2.3.2 BUBBLE COLLAPSE REBOUNDS

Whereas bubble collapse in the form of a torus and a water jet has been predicted and observed by a number of investigators, collapse rebounds appear to have been noted by relatively few observers. From a photographic study, Knapp R.T. and Hollander A. (1948) were able to plot the life history of a cavitation bubble. This consisted of a series of growths and collapses until the bubble was no longer visible (and presumably dissolved). Interestingly enough, the torus and water jet pattern was not observed (Section 2.3.1). Other investigators to observe rebounds were Shuttler N.D. and Messler R.B. (1965) and Kozirev S.P. (1968).

However, the rebounds observed by the latter represented secondary and tertiary splitting of the bubble. It was postulated that this occurrence was due to bubble surface instability. In contrast to this mechanism, Knapp R.T. and Hollander A. (1948) suggested that rebounds were caused by a water hammer effect at points where the liquid is subject to rapid compression.

Either of the above two mechanisms could be correct, though proof or disproof would require photographic studies and/or measurements on a microscopic scale to provide conclusive evidence. Perhaps an alternative mechanism could be suggested on the grounds of the effects of gas compression and turbulence. Assuming the bubble to collapse at a high rate (high bubble wall velocity), it is postulated by the author that there may be insufficient time for all of the gas/vapour in the bubble to be either condensed or dissolved; therefore compression will take place. This will continue until the pressure inside the bubble is greater than that of the surrounding liquid, hence causing the bubble to expand (regrowth), expansion continuing until the bubble again collapses and another regrowth cycle can take place, or the bubble is dissolved.

2.4 PREDICTION OF CAVITATION

The standard equation enabling the pressure head loss across an orifice to calculated is derived from the Bernoulli equation :-

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2}{2g} + Z_2 \qquad 2.7$$

For an ideal fluid with no change of potential head, the pressure head loss and pipe flow velocity are related by :

$$V = \sqrt{2g \ \Delta H} \qquad 2.8$$

$$\Delta H = \frac{V^2}{2g} \qquad 2.9$$

and for a real fluid the above two equations become

$$V = \sqrt{\frac{2g \Delta H}{K}} \qquad 2.10$$

$$\Delta H = \frac{K V^2}{2 g} \qquad 2.11$$

An alternative equation is

$$\Delta H = R Q^2 \qquad 2.12$$

as given by Douglas J.F. et al (1979).

In the above equation K represents the pressure loss coefficient for the pipe-orifice combination; this can also be calculated using the following equations (Miller D.S. 1978) :

$$K = \left(1 - \frac{A_v}{A_p}\right)^2 \left(\frac{A_p}{A_v}\right)^2 \qquad 2.13$$

or

$$K = \left(1 - \left(\frac{d}{D}\right)^2 C_c\right)^2 \frac{1}{\left[\frac{d}{D}\right]^4 \left[C_c\right]^2} \qquad 2.14$$

where C_c is the contraction coefficient.

The occurence of cavitation for an orifice can be explained by the following general statement. As the flow through an orifice increases, the associated pressure drop increases at a rate proportional to the square of the pipe velocity; this can theoretically continue until the pressure drop is equal in magnitude to the upstream pressure. At a point between these two values, the pressure at the orifice and the turbulence level reach values that allow cavitation to occur; and as a consequence vibration and erosion of surfaces can also occur (Heathcock C.J. et al 1979).

When considering orifice induced cavitation, the only methods available for its prediction appear to be those given by investigators at the University of Colorado, USA - specifically Tullis J.P. and Ball J.W. (1974), Sweeney C.E. (1974) and Ball J.W. et al (1975). The work of Tullis J.P. and Ball J.W. (1974) indicates that no universal values are available to describe cavitation levels, as all equipment appears to have a unique cavitation performance. This is an important point as it necessitates work having to be repeated when cavitation limits are required for a new design of equipment; such factors as the form of the equipment, the system housing the equipment, the state of the fluid before it cavitates and other factors, some of which are given in this chapter, are thus important. This suggests that care should be exercised in the choice of any particular cavitation method

The particular approaches formulated by the investigators at the University of Colorado rely on the use of reference data, thus making prediction a more complicated method than if the equations put forward were explicit. Sweeney C.E. (1974) investigated cavitation at the incipient damage level, and derived the following equation :

$$V_{ID} = V_{IDR}\left(\frac{P_D - P_V}{P_{UR} - P_{VR}}\right)^{0.45}\left(\frac{\beta_R}{\beta}\right)^{1.07} \qquad 2.15$$

$2 < \beta < 6$

The incipient damage level was defined as that corresponding to a damage level of 1 pit/in^2 - minute. This is said to have a pressure scale effect, ie. as the upstream pressure changes (for the same pipe and orifice size), the velocity at which incipient damage cavitation occurs also changes. If the equation is evaluated on the basis of material removal from an aluminium surface, a size scale effect is said to be present (ie. for the same upstream pressure and orifice ratio, a change in pipe size will change the cavitation limit). Considering that erosion of surfaces is an important facet of cavitation, it would appear that the above equation should preferably have taken into account material removal. In addition to this comment, it is also suggested that the material under test should be representative of that used to construct the system for which cavitation prediction is being attempted.

Ball J.W. et al (1975) appear to have carried out the most work on orifice cavitation effects. They put forward for incipient and critical cavitation levels :-

For incipient and critial cavitation, $D/D_R > 1$

$$V = 0{,}94\, V_R \left(\frac{P_U - P_V}{P_{UR} - P_{VR}}\right)^{0,5} \left(1 - \frac{\log D/D_R}{10^{[0,4 - 0,52 \log C_d]}}\right) \qquad 2.16$$

and for $D/D_R < 1$

$$V = \frac{V_R \left(\frac{P_U - P_V}{P_{UR} - P_{VR}}\right)^{0,5}}{0{,}94 \left(1 - \frac{\log D/D_R}{10^{[0,4 - 0,52 \log C_d]}}\right)} \qquad 2.17$$

where $C_d = \frac{V}{\left(\frac{[P_U - P_D]}{\rho} + V^2\right)^{0,5}}$ 2.18

The data used for the above equations (2.16 & 2.18) are shown in Figure 2.6a and 2.6b (Tullis J.P. 1973).

Also, for incipient damage cavitation the following equation was out forward :

$$V_{ID} = V_{IDR} \left(\frac{P_U - P_V}{P_{UR} - P_{VR}}\right)^{0,45} \left(\frac{\beta_R}{\beta}\right)^{1,09} \qquad 2.19$$

This is similar to the equation of Sweeney C.E. (1974), equation 2.15 above.

The scale effect which is said to exist for the incipient and critical cavitation levels results from change of size. The cavitation level defined as choking (for which no prediction equation has been formulated) is said not to have size or pressure scale effects associated with it.

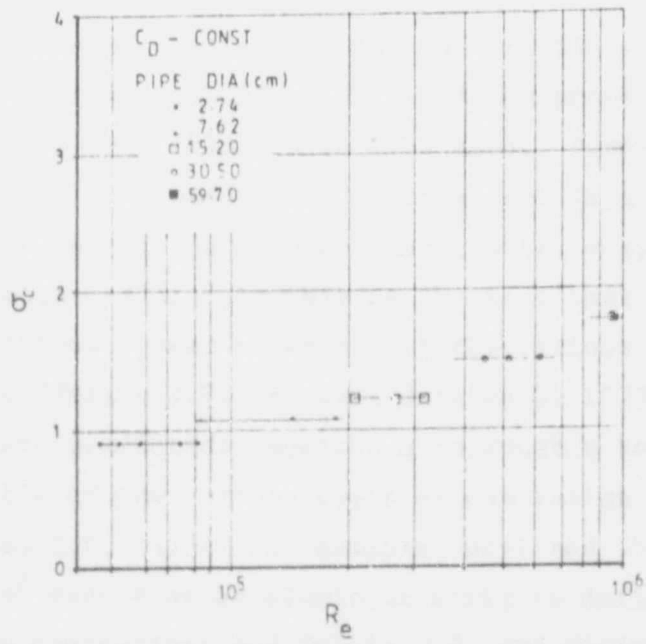

FIGURE 2.6a SIZE SCALE EFFECTS FOR ORIFICES (TULLIS J.P. 1973)

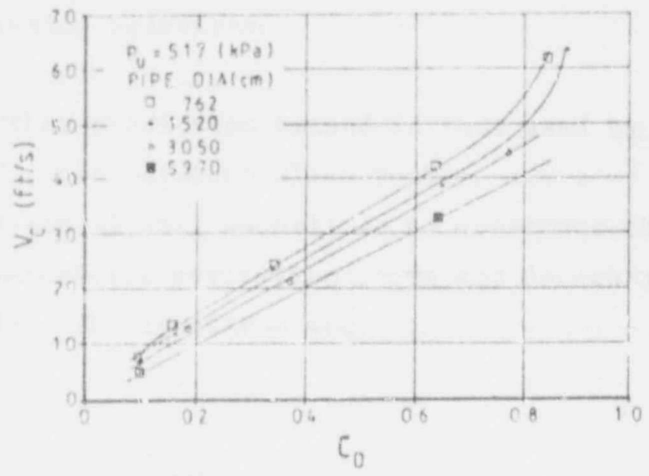

FIGURE 2.6b SIZE SCALE EFFECTS FOR CIRCULAR ORIFICES (TULLIS J.P. 1973)

The limits of application for the equations are the diameter ratios, 0,38 to 0,80 and the pressure range, 30 PSI to 200 PSI (206 kPa to 1379 kPa). Further to these is the above mentioned need for reference data, which could be restrictive if the data are unreliable, suspect, or not available. Allied to this is the fact that few exact definitions appear to exist for the various cavitation levels (Tullis J.P. and Govindarajan R. 1973); thus accurate prediction requires a thorough a knowledge as possible of the various types of cavitation phenomena. Sweeney C.E. (1974) for example, utilised the limit of 1 pit/in^2 minute on an aluminium strip to define incipient damage cavitation; and Tullis J.P. and Govindarajan R. (1973) defined incip[illegible]itation from a graph (Figures 2.4 & 4.5a) of nois[illegible]ion index (equation 2.20), the turning point w[illegible]ation noise beings to rapidly increase being given as indicative of the occurrence of incipient cavitation. Errors can obviously arise if the equations are used outside their operating ranges, or they are used to scale from reference data associated with a system which is different from one used to produce the prediction equations.

A further prediction method is that used by Ball J.W. (1975); here dimensionless numbers are used to interpret experimental data as well as to construct the characteristic cavitation curve and determine cavitation levels. The equations are

$$\sigma_1 = \frac{P_D - P_V}{P_U - P_D} \qquad 2.20$$

$$\sigma_2 = \frac{P_D - P_V}{\rho V^2} \qquad 2.21$$

and form the ratio of pressure suppressing cavitation to pressure differential (or velocity head tending to create cavitation). However, it was mentioned that researchers have experienced problems in the application of the above, again due to scale effects. It should also be noted that neither equation incorporates a term to describe the form of the cavitating device.

Despite this, and in view of the extended upstream pressure range intended to be used in the experiments, described here, it was decided to examine these numbers as an aid to interpreting experimental data.

2.5 EXPERIMENTAL PROCEDURES AVAILABLE FOR INVESTIGATING CAVITATION

There appear to be five main experimental procedures available for investigating cavitation. These are :-

i) Vibratory
ii) Ultrasonic
iii) Rotating Disk
iv) Impingement
v) Water Tunnels

The first four procedures are termed accelerated damage methods, and are used primarily to measure the cavitation erosion rates of materials. Specifically, the first and second procedures are static tests, where the same fluid is used continuously, cavitation being induced by vibration. The third and fourth procedures are fixed flow pattern tests, in which flow sets up cavitation. The fifth method is also a flow test, the difference being that actual flow conditions are simulated.

It is only the fifth test method which is of immediate interest in this investigation. However, all of the methods will be briefly described and discussed

2.5.1 VIBRATORY

The vibratory cavitation test device is used to determine the cavitation erosion rates of materials, a typical device being shown schematically in Figure 2.7. The device consists primarily of an oscillator, the test material forming the oscillator tip. The fluid in which cavitation is to be set up is contained in a special vessel in which both pressure and temperature can be set as required. The oscillator is located on top of the vessel, the tip being immersed in the fluid. Cavitation is produced by the vibration of the oscillator, the vibrating test material inducing cavitation in the fluid at the material/fluid interface. The literature does not indicate that the cavitation level can be varied, or that it is a measurable quantity that can be related to an actual cavitation situation. However, the method allows material erosion rates to be measured more easily and more rapidly than in an actual sitation, and the results obtained provide what can primarily be termed a rank of erosion rates. This is due to the no flow nature of the system and hence of the method for producing cavitation. A difference between the operation of this device and testing under actual flow conditions lies in changing fluid properties. In the vibratory device the fluid is used continuously, and hence fluid properties (eg. air content), may change during the test, whereas in flow testing new fluid is continually supplied. A further difference is that pressure and temeprature gradients in the vibratory device may also be different to those of flow tests.

2.5.2 ULTRASONIC

The ultrasonic cavitation device is similar in operation to the vibratory device (Section 2.5.1), a typical example being shown in Figure 2.8. The device consists of a glass vessel in which a stainless steel block is located in the base; test specimens are located in a recess which has been

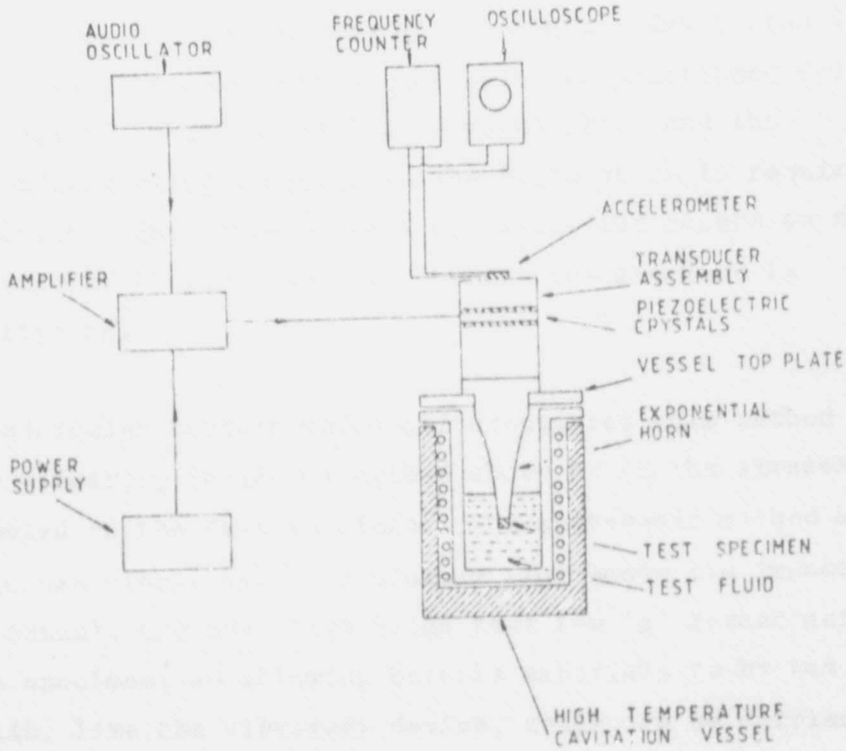

FIGURE 2.7 **VIBRATORY CAVITATION TEST DEVICE (GARCIA R. ET AL 1967)**

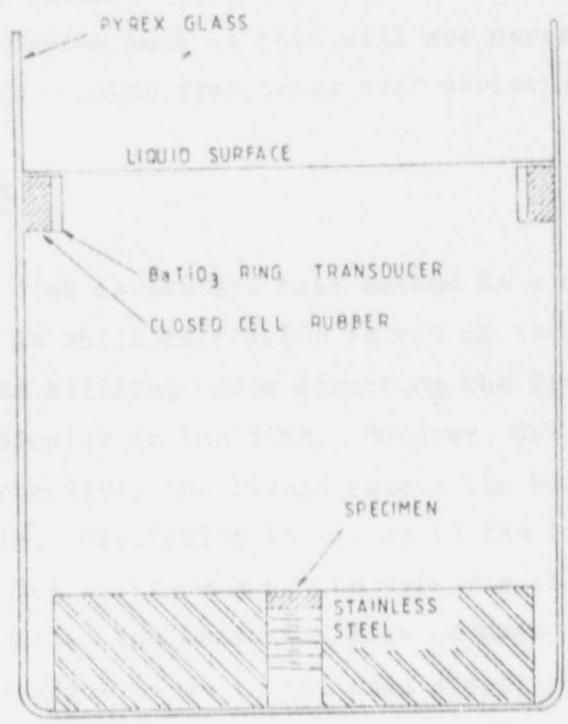

FIGURE 2.8 **ULTRASONIC CAVITATION TEST DEVICE (ELLIS A.T. 1955)**

drilled on the centre line of the block. Cavitation is set up by an ultrasonic transducer which is positioned within the vessel, both the stainless steel block and the transducer being immersed in the fluid which is required to cavitate. The maximum level of cavitation occurs on the centreline of the vessel (ie. where the specimen is positioned).

A particular feature which differentiates this method from the vibratory device described above is in the stresses imposed on the test specimen. The ultrasonic method keeps specimen vibrations to a minimum (and hence the imposed stresses), the advantage being that low 'g' forces act on the specimen, so allowing brittle materials to be tested. Again, like the vibratory device, tests can be carried out rapidly and easily due to the concentrated cavitation on the specimen. However, the cavitation level cannot be related to an actual flow situation (as with the vibratory device). This means that material erosion rate results can again only be ranked. It should also be noted that results from any one device such as this will not necessarily correlate with results from other test devices.

2.5.3 ROTATING DISK

The rotating disk cavitation test method is a device (Figure 2.9) in which cavitation is set up in a flow situation, the stilling vanes directing the liquid at an angle perpendicular to the disk. However, due to the rotation of the disk, the liquid enters the holes at a modified angle. Cavitation is set up in the liquid as it leaves the holes on its way to the exit via the stilling vanes On exiting the hole, the flow adjacent to the disk's back surface moves in the same direction as that of rotation. Hence, the cavitation bubbles flow over the surface of the disk, collapsing on the disk's downstream surface. Material specimens for erosion testing are mounted on the back surface of the disk in the cavitation

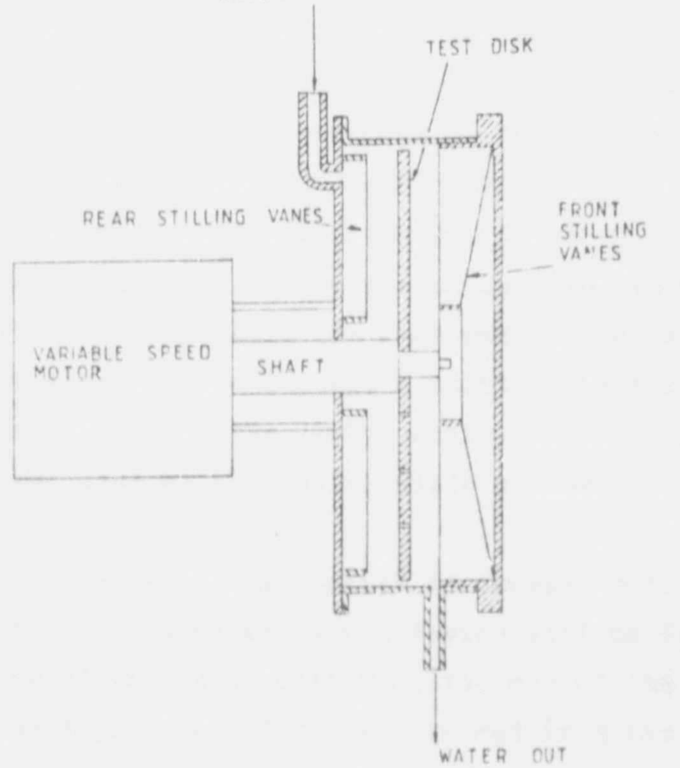

FIGURE 2.9 ROTATING DISK CAVITATION TEST DEVICE (LICHTMAN J.Z. & WEINGRAM E.R. 1964)

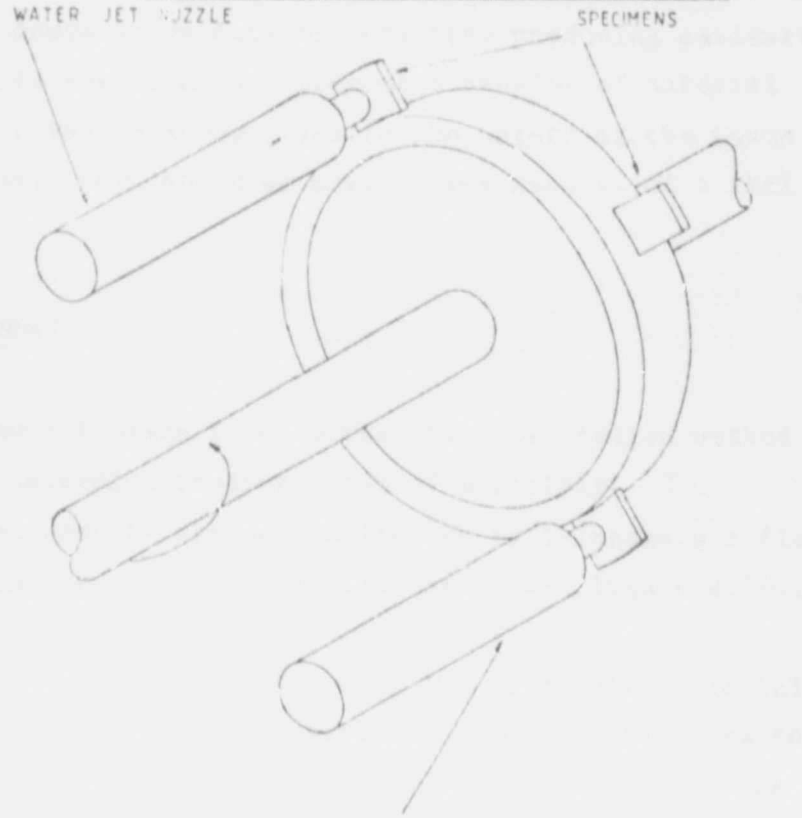

FIGURE 2.10 IMPINGEMENT CAVITATION TEST DEVICE

bubble collapse regions downsteam of the holes. The use of a disk means that more than one material can be tested at one time, or that multiple specimens of the same material can be tested simultaneously, and an average result obtained. Depending on the fluid used, the level of temperature and pressure can be varied to simulate various flow conditions. Generally, the flow path can be said to resemble the flow pattern through a turbine where fixed and moving blades are used, the casing acting as the fixed blades and the disk as the moving blade system.

The cavitation level in this device is caused by flow. This means that fluid entering the device will be fresh, and should be of the same quality at the end of the test as it was at the beginning. Results obtained from the tests will thus be more representative of actual cavitation. However, this technique is basically a procedure for erosion testing of materials, and as such, it cannot provide comparative data for the flow producing cavitation. Once again the results represent a ranking of material erosion rates, although, due to the nature of the tests performed, they should be more representative of a real system.

2.5.4 IMPINGEMENT

Impingement testing is a further flow cavitation method used to determine erosion rates of materials. The technique used to produce cavitation is in essence a fluid jet impinging on a material test specimen (Figure 2.10).

The apparatus consists of a rotating disk, with material specimens mounted on its periphery. Mounted parallel to the axis are the nozzles to produce the fluid jets (the nozzles do not move). As the disk rotates the specimens cut through the jets; the action of the fluid on the specimen surface causes cavitation, and thus erodes the bubble collapse regions downsteam of the holes. The use of a disk means that more than one material can be tested at one time, or that multiple specimens of the same material can be tested simultaneously, and an average result obtained. Depending on the fluid used, the level of temperature and pressure can be varied to simulate various flow conditions. Generally, the flow path can be said to resemble the flow pattern through a turbine where fixed and moving blades are used, the casing acting as the fixed blades and the disk as the moving blade system.

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2.5.5 WATER TUNNEL

There are two types of water tunnel - open and closed - the difference being that open tunnels use continuously 'new' water from a large tank or reservoir, and closed tunnels use recirculated water. Closed tunnels are the most commonly used type (J v.d. Meulen 1973, Hammitt F.G. 1964, and Pearce I.D. and Lichtarowicz A.1971). They do not require a special external supply of water, and are relatively compact in size; thus they can readily be incorporated into laboratories.

A feature of both open and closed tunnels is the level of control available in the case of the fluid. With the correct equipment, pressure, temperature, air content, etc., can all be varied.

A typical closed water tunnel is shown in Figure 2.11. In this circuit, fluid is pumped to the test section where the test material is situated (and where cavitation is allowed to occur). After passing through the test section, the fluid passes through a flow meter to the suction of the pump, and is then recycled to the test section.

Open water tunnels are essentially the same in operation as closed tunnels, the difference being that no pump is required; the necessary pressure is normally attained by adjusting the reservoir elevation.

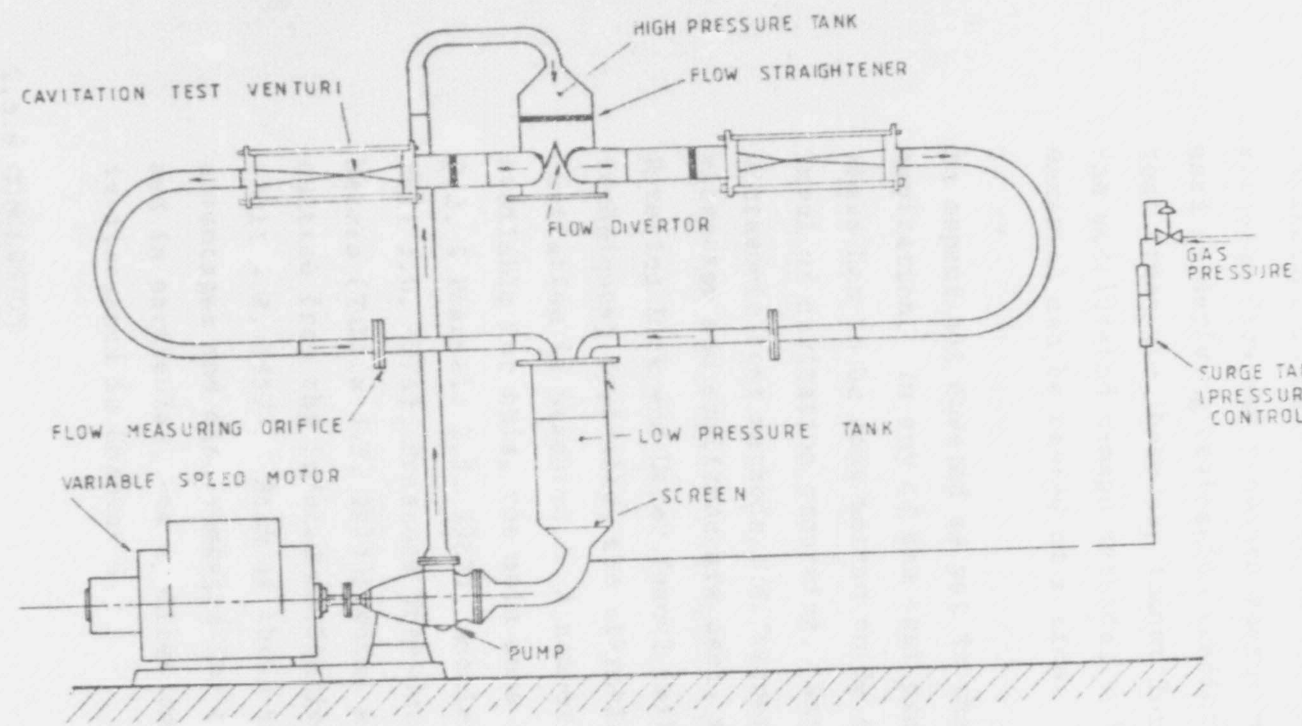

FIGURE 2.11 WATER TUNNEL CAVITATION TEST DEVICE (HAMMITT F.G. 1964)

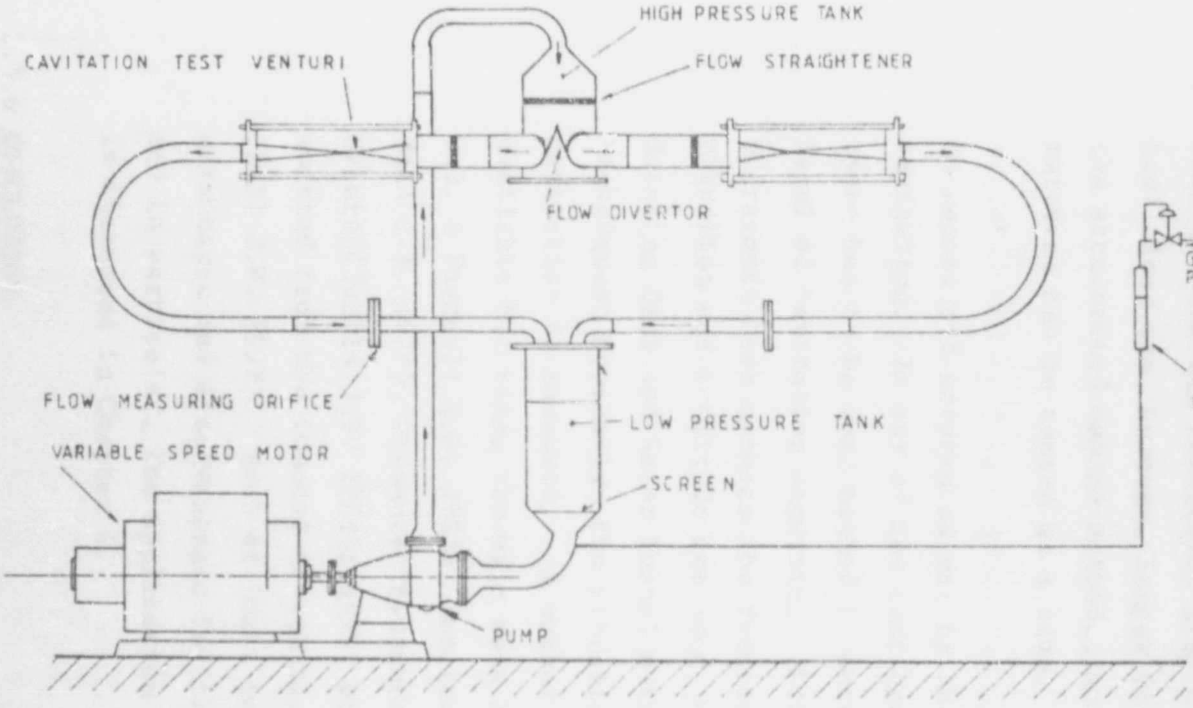

FIGURE 2.11 WATER TUNNEL CAVITATION TEST DEVICE (HAMMITT F.G. 1964)

The fundamental difference between the use of water tunnels and the accelerated damage methods is in the flow simulation. The latter represent either static or fixed flow tests whereas a water tunnel allows actual flow conditions to be modelled in the test section, thereby allowing flow and pressure measurements to be taken, and used in deriving cavitation prediction data. The required test times are, however, longer for this method than for the accelerated damage methods, and generally only one material can be tested at a time.

An aspect not covered as yet is the measurement of cavitation. In any of the test procedures mentioned above there has to be some method to determine and record the level of cavitation occurring. With the Vibratory and Ultrasonic test methods the frequency of the applied vibration and amplitude are used, whereas the Impingement, Rotating Disk and Water Tunnel methods require alternative techniques; typically, the vibration set up by the cavitation is measured. A number of techniques are available for this, the main ones being Hydrophone (McNulty P.J. & Pearsall I.S. 1982), Accelerometer (Tullis J.P. & Ball J.W. 1974), Pressure Transducers and Sound Level Meters (Tullis J.P. 1973); aural measurement of the sound emitted from the induced cavitation has also been used (Ball J.W. 1957). Each of these techniques has its advantages and disadvantages for the intended application, and in particular, the application relevant for this study is discussed in Chapter 4.

2.5.6 CONCLUSION

Of the five methods available for investigating cavitation, the procedure that appeared to be most suitable for evaluating cavitation under the conditions postulated was the water tunnel, because it allowed flow conditions to be modelled, flow measurements taken and, if necessary, the erosion of materials could also be investigated.

The other four methods are primarily for measuring the erosion rates of materials, but are not concerned with flow conditions. With the four accelerated damage methods, it can additionally be difficult to determine the intensity of the cavitation causing erosion, and the results obtained can not necessarily be correlated with other test data.

Experimental work was therefore undertaken on the principle of the water tunnel described above. The aim of the work was to provide information on the behaviour of orifice plates when dissipating large pressure heads in a high upstream pressure situation, and on the consequential cavitation; also, to provide cavitation information from a low pressure situation for checking the prediction equations listed in Section 2.4.

3. ORIFICE PLATE

The orifice plate has been used for a number of years as a device to dissipate pressure, or more commonly, to serve as a flow meter - the flow rate being proportional to the square root of the pressure difference across it; and because of the inherent simplicity, the orifice has achieved widespread use in engineering industries. However, it is surprising that the use of orifices as pressure dissipating devices appears to have been only briefly treated in published literature. The following section describes flow through an orifice and explains how the pressure head is dissipated.

3.1 ORIFICE FLOW

Starting at a position upstream of an orifice and assuming turbulent flow (Re N° > 2000) under incompressible conditions, a number of basic statements can be made :

i) Pressure is dissipated through an abrupt expansion by turbulence.

ii) The upstream velocity profile (Figure 3.1) is not affected by the presence of the orifice.

iii) The fluid shear stress is associated with two factors, one representing viscous shear (fluid property) and the other representing the effect of turbulence (flow property).

The expressions which are used to describe the above statements involve parameters that vary as the fluid passes through the orifice. As the flow approaches the orifice, the velocity profile becomes affected by the downstream obstruction, which involves an acceleration and a change of direction, the fluid gaining an mponent of velocity. Due to the change ection a small recirculation zone is created (2), and a stagnation point (strictly, line) occurs at the corner formed by the pipe wall and the plate. On reaching the

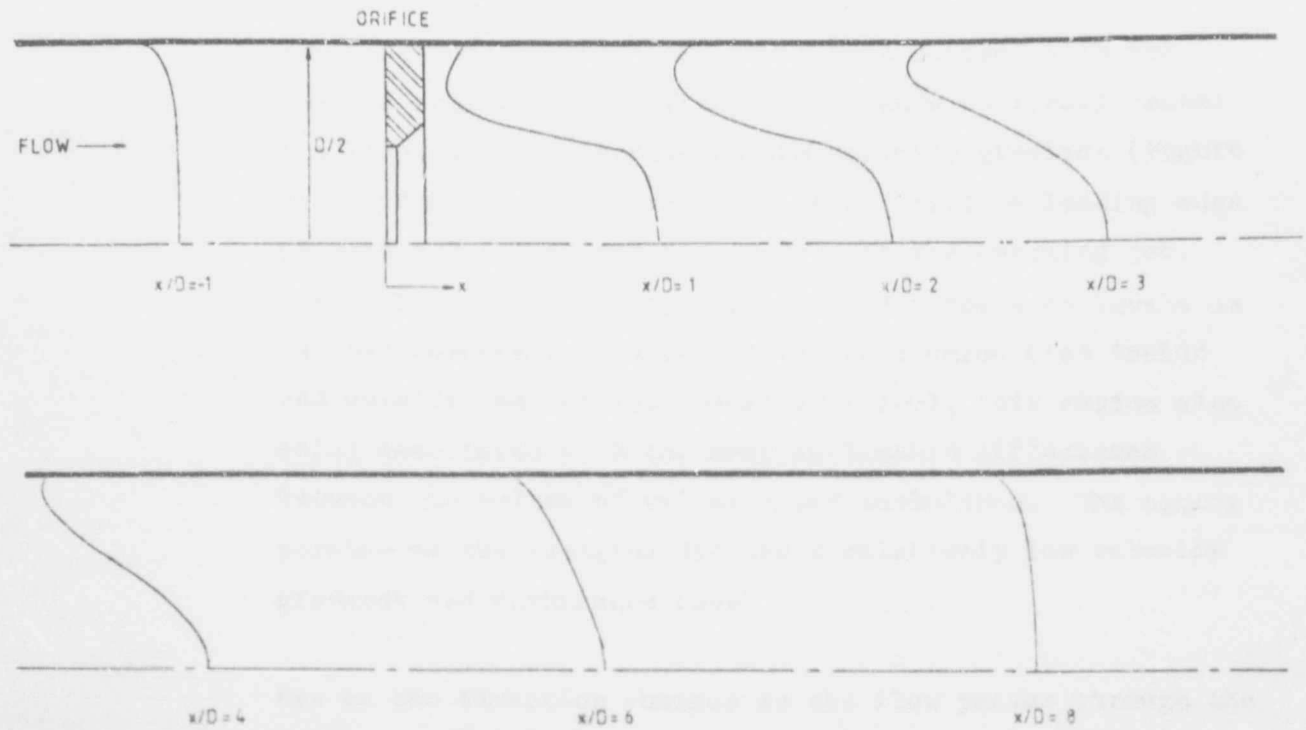

FIGURE 3.1 ORIFICE VELOCITY PROFILES
(CHATURVEDI M.C. 1963)

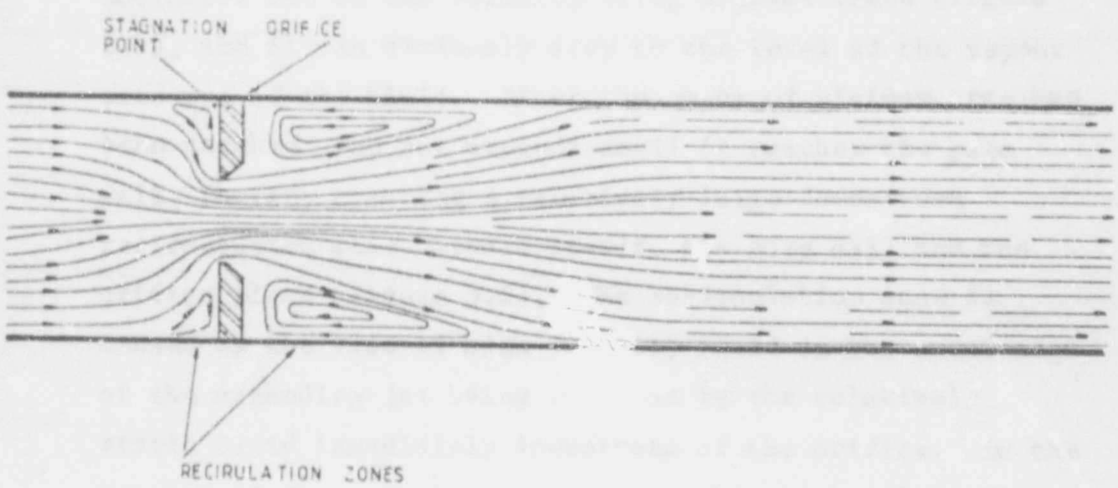

FIGURE 3.2 ORIFICE STREAMLINES

orifice, some of the fluid comes into contact with the leading edge of the orifice; this tends to locally shear the flow, thereby increasing the velocity gradient (Figure 3.1) and setting up turbulence at the orifice leading edge (Figure 3.3 & 3.4) and the surface of the emerging jet. The increase in velocity gradient and turbulence levels on the jet surface is due to the relative velocities inside and outside the jet (as described below), this region also being associated with the most noticeable differences between the values of velocity and turbulence. The centre portion of the emerging jet has a relatively low velocity gradient and turbulence level.

Due to the direction changes as the flow passes through the orifice, the streamlines in the jet are not parallel (Figure 3.5). The jet initially contracts to a point of minimum area called the vena contracta, its position being a function of the contraction ratio (Figure 3.6). Overall, the pressure of the jet is lo[illegible]posite the vena contracta due to the velo[illegible] highest there (Figure 3.5), and it can obviously drop to the level of the vapour pressure of the fluid. After the point of minimum area has been reached, the jet expands until it reaches the pipe wall, thereby creating a relatively large downstream recirculation zone between itself, the pipe wall and the orifice plate (Figure 3.2). The recirculation zone is caused by the flow of high velocity fluid on the outer edge of the expanding jet being retarded by the relatively static fluid immediately downstream of the orifice. In the process of jet retardation, some of the static fluid is carried downstream with the flow, thereby initiating the characteristic recirculation pattern.

On contact with the pipe wall the boundary layer becomes re-established, a typical turbulent velocity profile being developed at this point, the pressure of the fluid being higher then at the vena contracta due to the diffussion effect. There is also a net pressure loss across the orifice due to the turbulence set up by contraction and re-expansion.

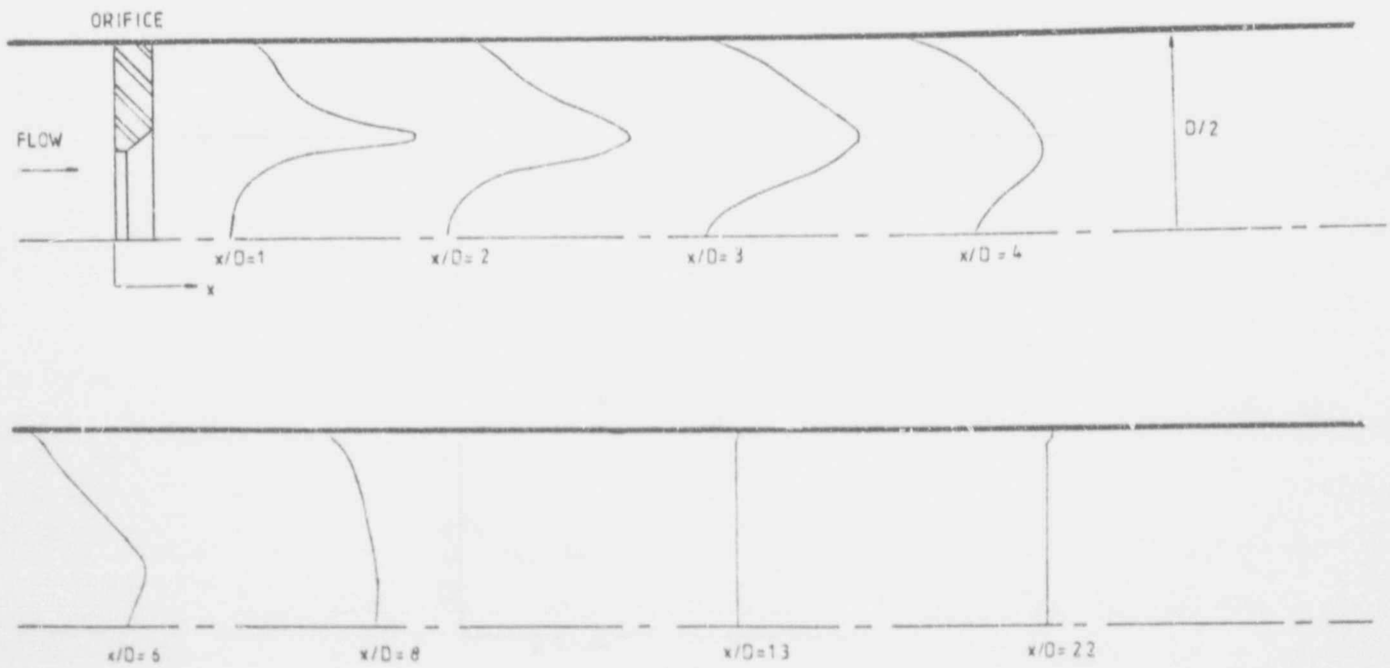

FIGURE 3.3 ORIFICE - AXIAL TURBULENCE (CHATURVEDI M.C. 1963)

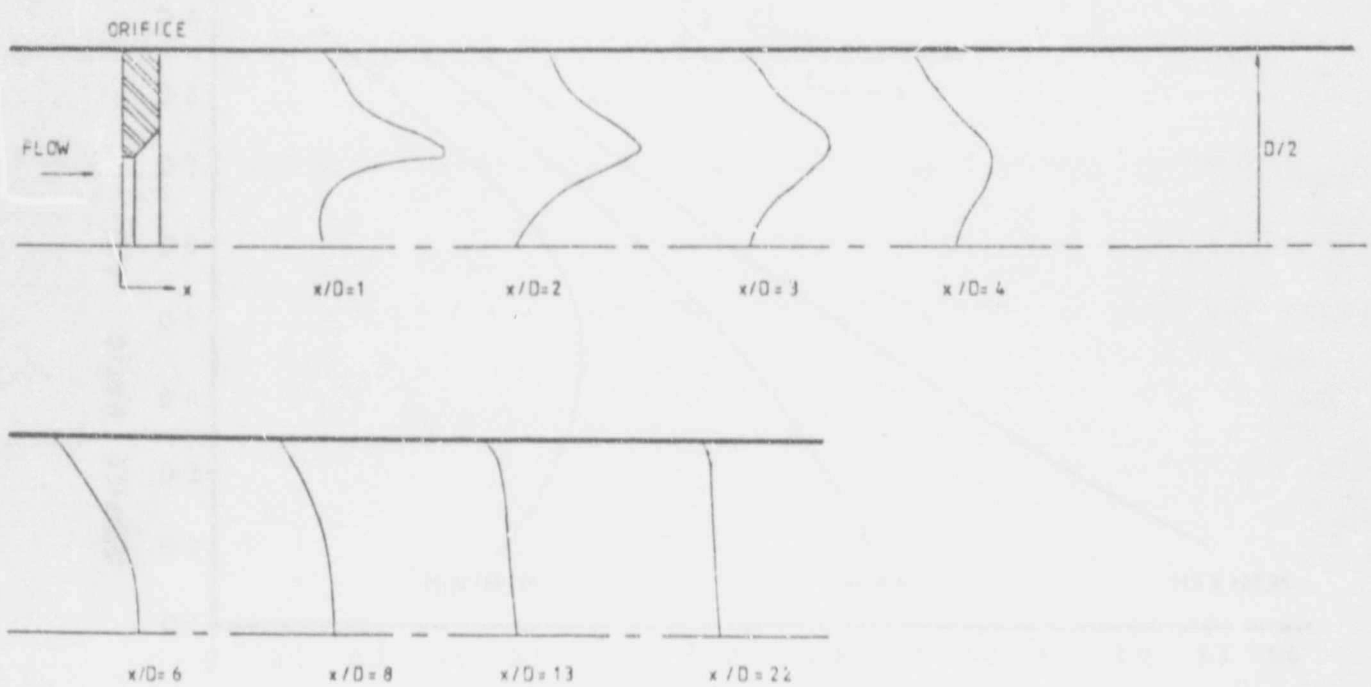

FIGURE 3.4 ORIFICE - RADIAL TURBULENCE (CHATURVEDI M.C. 1963)

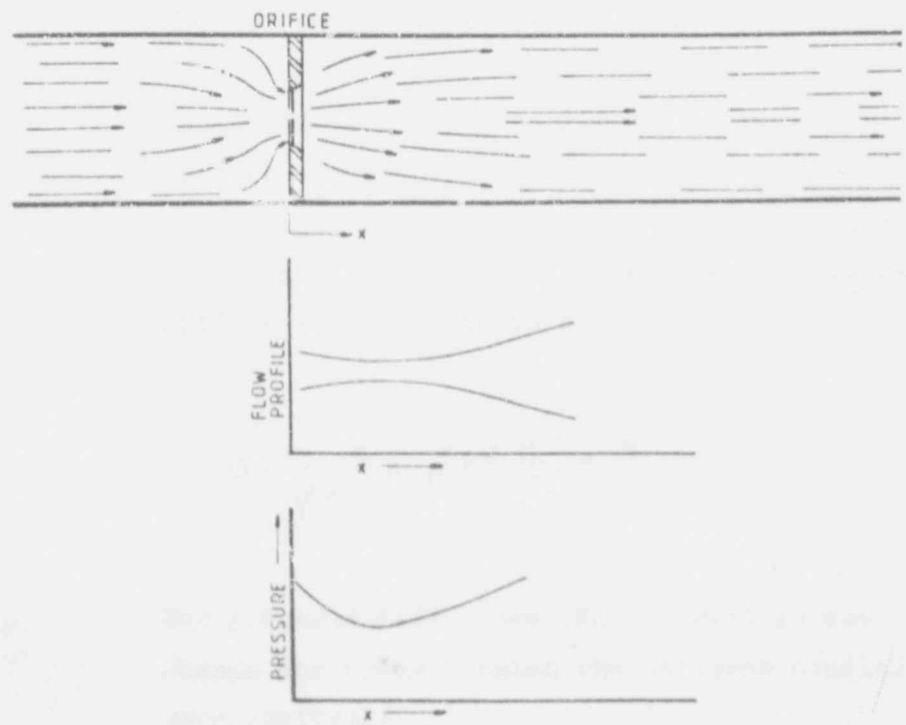

FIGURE 3.5 ORIFICE - TYPICAL PRESSURE PROFILE

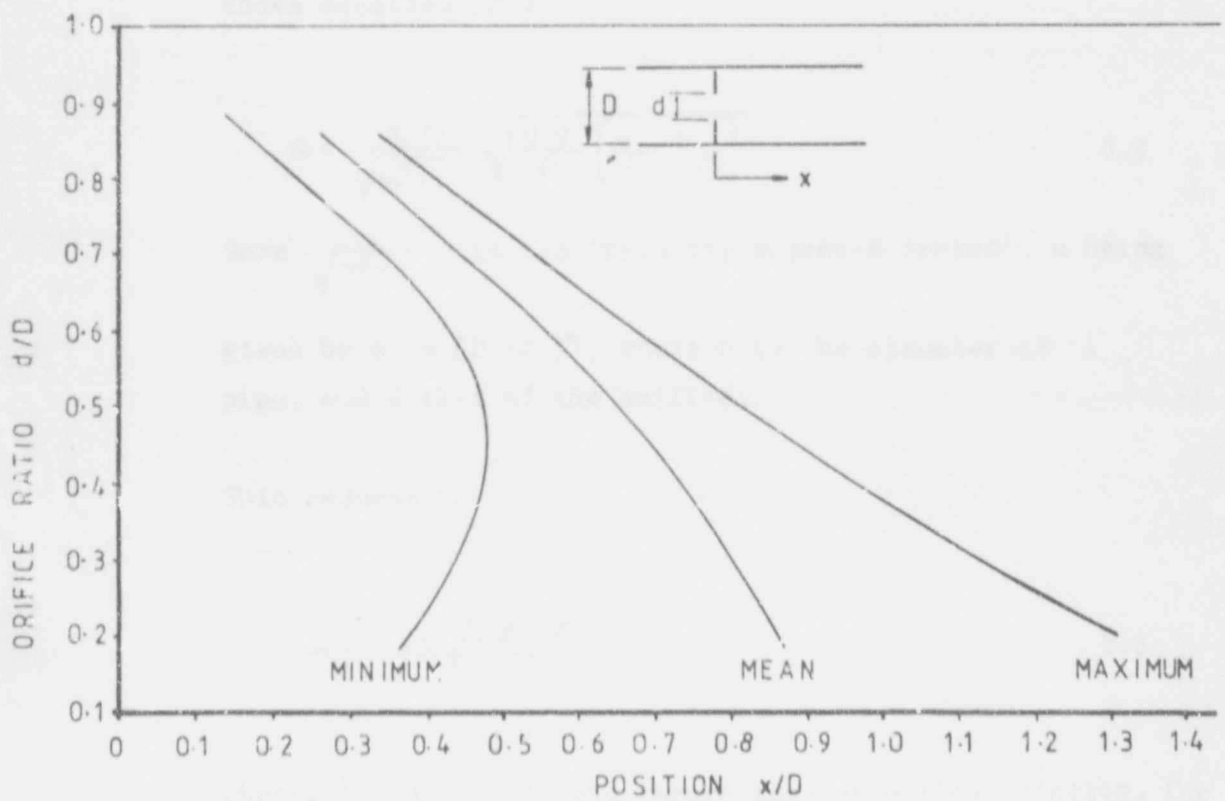

FIGURE 3.6 POSITION OF MINIMUM PRESSURE DOWNSTREAM OF AN ORIFICE (ASME 1959)

Author Greenfield Paul Somerford
Name of thesis Investigation Of Incipient Cavitation Limits For Square-edged Orifice Plate Pressure Dissipators In High Pressure Water Reticulation Systems. 1985

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