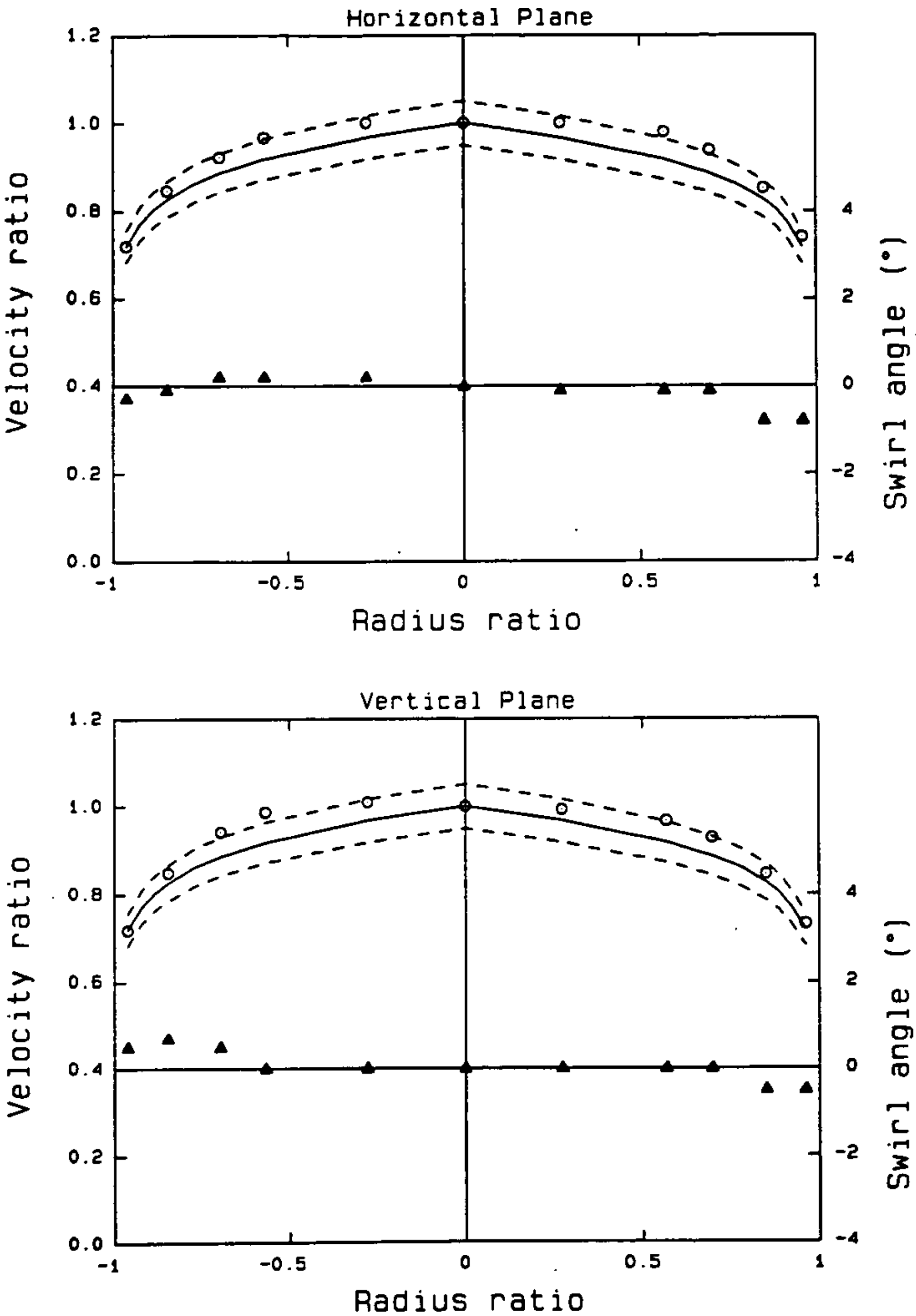


Fig 19 Tube bundle - Profile at 19D

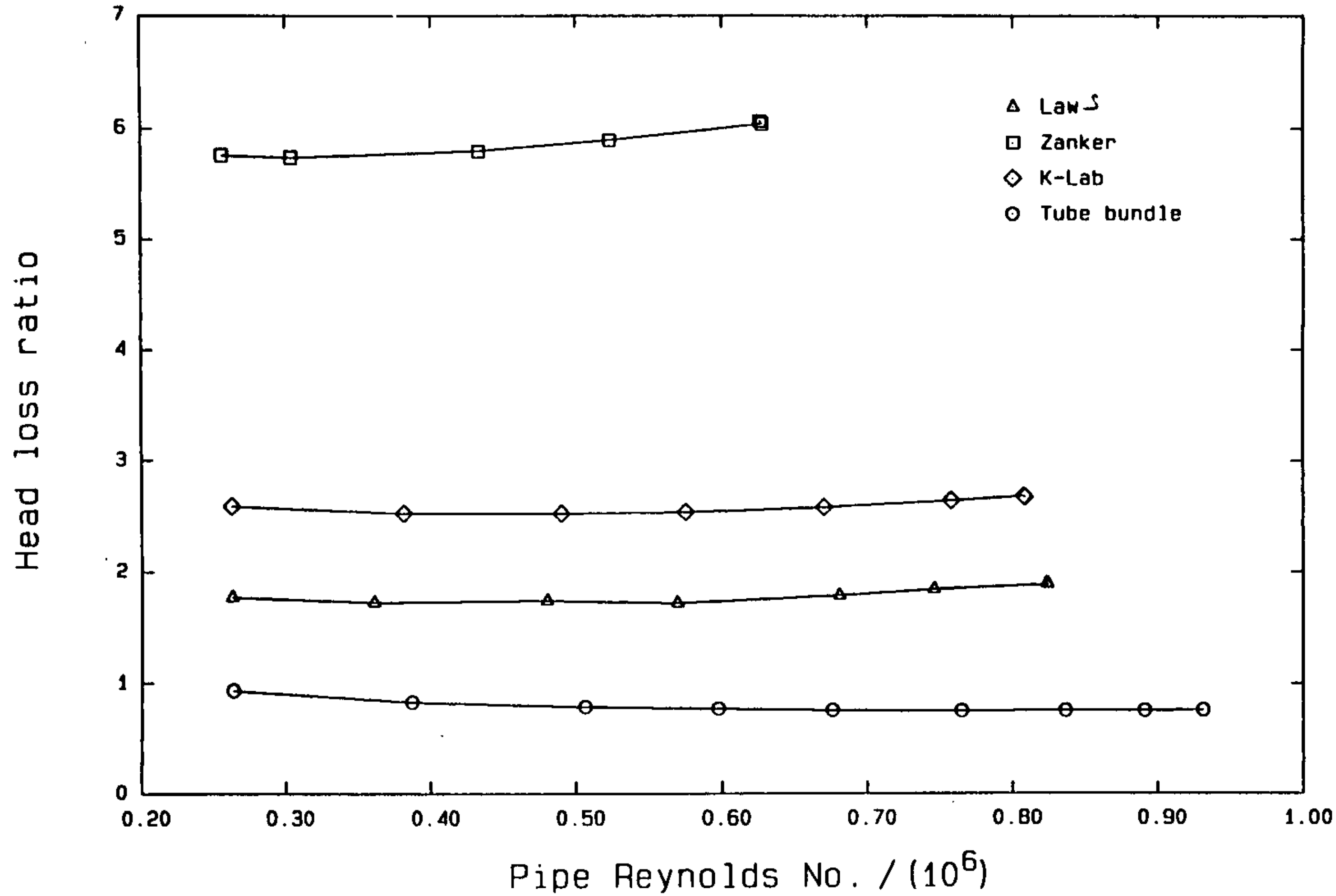


Fig 20 Flow conditioner head loss

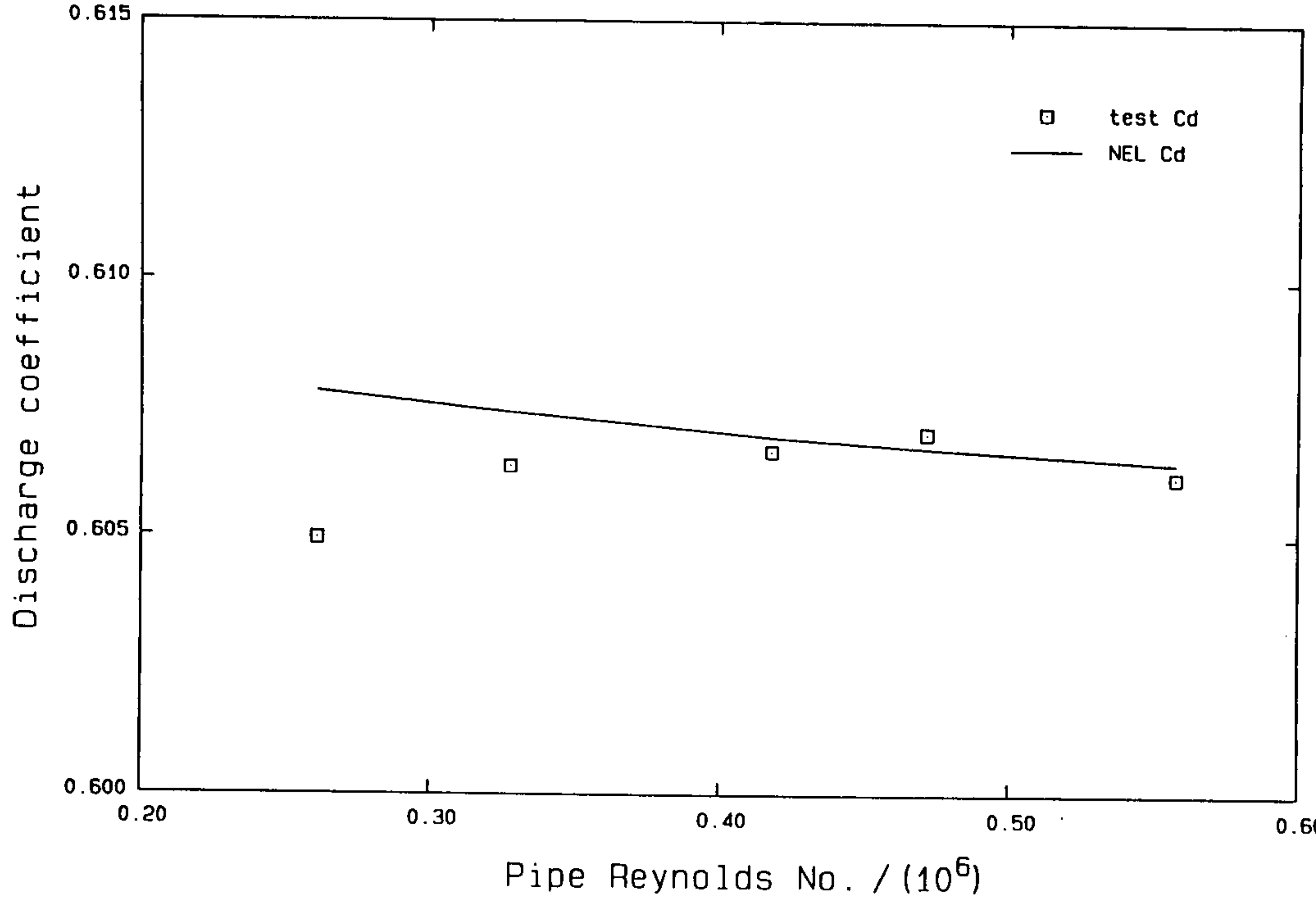


Fig 21   Discharge coefficient - Laws at 9D

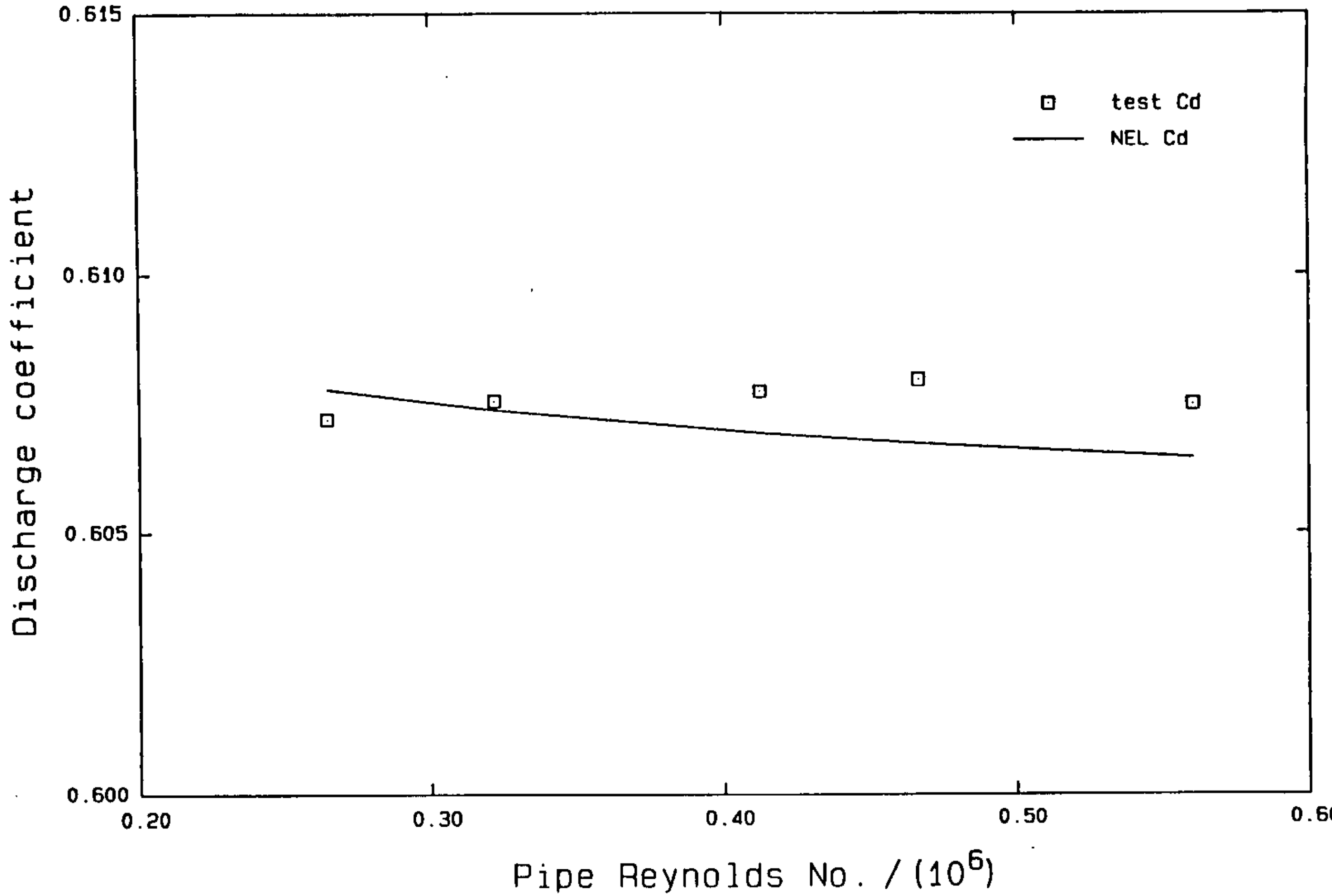


Fig 22   Discharge coefficient - Laws at 19D

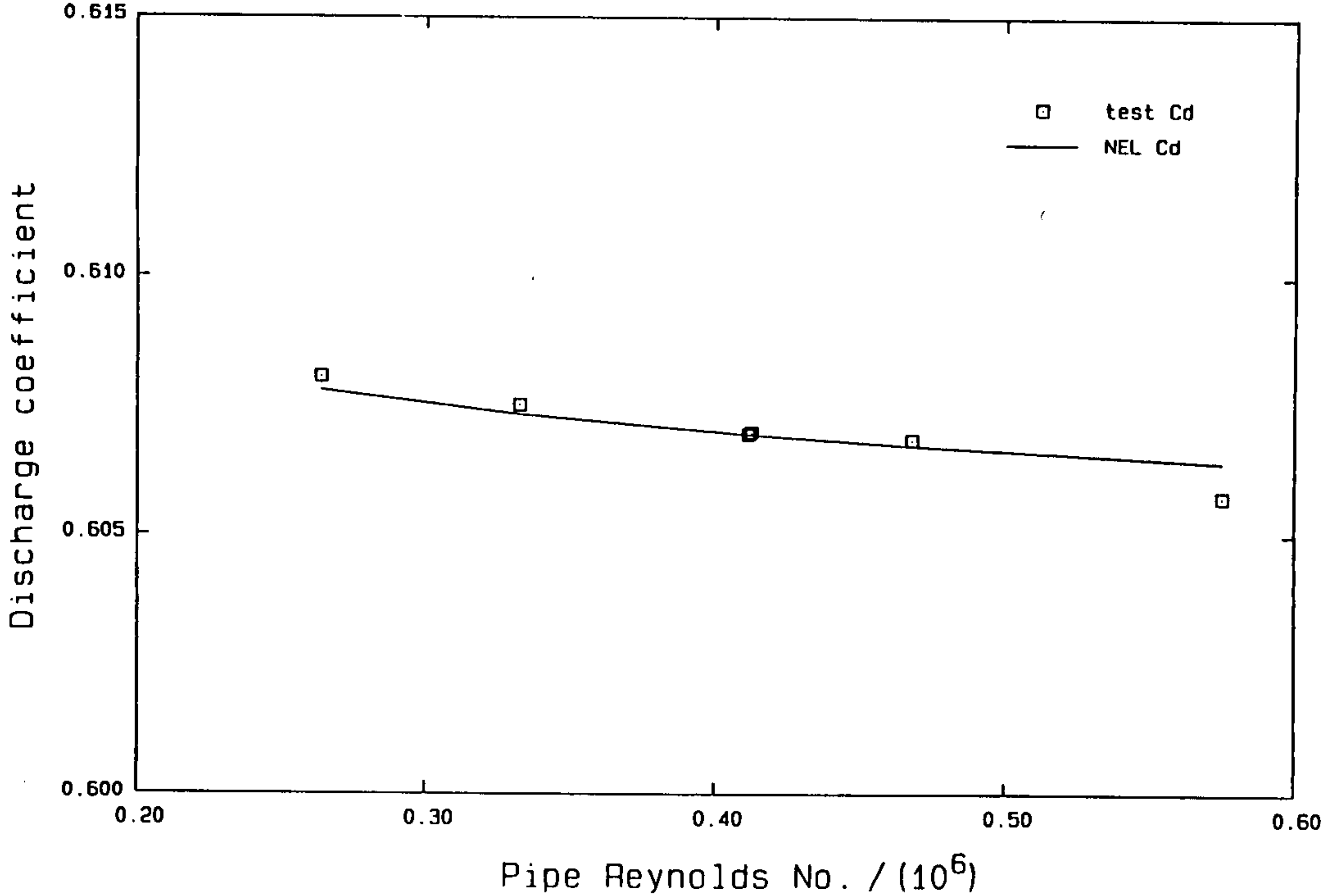


Fig 23 Discharge coefficient - Tube bundle at 13D

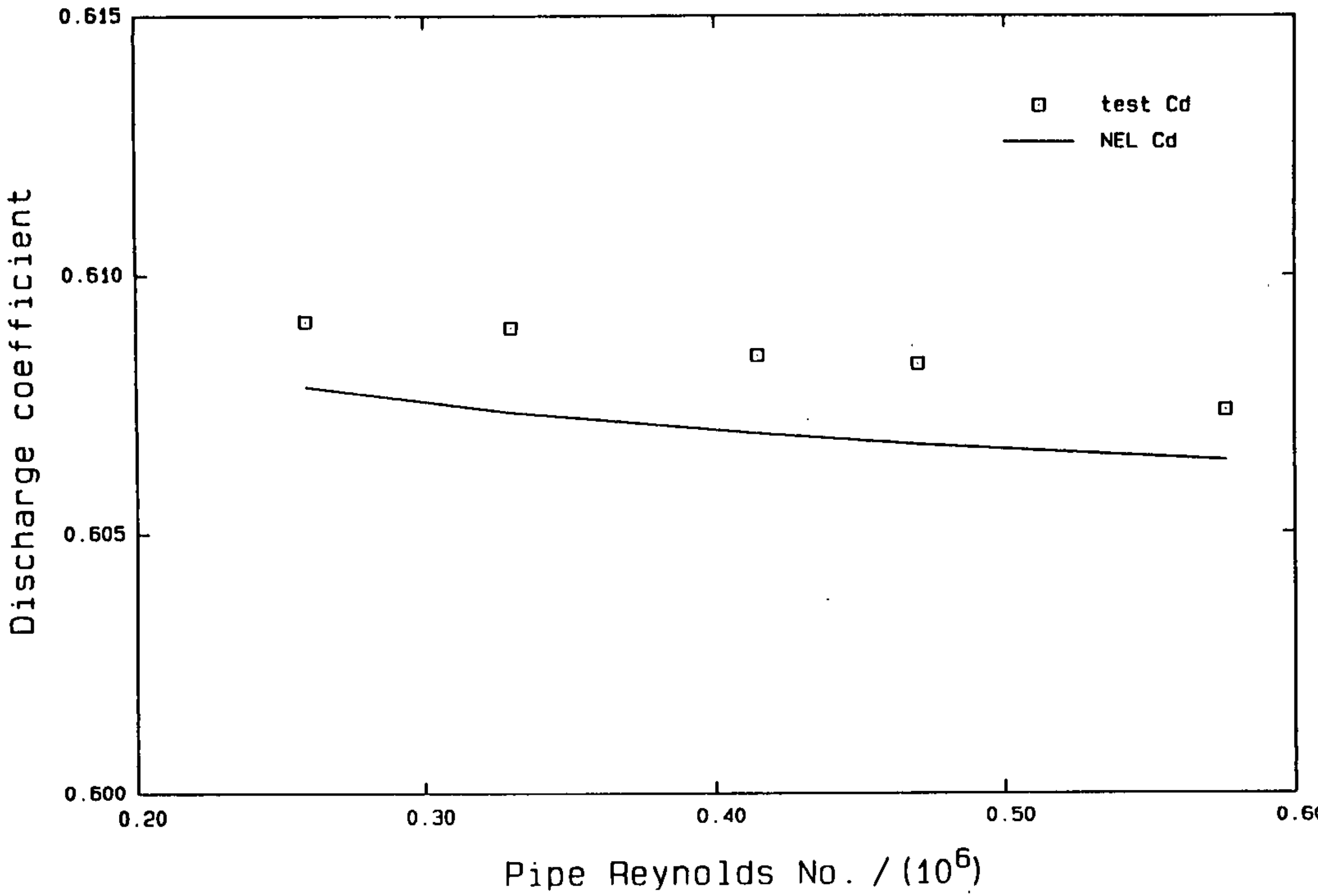


Fig 24 Discharge coefficient - Tube bundle at 13DR

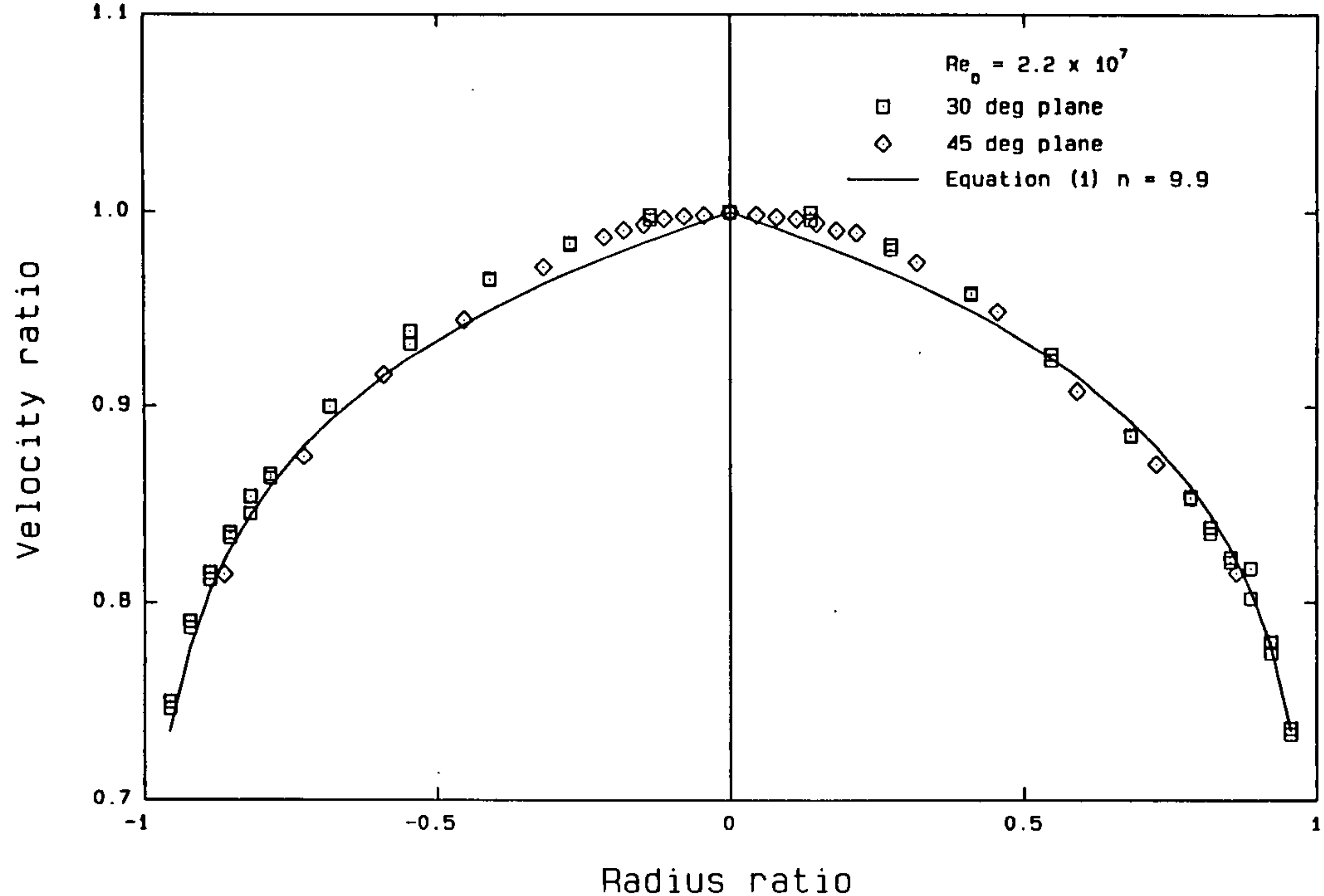
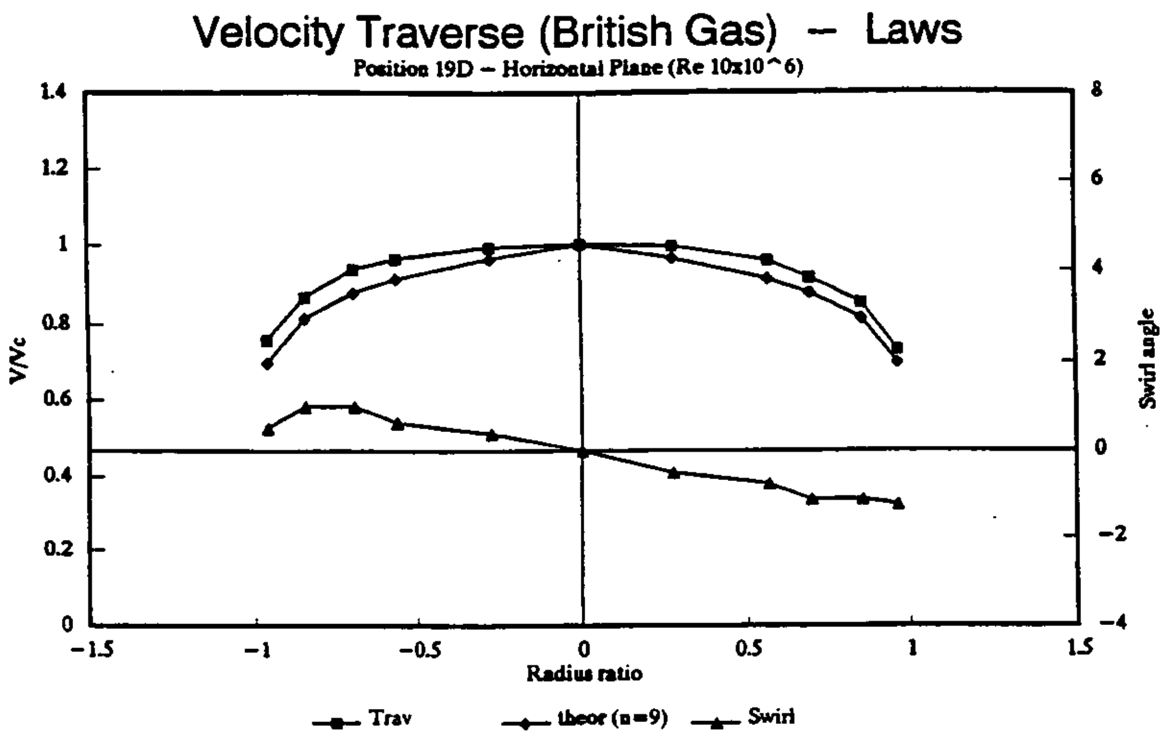


Fig 25 Velocity profile - British Gas 600mm pipe


Velocity Traverse (British Gas) – Laws
Position 19D – Horizontal Plane (Re 10x10^6)
V/Vc
Swirl angle
Radius ratio
Trav
theor (n=9)
Swirl

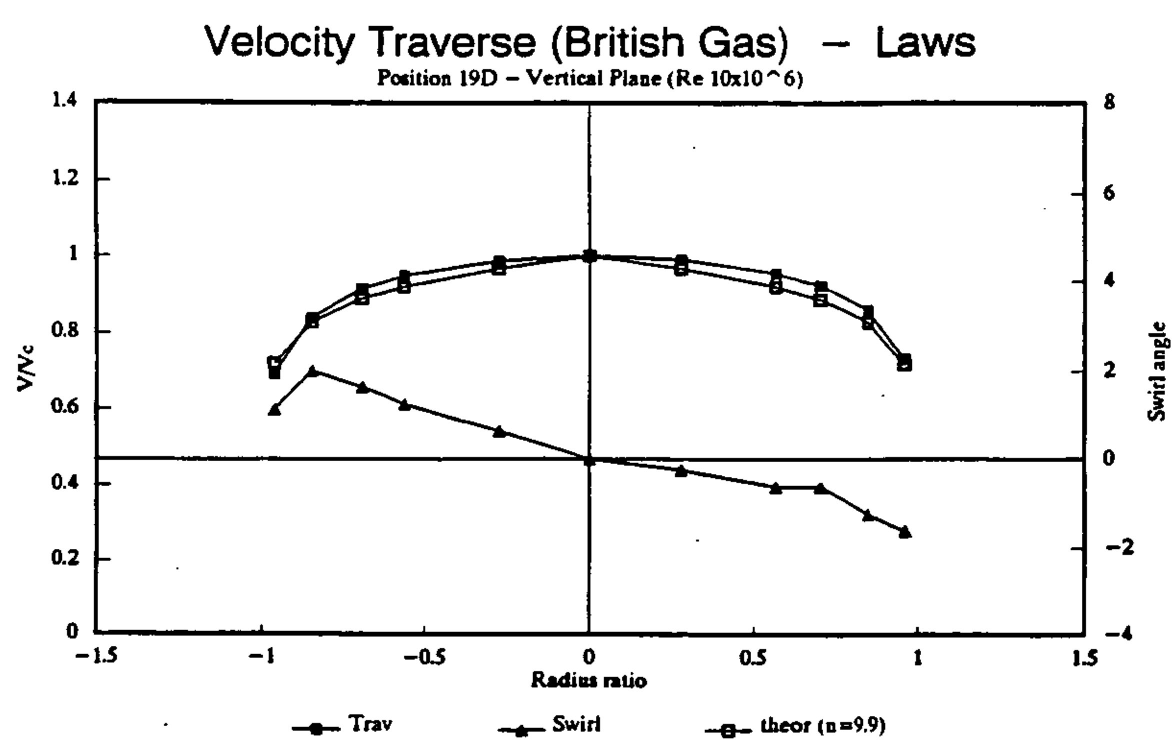

Velocity Traverse (British Gas) – Laws
Position 19D – Vertical Plane (Re 10x10^6)
V/Vc
Swirl angle
Radius ratio
Trav
Swirl
theor (n=9.9)

Figure 26

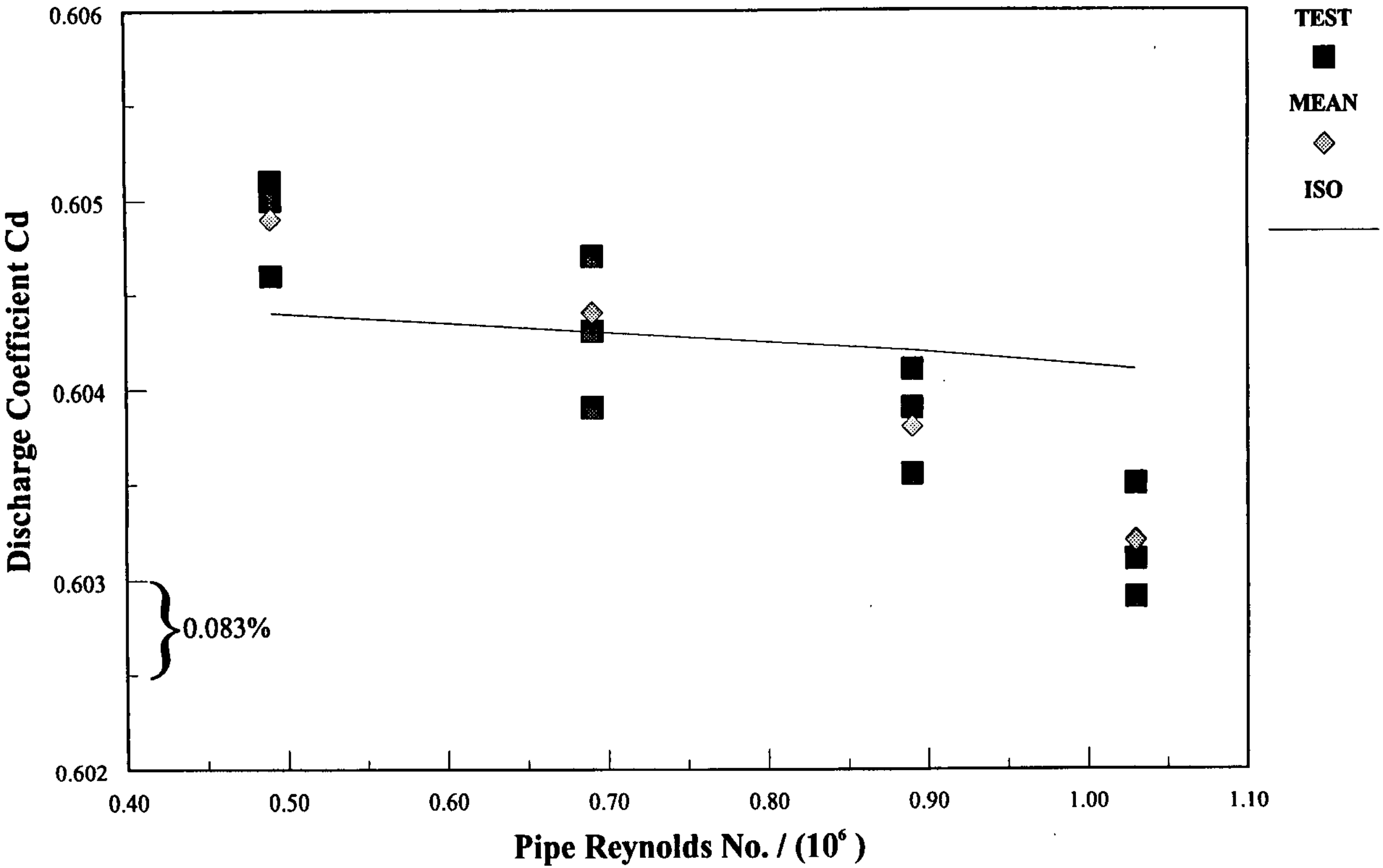


Fig 27 British Gas - Cd v Pipe Reynolds No.

Beta = 0.597 at 19D (Laws : 2nd test)

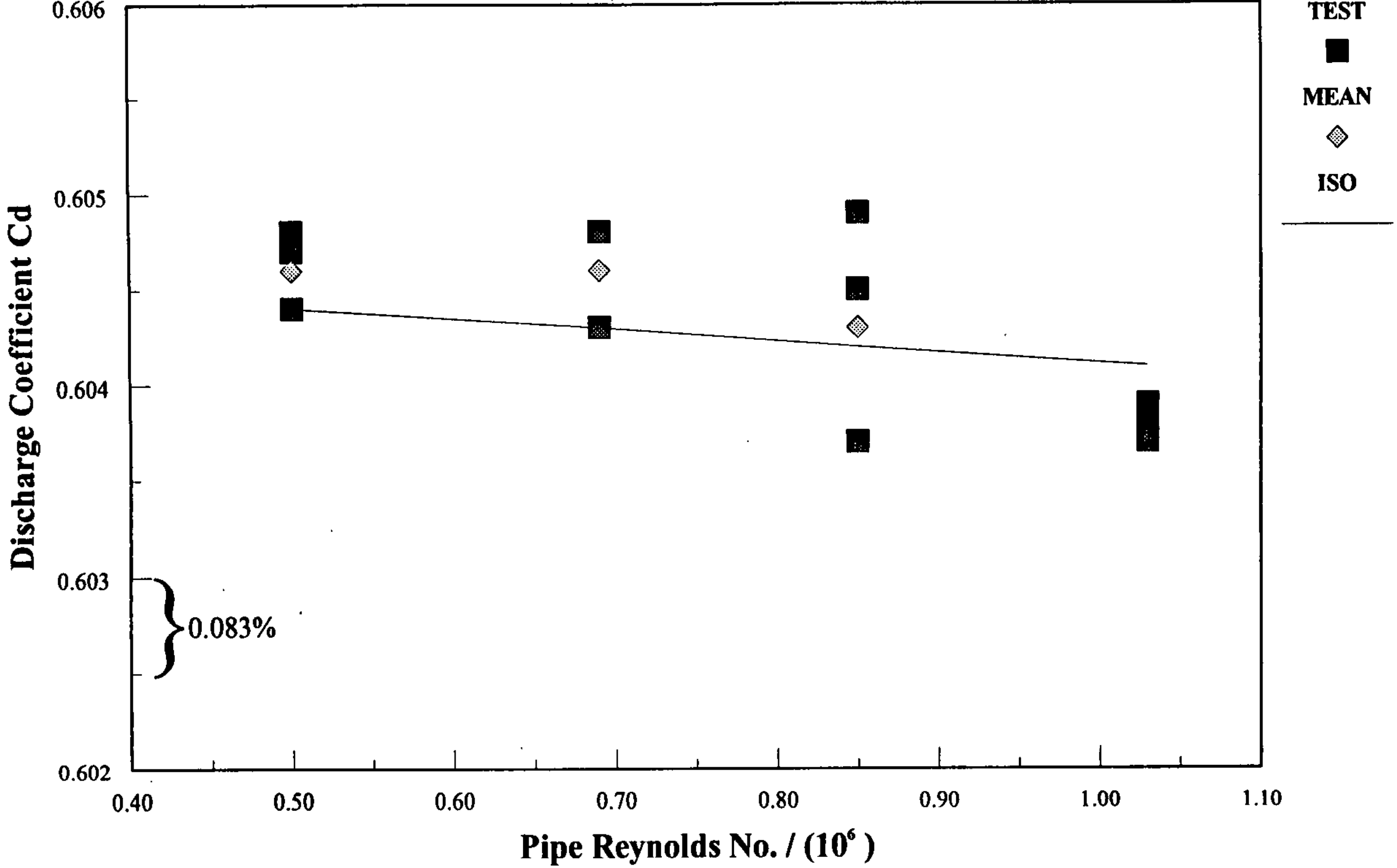


Fig 28 British Gas - Cd v Pipe Reynolds No.

Beta = 0.597 at 9D (Laws)