Theory (Douglas J.F. et al 1979)

Since the orifice plate dissipates pressure, it can be used as a flowmeter, the flow being proportional to the square root of the pressure drop. Using the Bernoulli and continuity equations, the theoretical flow through an orifice can be shown to be :

$$Q = \frac{A}{\sqrt{m^2 - 1}} \sqrt{\frac{2g}{\rho} \left[P_U - P_{VC}\right]} \quad 3.1$$

The pressure difference (Pu - Pvc) is due to the velocity change occurring between the upstream conditions and the vena contracta.

In practice, extra energy losses occur, thus modifying the above equation to :

$$Q = \frac{C\,A}{\sqrt{m^2 - 1}} \sqrt{\frac{2g}{\rho} \left[P_U - P_{VC}\right]} \quad 3.2$$

Here $\frac{1}{\sqrt{m^2 - 1}}$ is the 'velocity approach factor', m being given by $m = (D/d)^2$, where D is the diameter of the pipe, and d that of the orifice.

This reduces to :

$$Q = C_d A \sqrt{\frac{2g\Delta P}{\rho}} \quad 3.3$$

where $\sqrt{\frac{2g\Delta P}{\rho}}$ is the theoretical pipe flow velocity, C_d is the coefficient of discharge, and A the upstream flow cross-sectional area.

The coefficient of discharge C_d is composed of two coefficients, associated respectively with jet contraction and jet velocity. These are defined as the Contraction Coefficient, C_c, given (to a first order approximation) by

$$C_c = \frac{\text{Area of jet at vena contracta}}{\text{Area of orifice}} \qquad 3.4$$

and the Velocity Coefficient, Cv, given by

$$C_v = \frac{\text{Velocity at vena contracta}}{\text{Theoretical orifice velocity}} \qquad 3.5$$

These are related to the coefficient of discharge by :

$$C_d = C_c \times C_v \qquad 3.6$$

To calculate the permanent pressure loss across an orifice the following equation can be used :

$$\Delta P = \frac{K \rho V^2}{2} \qquad 3.7$$

where K is the pressure loss coefficient. Actual values of K are given in Figure 3.7

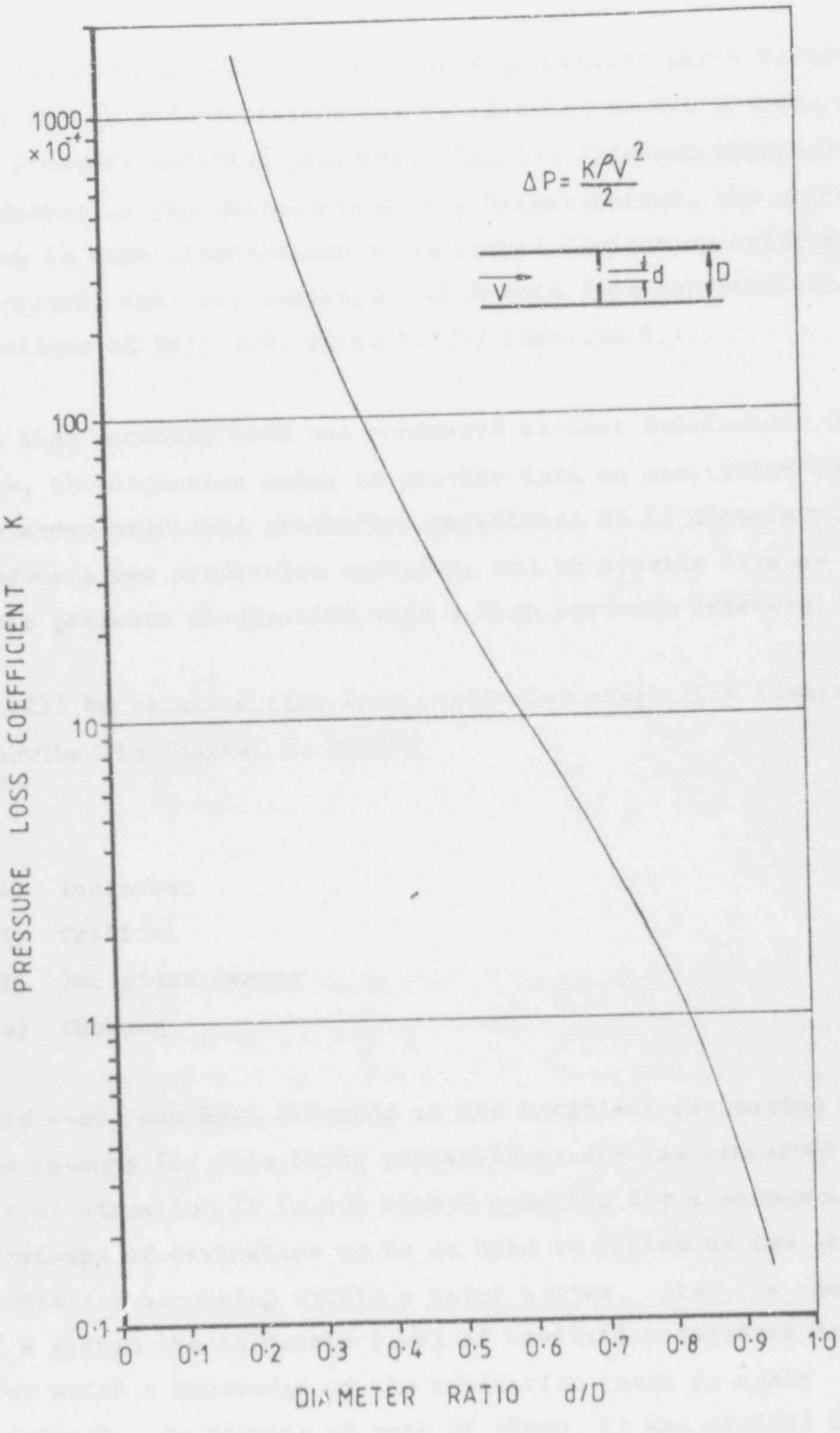


FIGURE 3.7 ORIFICE - PRESSURE LOSS COEFFICIENTS (MILLER D.S. 1978)

4. EXPERIMENTAL FACILITIES, PROCEDURES AND TESTS

The experimental part of this study on orifice plate pressure dissipation and cavitation was carried out in two phases, namely, low pressure and high pressure. The low pressure part was conducted at the University of the Witwatersrand, the objectives being to make observations on an actual cavitating orifice, and to provide data for comparison with data from the prediction equations of Ball J.W. et al (1975) (Section 2.4).

The high pressure work was conducted at East Driefontein Gold Mine, the objective being to provide data on cavitation to check the above mentioned prediction equations, or if necessary, to produce a new prediction equation, and to provide data on orifice plate pressure dissipation with a high upstream pressure.

It will be recalled that four particular cavitation levels were described in Chapter 2, namely

i) Incipient
ii) Critical
iii) Incipient Damage
iv) Choking

This study has been directed at the incipient cavitation level, the reasons for this being primarily safety and conservation. In a real situation it is not always possible for a person with a knowledge of cavitation to be on hand to decide on the level of cavitation occurring within a water system. Also, in the design of a system the tolerable level of cavitation requires definition (for which a knowledge of the cavitation level is again required). In respect of both of these, it was decided to opt for incipient cavitation as it is the first level and can be interpreted as a no cavitation/cavitation boundary, thus hopefully leaving very little doubt in an investigator's mind as to the cavitation level occurring.

4.1 UNIVERSITY OF THE WITWATERSRAND

As stated above, the low pressure tests were conducted in the Mechanical Engineering Laboratory of the University of the Witwatersrand. The fluids section of this laboratory is situated above and underground sump which contains water at a relatively constant temperature of 16°C, thus allowing testing to be carried out with water in which the vapour pressure did not significantly vary.

4.1.1 TEST FACILITY

The test equipment is shown in Figures 4.1 & 4.2, the main components being :

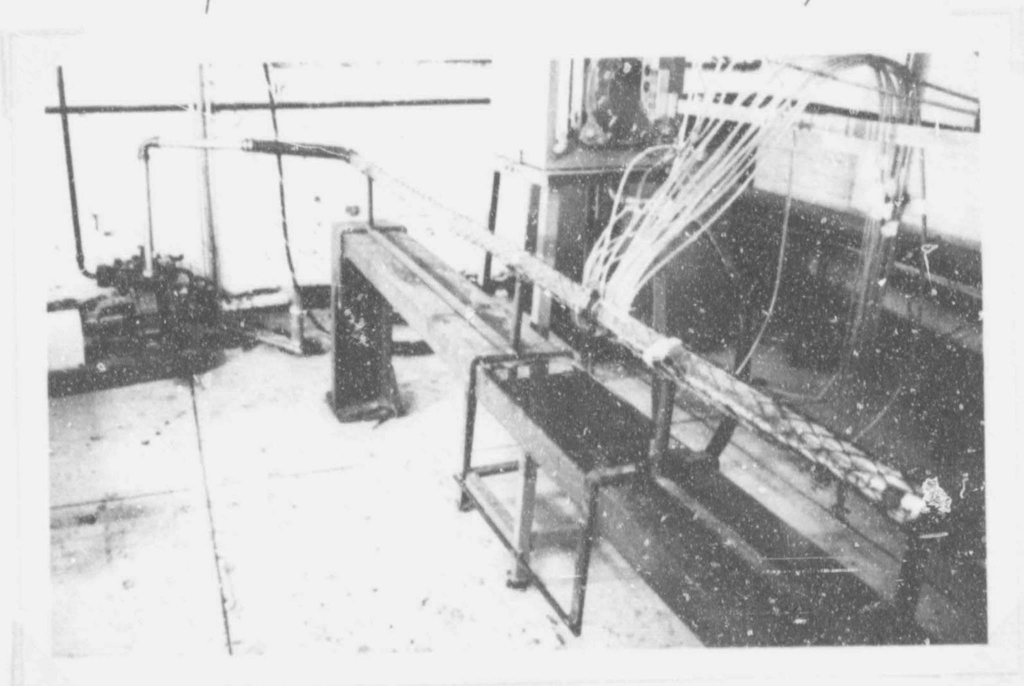
i) Pump
ii) Perspex test section
iii) Orifice
iv) Throttling valve
v) Flowmeter

The test section consisted of two flanged perspex tubes of 33,5mm internal diameter, each flange being recessed to house an 'O' ring. The orifice plate was located between the flanges and the 'O' rings (Figure 4.3), the assembly being clamped by six bolts around the flange. Both upstream and downstream of the flanges were a series of pressure taps, 6 upstream and 15 downstream, to allow pressures to be sampled at various positions upstream and downstream of the orifice.

The orifice plates were made from 5mm thick brass plate (Figure 4.3) and designed in accordance with B.S. 1042 - square edged.

PUMP

ORIFICE



PERSPEX TEST SECTION

FIGURE 4.1 PHOTOGRAPH OF CAVITATION TEST RIG - UNIVERSITY OF THE WITWATERSRAND

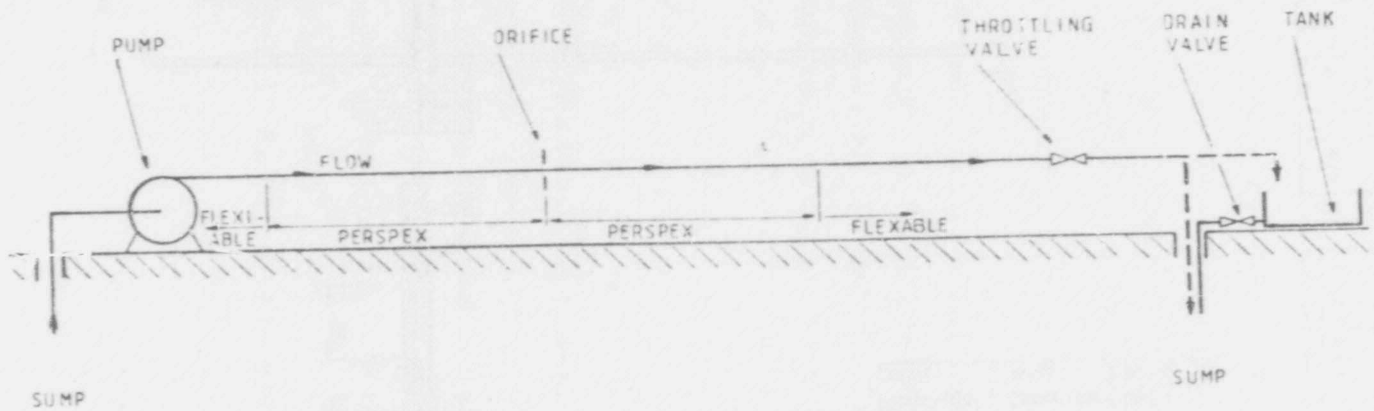


FIGURE 4.2 SCHEMATIC VIEW OF TEST RIG - UNIVERSITY OF THE WITWATERSRAND

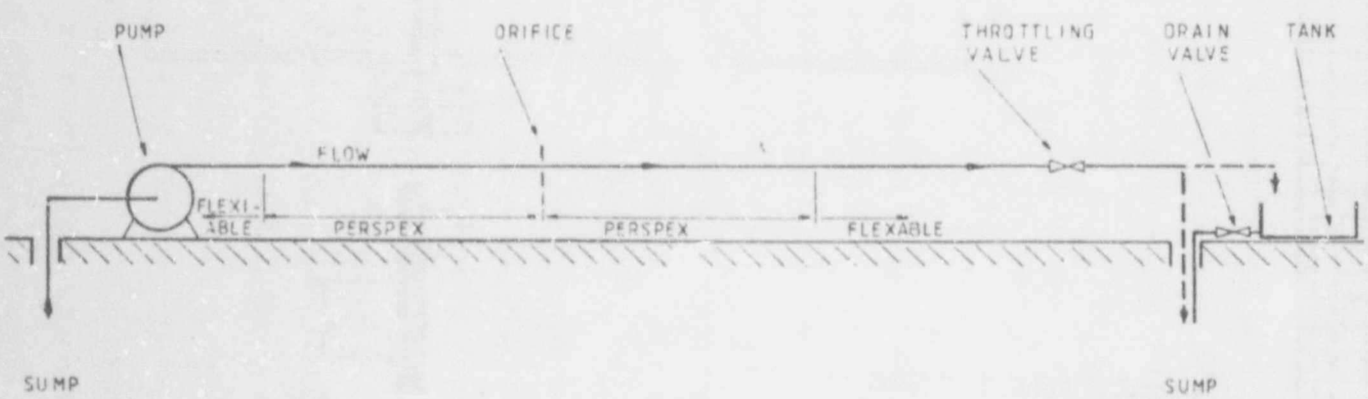
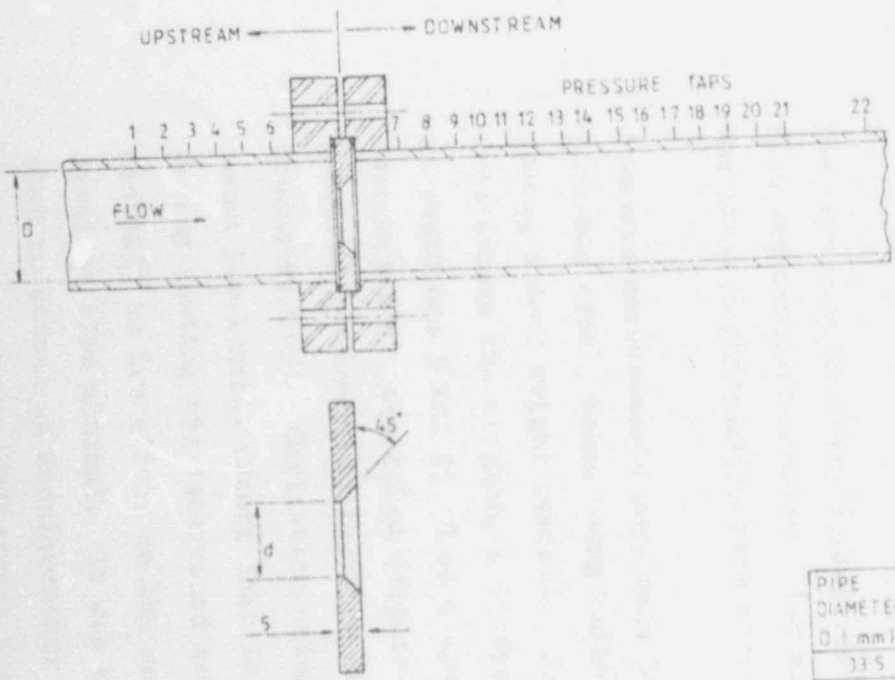


FIGURE 4.2 SCHEMATIC VIEW OF TEST RIG - UNIVERSITY OF THE WITWATERSRAND



PIPE DIAMETER, D (mm)	ORIFICE DIAMETER, d (mm)	DIAMETER RATIO, d/D
33.5	8.2	0.24
"	14.4	0.43
"	20.4	0.61
"	26.6	0.79

PRESSURE TAP POSITIONS	
POS'N	DISTANCE FROM LEADING EDGE mm
1	-47
2	-41
3	-36
4	-32
5	-27
6	-22
7	19
8	24
9	30
10	35
11	40
12	45
13	50
14	55
15	60
16	65
17	70
18	75
19	80
20	85
21	90
22	805

FIGURE 4.3 TEST SECTION ORIFICE ASSEMBLY - UNIVERSITY OF THE WITWATERSRAND

To rou· the flow from the test section to the sump, a flexible rubber hose was used. Located in the hose was a final pressure tap, and a gate valve to control the flow rate. For flow measurements the hose could either be routed directly to the sump or via a graduated tank for a volume check.

In addition to the above mentioned test equipment, a non-flow apparatus was also set up to observe water cavitation at reduced pressured (ie. below atmospheric). This equipment consisted of a vacuum flask coupled to a vacuum pump and a mercury manometer (Figure 4.4).

4.1.2 MEASUREMENTS

The measurements taken during the flow tests were pressure, flow and cavitation noise. For conditions where cavitation was present photographs were also taken.

Pressure measurements were made by means of pressure gauges (Bourdon type), these being calibrated before and after use (using a dead weight tester). To calculate the pressure drop across the orifice, a difference of pressures measured at positions 6 and 22 (0,66 D upstream and 24 D downstream respectively), was taken (Figure 4.3). Flow rate was measured by deverting the flow from the sump to the graduated tank. Cavitation noise was measured using a sound level meter (Scott Inst Lab. Type 452, Sr No. 6173); during testing the background noise in the laboratory was minimal, so its effect on the measured cavitation noise level as also minimal. It was easier to use this procedure than to attach an accelerometer to the perspex pipes where there were space limitations due to pipe diameter and flange sizes.

In the vacuum flask test, a mercury manometer was used to measure the pressure.

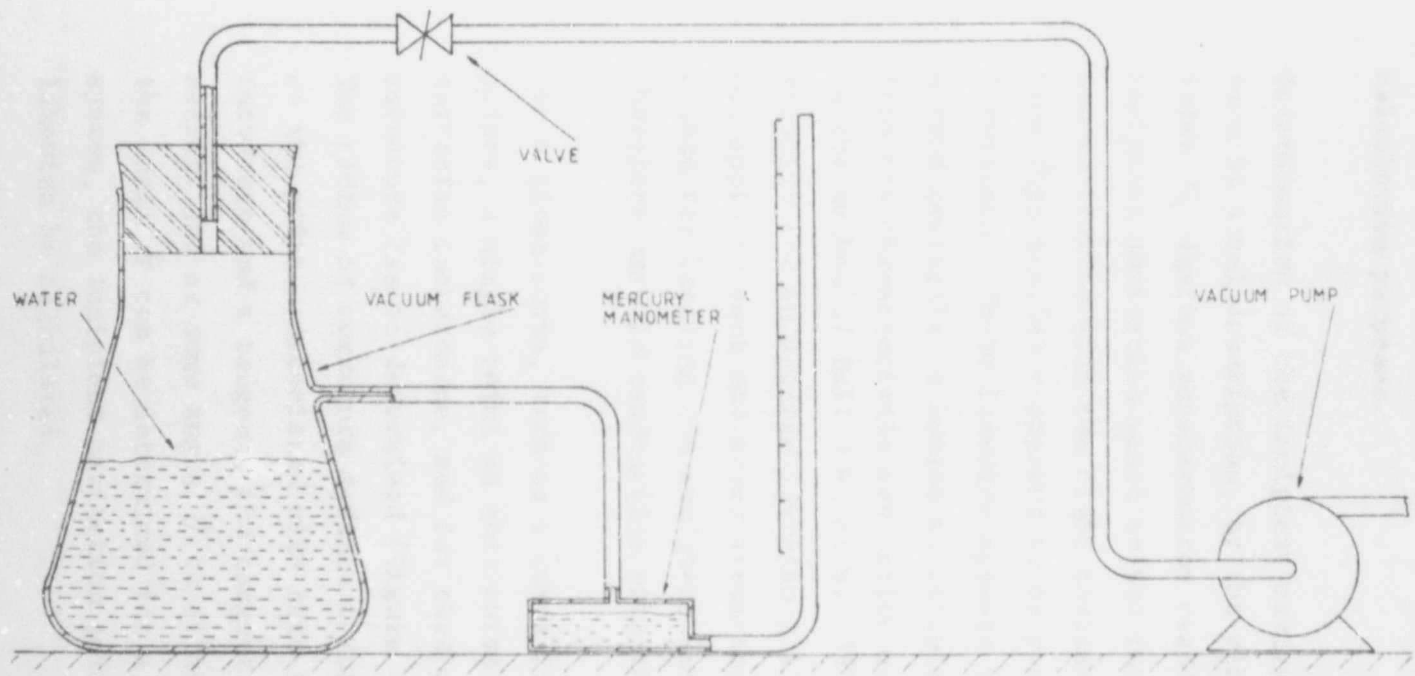


FIGURE 4.4 REDUCED PRESSURE TEST EQUIPMENT - UNIVERSITY OF THE WITWATERSRAND

For the pressure and flow rate measurements an error analysis is given in Section 5.1.2. The measurements of cavitation noise, and mercury manometer measurements for the vacuum flask test, are not included in the error analysis as these tests were qualitative and not used for calculation purposes.

Determination of the incipient cavitation point - other than by aural description, or the plotting of cavitation index σ_1 against accelerometer reading and evaluating the incipient cavitation point as the intersection of the non-cavitation with the light cavitation part of the curve (See Figure 4.5a) - appears to be poorly defined in the literature. There likewise appears to be no quantitative method available to locate an incipient cavitation point from the characteristic cavitation curve. Obviously, there is the method of Ball J.W. et al (1975) to predict a flow velocity for an orifice (Section 2.4); however, this does not apply to each and every situation. The following method for locating the incipient cavitation point was therefore used in conjunction with the prediction method.

For a given curve, such as a curve fitted to a set of data points, a single point on that curve can be located by cartesian coordinates, and for that point a radius of curvature can be determined (Figure 4.5b) (Pedoe J. 1971). The radius of curvature defines a curve of length ΔS at the point. Associated with this is a centre of curvature and a tangent, the tangent being at 90° to the radius, and at some angle θ to either axis. Now provided the angle θ can be determined for a particular type of system, the incipient cavitation point for the system can likewise be calculated.

Unfortunately, the above method creates a problem in that the results obtained will probably be different to those of Ball J.W. et al (1975), who provided a prediction method rather than a means to determine incipient cavitation. Therefore, to compare experimental results to predicted data is stricly incorrect. However, one must have a method

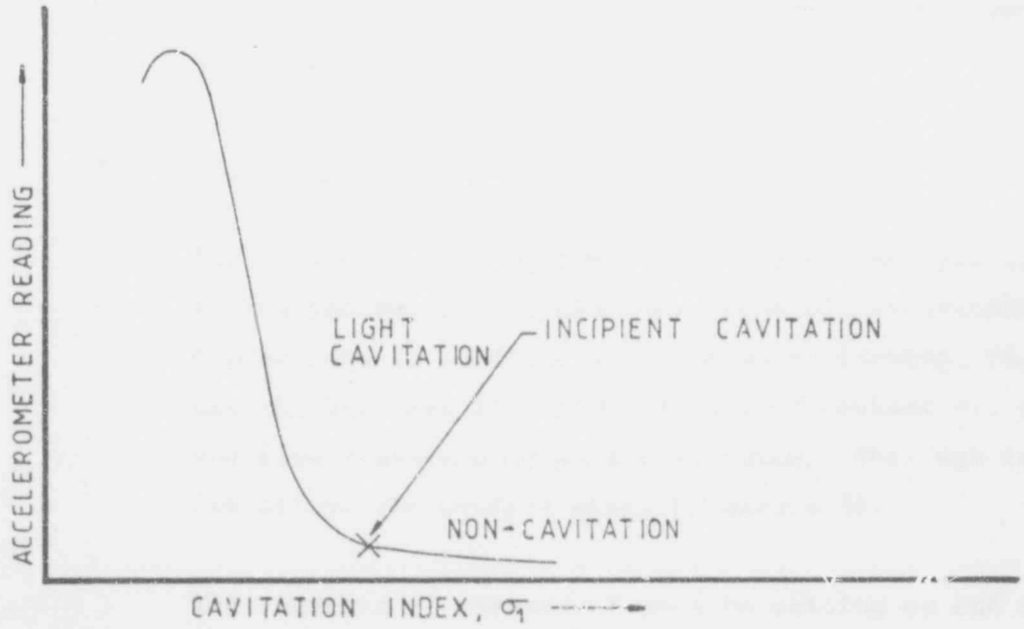


FIGURE 4.5a INCIPIENT CAVITATION POINT

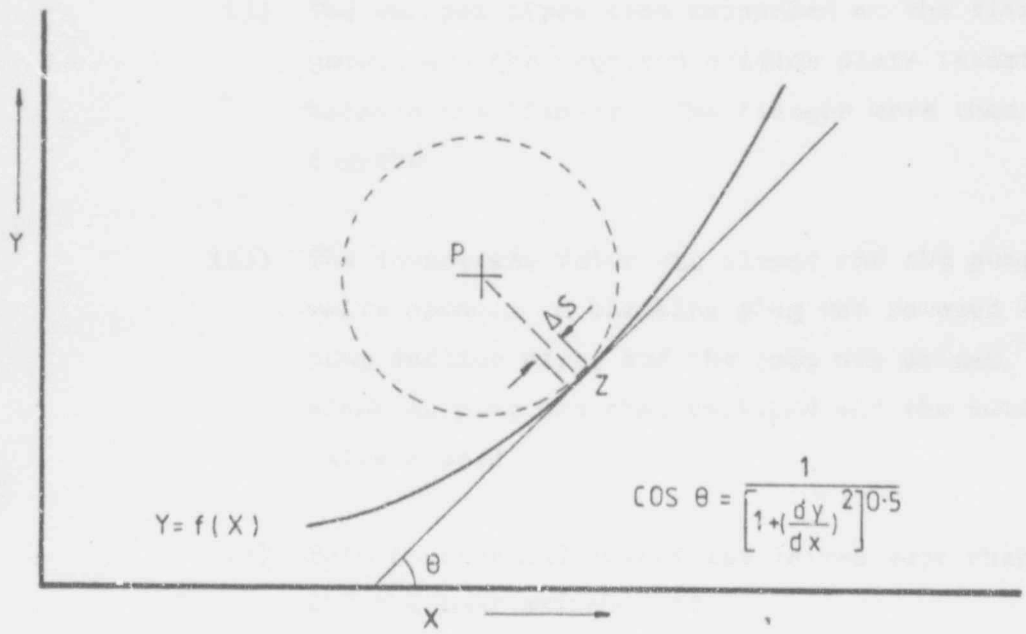


FIGURE 4.5b TANGENT TO RADIUS OF CURVATURE FOR A FITTED EQUATION

for determining the incipient cavitation point, and so to be able to check the prediction equation as well as to provide data to possibly extend its range or to derive a new equation.

4.1.3 TESTS AND PROCEDURES

The orifice test programme consisted of locating an orifice in the perspex pipes, and then, with all instrument connections in position and with water flowing, the orifice was photographed at various stages of cavitation; pressure and flow measurements were also taken. This was repeated for all of the orifice sizes (Figure 4.3).

The sequence of operations used in setting up and operating the equipment described in the foregoing section for the main test was as follows :-

i) With the pump off, the pump suction valve was closed and the downstream throttle valve opened.

ii) The perspex pipes were uncoupled at the flanged joint, and the required orifice plate inserted between the flanges. The flanges were then bolted together.

iii) The downstream valve was closed and the pump suction valve opened. A blanking plug was removed from the pump suction pipe, and the pump was primed. The blanking plug was then replaced and the suction valve closed.

iv) Both suction and downstream valves were then opened, and the pump switched on.

v) With the downstream valve adjusted to give minimum flow rate, pressures, flow rate and noise level were measured (under cavitating conditions, photographs were also taken).

vi) The flow was then increased to give the next flow/cavitation condition.

vii) Steps v and vi were then repeated until the maximum flow or cavitation condition for that orifice had been observed and recorded.

viii) The next orifice was tested by repeating steps i to vii.

Also, the theoretical incipient cavitation pipe flow velocities for the various orifice sizes were calculated using equations 2.16 and 2.17, the data being shown in Figure 4.6. These data are later used for the calculation of theoretical pressure drops (for incipient cavitation), using equation 3.7 and the coefficients in figure 3.7; these are compared to the data from the experimental tests.

The results of the test are to be found in Section 5.1.

The reduced pressure test programme procedure was to take water samples, and then using the vacuum flask and vacuum pump, reduce the pressure (below atmospheric) progressively; in so doing bubble growth could be observed and the vapour pressure of the water sample noted. Two samples of water from the same source were tested, the first of which had been standing overnight (the air/water thus being in an equilibrium state), and the second having been agitated immediately prior to testing.

The following procedure was used for this test:

i) The flask was cleaned using hot soapy water, followed by flushing with hot water.

ii) The flask was filled with the sample of water for testing.

iii) The vacuum pump, mercury manometer, and flask were connected (Figure 4.4).

iv) All valves interconnecting equipment were opened, and the vacuum pump switched on.

v) As the pressure reduced, observations were made and recorded, along with the manometer reading.

vi) Steps i and v were repeated for the second water sample.

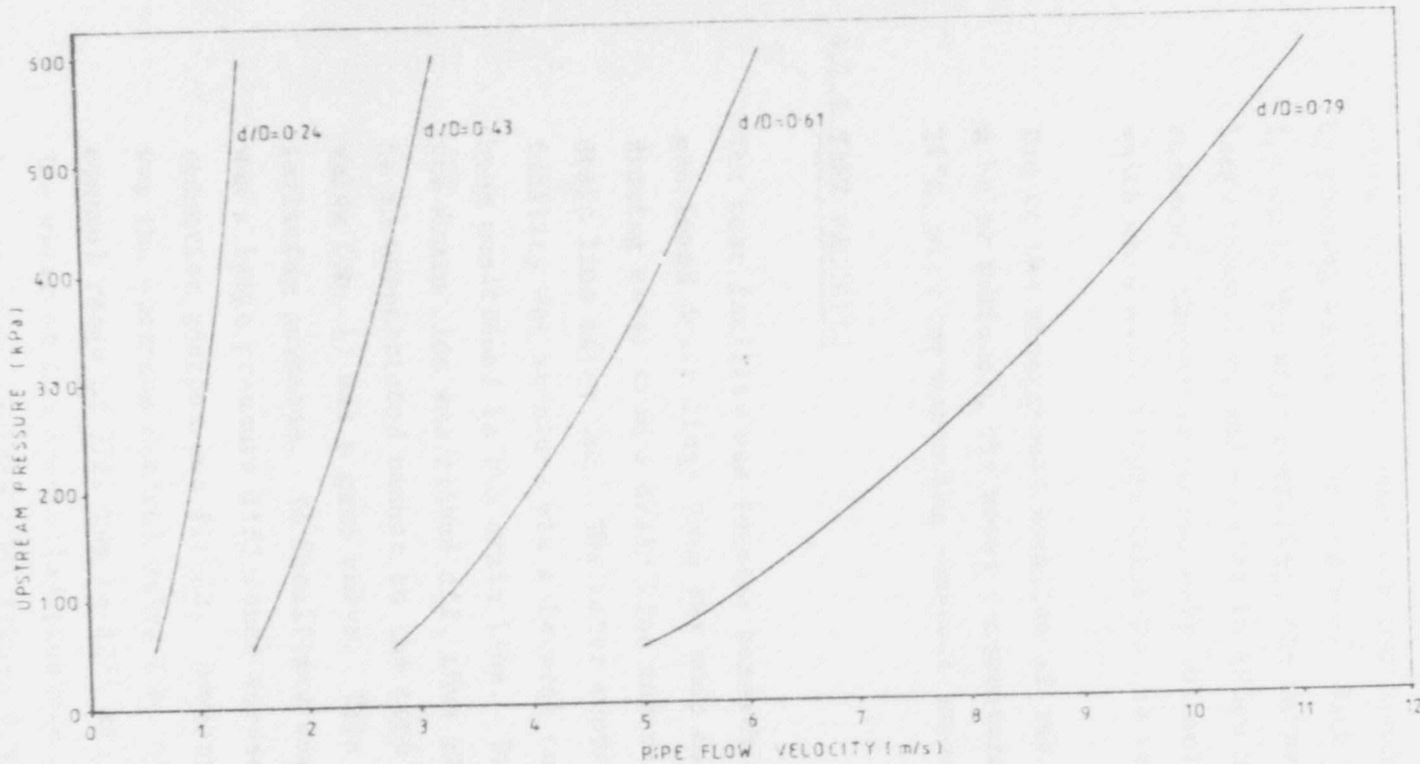


FIGURE 4.6 PREDICTED INCIPIENT CAVITATION FLOW VELOCITIES FOR UNIVERSITY OF THE WITWATERSRAND TESTS

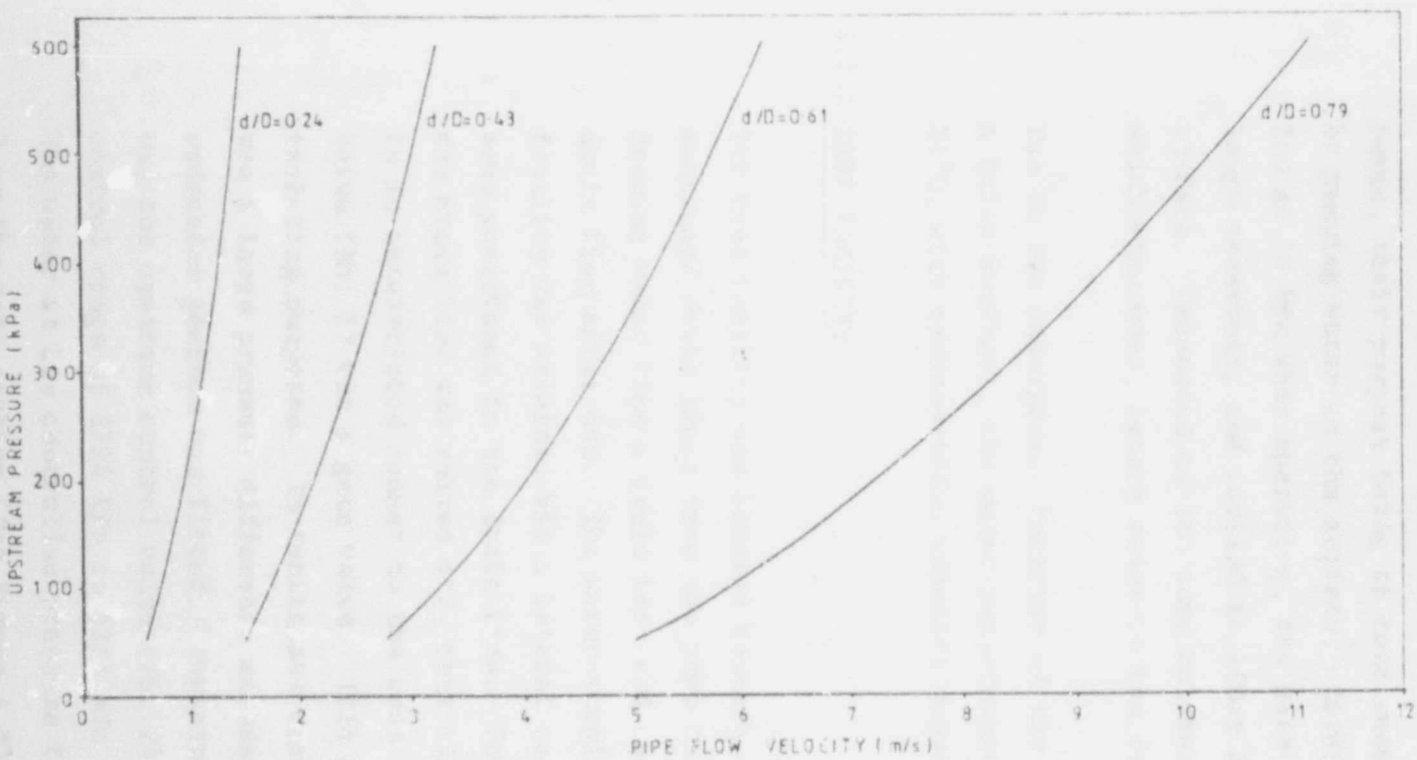


FIGURE 4.6 PREDICTED INCIPIENT CAVITATION FLOW VELOCITIES FOR UNIVERSITY OF THE WITWATERSRAND TESTS

4.2 EAST DRIEFONTEIN GOLD MINE CO LTD

The high pressure part of the study was conducted at the 7 Level Pump Station, North Shaft, East Driefontein Gold Mine. Situated at the pump station are 9 high pressure pumps, their purpose being to continuously dewater the mine by pumping water to the surface. Each pump delivers 200 l/s at 10 MPa when operating, the water being drawn from a large reservoir, and carried in 400mm N.B. columns to the surface. Connected to the pump columns are drain lines, which when used, return water to the reservoir.

Due to the underground location of the pump station (1000 m below surface), the water temperature remains constant at 24°C, with corresponding constant vapour pressure.

4.2.1 TEST FACILITY

The test facility was located beneath one of the above mentioned drain lines from the pump columns (Figure 4.7), drawing water from a drain line and returning it to the drain line after use. The water supply to the test facility was attained via a lateral tee section which had been positioned in the drain line. Downstream of the tee, the drain line was valved off, thus allowing water to flow in an unrestricted manner to the test facility. The first valve (No. 1) was a gate valve. This was used for isolating purposes. To facilitate easy opening when there was a large pressure difference across the valve, a reduction gearbox was fitted. Downstream of valve No. 1 was the upstream control valve (No. 2) which had a pressure control range of 1724 kPa to 8274 kPa (250 - 1200 PSI). The water at its controlled pressure flowed from valve No. 2 to the test section (See Figure 4.8) where the test orifice was situated.

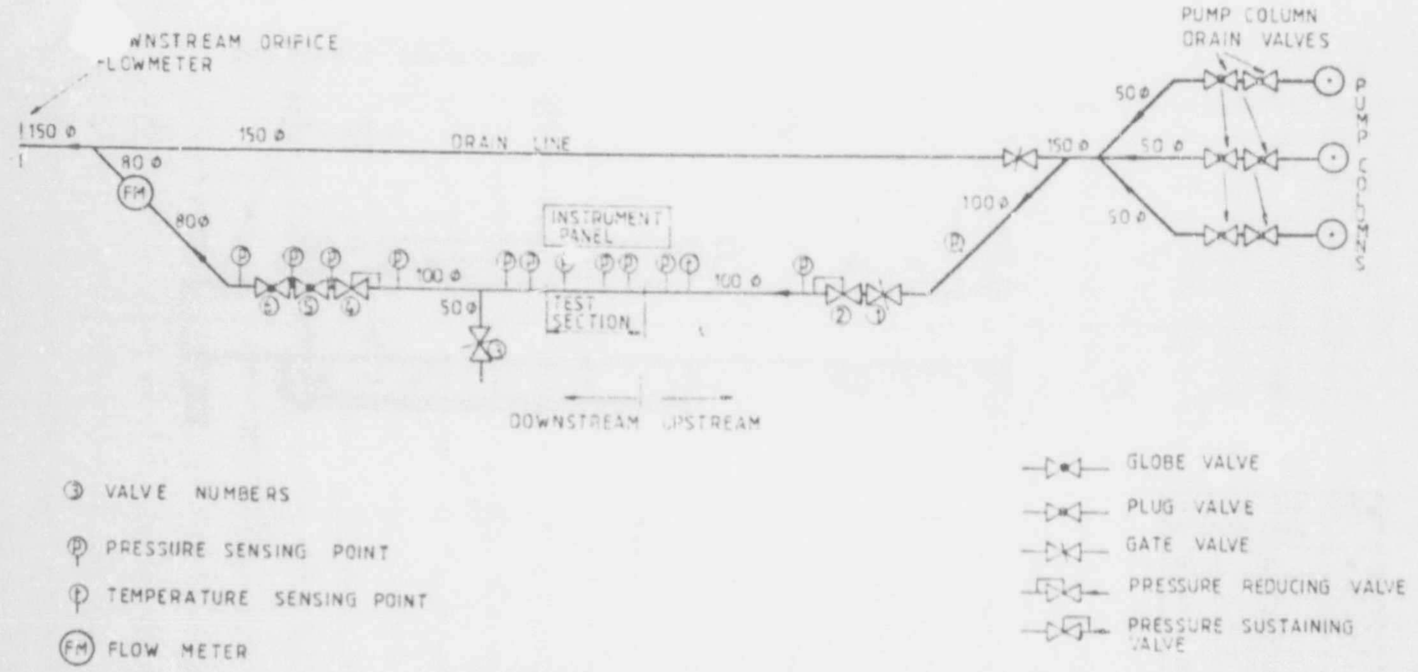


FIGURE 4.7 SCHEMATIC VIEW OF THE EAST DRIEFONTEIN GOLD MINE CAVITATION TEST FACILITY

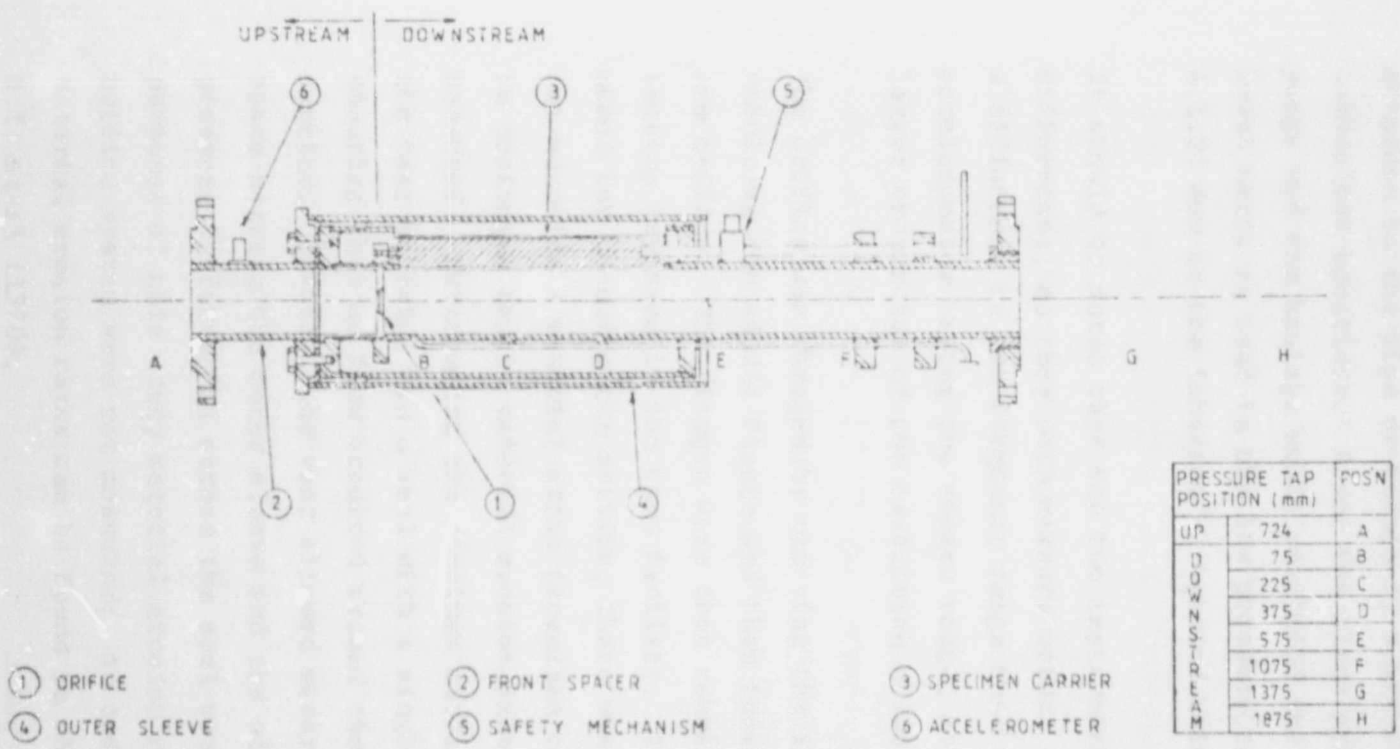


FIGURE 4.8 CAVITATION TEST SECTION - EAST DRIEFONTEIN GOLD MINE

Located upstream and downstream of the orifice were pressure tapping points, and a position for the location of an accelerometer to measure cavitation vibration. An accelerometer was chosen as it could be conveniently attached to the pipe or flange by a magnet or a stud at convenient locations. Also, the close proximity of the pumps and the haulage walls precluded the use of the sound level meter as used in the low pressure tests (see Section 4.1.2) due to the inherent background noise level.

It should be noted that the two instruments have minimal differences, as they both measure noise. However, there is a difference in the frequency range that is measured, the accelerometer having the widest range, so capturing a larger proportion of the cavitation noise.

The orifice was changed by removing the test section, unbolting the middle flange and then inserting the desired new orifice. The flanges were then rebolted and the test section replaced in the test facility. In addition to the means for changing the orifice, there was also a facility for mounting a material strip (specimen carrier), so that in prolonged tests, material erosion rates could be measured. Surrounding the specimen carrier which housed the test material was a seal with a single vent in it, thus ensuring that no flow occurred around the specimen carrier. However, the vent allowed water to enter the space between the outer sleeve and the pipe, so the pressure differential across the seal was minimal. For the purposes of this study material erosion rates for the orifice system were not measured; an indication of typical material erosion rates can be found in the work by Knapp R.T. et al (1970).

Above the test section was positioned an instrument panel, coupled to which were the pressure taps, and electrical measuring equipment (which consisted of an electrical pressure transducer and a differential pressure transmitter). Power supply, signal conditioning amplifiers, flow chart recorder and a digital panel meter were contained in a portable instrument cabinet mounted in the panel. Electrical measuring equipment mounted external to the panel were the flow meter and the accelerometer, the signals being transmitted to the instrument cabinet.

To measure flow rate a vortex flow meter was used, a useful feature of this instrument being its adjustable range, ie. the full scale electrical output could be set for the required flow range. The accuracy of this measurement is detailed in Section 5.2.2. As a check on the flow measurement an orifice plate flow meter was also used. This was positioned in the drain line 40 D downstream of the vortex flow meter.

The pressure gauges used were all liquid filled and had an accuracy specification of 0,5% of full scale deflection. These were mounted on the test facility pipes and the instrument panel, thus allowing valves to be adjusted correctly and to provide a visible indication of the pressure dissipation process. All the gauges mounted on the panel were connected to the facility pipe work by the circuit of instrument pipes, valves and hydraulic hoses shown in Figure 4.9.

The pressure transducer (Kistler, type 4043) was mounted in a steel block on the instrument panel, the generated signal being transmitted to an amplifier (Kistler, type 4601) for conditioning, the amplifier output then being displayed on the digital panel meter (Figure 4.9). To enable the pressures from the individual pressure taps to be measured by the single transducer, all of the pressure lines on the panel were routed through a series of multiport valves.

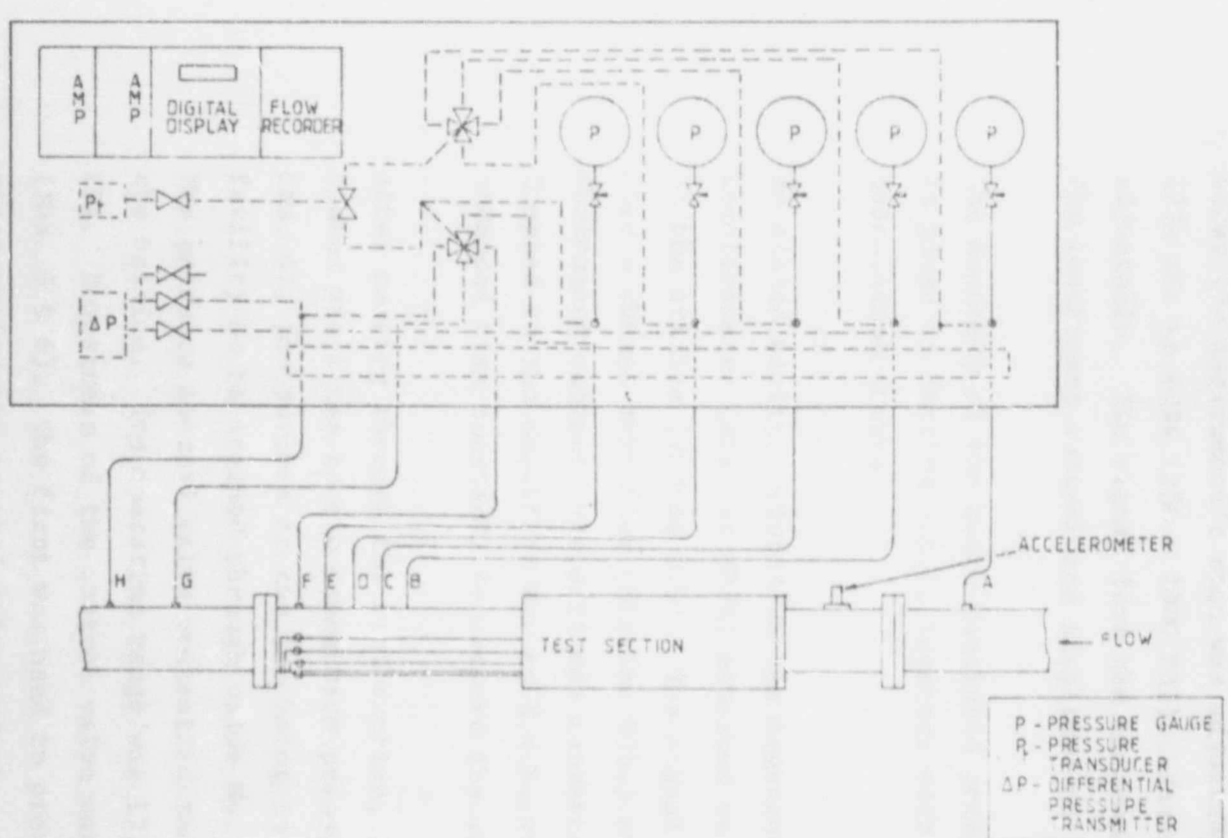


FIGURE 4.9 INSTRUMENT PANEL-EAST DRIEFONTEIN GOLD MINE

The differential pressure across the orifice was measured using a differential pressure transmitter (Gould, model PDH 3000-01M-12-11). This was connected across positions 1 and 8, respectively 4 D upstream and 24 D downstream of the orifice (Figure 4.8). The transmitter was mounted on the instrument panel (Figure 4.9), and as with the vortex flow meter the instrument's span was adjustable over the range 1724 kPa to 6894 (250 - 1000 PSI). The zero was also adjustable. The signal from the instrument was scaled in the instrument cabinet and displayed on the panel meter.

The accuracy of the above mentioned pressure measurements is given in Section 5.2.2, together with associated calculation errors.

As stated earlier, vibration was measured using a accelerometer (Kistler 808A) attached to the pipe upstream of the orifice (Figure 4.8). The signal produced was fed into a charge amplifier (Kistler 504A) mounted in the instrument cabinet, where it was converted into a voltage. Coupled to the amplifier was an R.M.S. voltmeter (with an extended time constant) to measure the output voltage.

After passing through the test section, the water then flowed via a tee to the downstream pressure control valve (No. 4), the purpose of the tee being to allow the test facility to be drained through valve No. 3 if necessary. The pressure control valve controlled the back pressure on the orifice. Its operating range was 1724 kPa to 8274 kPa. Downstream of the control valve were two globe valves (Nos. 5 & 6). The first was used to provide a back pressure for the control valve and also as an isolating valve; the second valve was also used as an isolating valve. Both of these valves were used as adjustable devices for dissipating pressure before the water passed into the low pressure side of the test facility. The water then passed through the flowmeter (a vortex type with an adjustable range), and then through another lateral tee on its way to the drain line for return to the pump reservoir.