Hydraulics Research
Wallingford

IMPACT PRESSURES IN FALLING-JET ENERGY DISSIPATORS

Literature review and preliminary experiments

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EXECUTIVE SUMMARY

Plunge pools constitute an important category of energy dissipator, and have often been used in conjunction with overflow spillways in arch dams. Experience has shown that plunging jets can cause serious damage to the protective aprons which may be needed to prevent scour on the downstream sides of such dams.

A literature review was carried out to determine what information was available about the behaviour and effects of falling jets. It was found that although several studies had been made of scour depths in unlined plunge pools, there were no data which would enable designers to assess impact pressures on protective aprons. It was therefore decided that experiments should be carried out to determine the relationships between such impact pressures and the characteristics of jets entering plunge pools of various depths. The amount of air entrained in a falling jet is believed to have a major effect on the pressures which it exerts, so the test rig was designed to allow air to be added to the jet in a controlled manner.

To assist in the design of the rig, a 1:3 model of the jet nozzle and aeration device was built and tested, and provided useful information which was incorporated in the full-size rig. The latter produces a rectangular jet measuring 200mm by 67mm with water velocities of up to 5m/s. Mean and fluctuating pressures are measured by fifteen transducers mounted on a plate in the floor of the rig. The length of the jet nozzle can be varied so that both free-falling and submerged jets can be studied. Measurements and analysis provide data on the turbulence in the jet, the energy and range of the pressure fluctuations, their spatial and spectral distributions, and the local concentrations of air in the flow.

The report contains results of preliminary tests on the full-size rig. Measurements were made at jet velocities between 2.4m/s and 4.5m/s with turbulence intensities of about 3%. The mean impact pressure produced by the core of a submerged jet discharging without aeration just below the surface of the plunge pool was found to be comparable to the velocity head of the jet. A free-falling jet subject to natural aeration produced lower mean pressures but larger fluctuations than an equivalent submerged jet.

Further tests are planned with and without controlled aeration for a range of jet velocities and water depths. Improvements to the recording system will allow more detailed analysis of the results.

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1 INTRODUCTION

The stated aim of this research was to measure impact pressures produced by free-falling jets on a solid surface. The ultimate objective was to develop a scaling relationship that could be used to predict prototype forces from measurements made on small scale models. Another development could be the estimation of scour depths in situations where the jet is landing on a rock surface.

The research has fallen into two distinct parts. Initially a literature survey was carried out in order to determine what research had already been done, and hence to define areas in which further work was necessary. Following the drawing up of a suitable research programme, an experimental rig was designed and built: a start has now been made on a series of experiments.

The literature survey describing previous research on the subject is contained in Appendix A. The main part of this report sets out the justification for the proposed new study, briefly reviews the main conclusions from previous research, and describes the work done so far.

2 GENERAL BACKGROUND

When a spillway is designed so that it discharges freely into the atmosphere, there are three commonly adopted solutions to the problem of how to deal with the jet when it hits the ground on the downstream side of the dam. These are:

(a) to construct a plunge pool, with the water cushion created by a control weir at the downstream end of the pool;

(b) to allow a scour hole to form in the bed rock, with some raising of the natural tailwater level, but not to the same extent as in (a);

(c) to allow erosion to occur in the impact zone, without any attempt to increase the tailwater level above that created by the existing natural channel.

Whatever the solution that is adopted, the basic problem is the same viz what are the impact forces that are generated? These pressures can be high: in some cases very nearly equal to the overall head difference between the reservoir water level upstream and the tailwater level downstream. At Morrow Dam in the USA impact pressures of roughly one-third of the overall head of 110m were measured in model tests. The model studies of Victoria Dam in Sri Lanka (designed by a British firm of consulting engineers) revealed peak impact pressures 65 to 75 per cent of the gross head from reservoir level to plunge pool invert level: the mean impact pressures, on the other hand, were only 10 to 30 per cent of the gross head.

Of particular importance in designing a plunge pool are the peak fluctuating pressures, rather than the mean pressures. If these high dynamic pressures can penetrate cracks in the concrete floor of a plunge pool, or fissures in the bed rock, they can produce large upward forces, significantly larger than the downward force resulting from the weight of the rock or concrete and the hydrostatic pressure from the water in the plunge pool. The result is that severe erosion can occur relatively quickly, due to this rapidly fluctuating upward force.

There is evidence in the literature of the severity of these forces. At Malpaso Dam in Mexico, pressure fluctuations displaced concrete floor slabs, 12m square, 2m thick, weighing 720 tonnes: 46 per cent of the floor area had to be replaced. At Grandget Dam in the USA, blocks of concrete weighing more than 10 tonnes were displaced from the impact basin.

The scouring effect on rock can be equally spectacular. At Kariba Dam (another project designed by British consultants) the bed rock downstream from the dam has eroded to a depth of 75m in the space of 20 years, despite the cushioning effect of 20m of water over the impact zone. The scour depth has not yet reached equilibrium.

At Calderwood Dam in the USA, 15m of scour occurred downstream from the dam in 20 days during the construction period, because the weir controlling the tailwater level was still in the process of being built.

The design engineer is faced with one of two problems. How deep to make the plunge pool in order to avoid very high pressures? What pressures will be generated if a plunge pool of a certain depth is provided?

In order to provide answers to either of these problems, it is necessary to look at the fundamental processes that are involved in the dissipation of jets discharged into a body of fluid. At present it is customary to carry out model studies of spillways, and these could be expected to give answers on the conservative side, bearing in mind the out-of-scale effects of viscosity and surface tension in the model. However, problems are still being experienced and there is clearly need for more work on this aspect. In Developments in Hydraulic Engineering (16), Locher and Hsu have written "There is a need for a systematic study of the mean and fluctuating pressures on slabs under plunging jets as a function of pool depth and quantity of entrained air to help quantify these effects for design."

3 PREVIOUS RESEARCH

Although there is a significant body of research on jets, this has tended to concentrate on the diffusion process in jets discharged into fluid of the same or of different physical characteristics. Very little work has been carried out on water jets that discharge initially into the atmosphere, entraining air in the process, followed by entry into water. This latter application is the one that most closely mirrors the spillway jet discharging into a plunge pool.

When a jet is discharged into the atmosphere, its structure immediately starts to modify (see Fig 1). The surface of the jet becomes unstable, the degree of instability increasing with the distance travelled. Accompanying the development of the instability is the generation of turbulence in addition to that initially present; this gradually affects an increasing proportion of the flow in the jet, until eventually the whole flow structure of the jet has been modified. Close to the point of afflux, the central portion of the flow will be unaffected by the diffusion of turbulence that is occurring in the outer layers: this unaffected zone - the jet core - comprises fluid whose velocity is sensibly constant and can thus be regarded as irrotational. One of the consequences of the instability in the outer layers of the jet, is that air is entrained in the flow. This increases the lateral spread of the jet and reduces the mean impact pressures when the jet impinges on a solid surface.

The length of the core is a function of the Reynolds number of the flow, but is of the order of 5 to 7 times the initial width of the jet, based on the results of some early experiments (4). More recent work by Ervine, McKeogh and Elsawy (17) and by Ervine & Falvey (18), suggest that the rate of diffusion of turbulent jets is much less than the previous estimates. They argue that the break-up or core length is a function of the turbulent intensity in the incoming flow and that for circular jets with turbulent intensity of 3 to 8 per cent, the break-up length could be more like 50 to 100 times the initial width of the jet. If this is the case, then it has an important bearing on the case of many prototype spillways, when the height of fall to tailwater level is less than 50 or 100 times the head of water on the spillway crest. In such cases the core of spillway jet has not been completely affected by the diffusion process, so that within a very disturbed and unstable outer layer, there is a solid core of high velocity water, capable of producing very high dynamic impact pressures.

When a free falling jet plunges into a pool of water, the diffusion rate is much greater, not only relative to that for a jet discharging to atmosphere, but also for a jet whose initial afflux point is below the water surface. The explanation for this lies in the instability of the outer layers of the jet: lateral variations of the point of impact will cause instabilities to be set up that will propagate more widely than if the impact point was invariant with time. Air will be entrained at the surface of the pond, in addition to the air carried with the impinging jet itself, and this will have an effect on the diffusion process.

Much of the work on the diffusion of submerged jets was carried out by Albertson et al (19). They identified two flow regions (see Fig 1). Initially there is a zone in which the flow structure is changing to a marked extent (the flow establishment zone): this is analogous to the decay of the irrotational core in the case of the jet discharging into the air. In the flow establishment zone the rate of core decay is such that it has disappeared in a length of roughly six times the jet width. Beyond the zone of flow establishment, the outer boundaries of the jet will be expanding at a rate of roughly 1 in 5.

Some measurements by Ervine (18) have suggested that free falling jets will diffuse more rapidly in water than jets that are completely submerged. In the flow establishment zone in the water, the outer boundary of the free falling jet will expand at a rate of 1 in 5 (i.e. at roughly 12° to the jet centreline): this is similar to the rate at which the submerged jet will expand beyond the flow establishment zone. The net effect of the greater expansion rate is that the length of the flow establishment zone for the free falling jet is only 3 to 4 times the jet width, compared with 6 times for the submerged jet.

No data have yet been published for the decay rate of the inner core of the free falling jet, beneath the water surface, or for the general expansion rate beyond the flow establishment zone: Ervine suggests that the former might be 1 in 7 or 1 in 8.

The main conclusion from Ervine's studies is that the jet will diffuse much more slowly in the atmosphere than the previous work on submerged jets had indicated. However, when the jet subsequently plunges into a pool of water, its diffusion rate will be much greater than previous work had suggested.

Although there are data on the diffusion of submerged jets, there are little or no data on the dynamic pressures that they produce. Clearly, these will depend on the relationship between the jet break-up length, and the depth of water in the plunge pool. A further significant factor, which has not been systematically studied, is the influence of entrained air on the pressures. Johnson (8) carried out some experiments to determine the effect that injecting air into a jet, would have on the depth of scour in a gravel bed. Although the tests showed that the air significantly reduced the scour depth, they were of limited usefulness as far as spillway jets are concerned, because in every case the jets were discharging beneath the surface of the plunge pool, not into atmosphere.

The model experiments that were carried out on the Hendrik Verwoerd and P K Le Roux dams demonstrated that splitting and aerating the jet as it discharged into the atmosphere, reduced the depth of erosion downstream from the dam by 50 per cent.

Ervine has derived a relation for predicting the reduction in pressure as a result of entrained air, for plunge pools whose depth is less than the maximum depth to which air would penetrate into the pool. So far there are no experimental data against which this relationship can be calibrated. He has also derived an expression for estimating the RMS value of the pressure fluctuations, but again there are no data from which the constants in the equation can be derived.

4 PROPOSED PROGRAMME OF RESEARCH

It is evident from a study of the literature that very little information is available on the impact pressures produced on the floor of a plunge pool by jets containing entrained air.

The bulk of the work on jets has focussed on circular jets. In the main, the problem in civil engineering hydraulic structures is the dissipation of the energy of rectangular jets, and it is recognised that such jets do not behave in exactly the same way as those of circular cross-section.

There is a clear need for data, more relevant to the conditions commonly encountered by the civil engineering designer viz the dissipation process and impact pressures produced by rectangular, turbulent jets, containing significant concentrations of air. Accordingly a research programme has been drawn up, with the objective of measuring the fluctuating pressure on the floor of a plunge pool as a function of the tailwater depth. The jet will be rectangular in cross-section and of greater size than most of the jets hitherto studied: and there will be provision for varying the air concentration and turbulent intensity of the impacting jet.

5 EXPERIMENTAL ARRANGEMENT

5.1 Model rig

The basic concept was for a jet to be discharged from the end of a vertical, rectangular pipe. This would be fabricated in short sections, so that the afflux point could be varied relative to the water surface in the plunge pool.

In order to produce uniform flow conditions in the jet it was important that there were good conditions at the inlet to the vertical pipe. This was one aspect of the rig where it was anticipated that problems could be encountered. The other aspect was the method of injecting air into the jet in a controlled fashion.

The final rig would be a large construction that would be difficult and expensive to modify once it had been built. For this reason it was decided that a small scale version of the final rig (one-third full size) should be built in order to examine these aspects more carefully.

In view of the large discharge rate that it was intended to pump around the rig and its large overall height, it was decided that the tank at the inlet to the vertical pipe should be kept as small as possible. Because of the risk of air entraining vortices being generated if a large open tank were provided at the inlet, preference was given to an enclosed pressure tank. The initial arrangement is shown in Figure 2.

It was immediately obvious when the small rig was first commissioned that this was not satisfactory. Much swirling was evident and it was clear that a radically different arrangement was necessary.

The problems were more difficult to solve with the air injection system. The aim was to aerate the jet before it discharged into the atmosphere. A simple way of achieving this would be to perforate a short length of the vertical pipe; if the pressure in the jet at the perforated section, could be made sufficiently sub-atmospheric, air would then be sucked into the flow by the pressure difference. This basically, was the system that was developed, using the 1/3 scale model. Between the head tank and the air box the cross-section was smaller than the remaining length of vertical pipe in order to produce a local acceleration (and a drop in pressure): downstream from this constricted length, the cross-section expanded suddenly, and here, the walls of the pipe were perforated with a large number of small holes. Immediately downstream from the perforated section, the cross-section area is reduced to give the required dimensions of the final jet. The general arrangement is shown in Figure 2. The air injection device was designed to produce a sufficiently large pressure difference to enable air concentrations of up to 30 per cent to be achieved.

When the air injection system was first tested, considerable problems were experienced with air leaking into the jet in an uncontrolled fashion at the joints. This was in spite of care being taken in the manufacture and assembly: it highlighted the need for accuracy when constructing the system for the full size rig.

Once the problems with leaks had been overcome, the main faults with the system were found to be that the pressure drop in the constricted section was not sufficient to produce a well-aerated jet and that there was a great deal of splashing at the entrance to the contraction below the perforated section. A further disadvantage was that when the overall length of the vertical pipe was reduced, some separation from the wall of the pipe started to occur close to the exit.

After making a number of modifications to the geometry of the air injection system, a satisfactory performance was obtained: Plates 1 and 2 show the jet before and after the modifications were made.

The modified geometry is shown in Figure 3: it comprised a deflector in the section immediately upstream from the perforated section (similar to the deflector sometimes incorporated in spillway channels to induce flow aeration) and a slow transition section at the entrance downstream from the perforated section.

5.2 Full-size rig

The diagrammatic layout of the rig is shown in Figure 4. The solution that was adopted for the inlet arrangement was to make the discharge line from the pump of a large diameter: this was installed horizontally at a high level, with the vertical rectangular pipe connected to its invert. The mean velocity in the horizontal pipe was low, and a tapered transition piece between the vertical and horizontal pipes, ensured good flow conditions in the jet. The original intention had been to carry out the experiments on a jet 300mm x 100mm, with velocities up to 8m/s, but the cost of this rig would have been more than the budget would allow. The rig was then re-designed; the jet was reduced in size to 200mm x 67mm with a maximum velocity of roughly 5m/s. This is roughly equivalent to the size of spillway jets that typically occur in models constructed to scales of 1:50 to 1:80.

The vertical rectangular pipe was made as long as possible so as to produce a stable jet, and allow the maximum flexibility in the testing arrangement. The pipe consists of a number of short sections which are easily removable. This enables the pipe to be adjusted in length so that the jet discharges just below the water surface, thus preventing any uncontrolled air entrainment. Alternatively the jet can be discharged at a variable height above the pool in order to study the resulting effect on the pressure fluctuations.

For the initial tests, the air injection system has been omitted in order to limit the costs and allow the experiments to get under way. When later installed, the air-box will be designed on the basis of the 1/3 - model tests described previously, and will be located near the top of the vertical rectangular pipe.

The plunge pool is arranged with overflow weirs on all four sides so that the effects of changes in the exit flow pattern on the impact pressures can be examined.

Directly beneath the vertical pipe, a steel panel, 1m square, has been set in to the floor. Pressure transducers are mounted in this panel to measure fluctuating pressures. Although there are 45 measuring positions (Fig 5), no more than fifteen will be occupied at any one time. The aim of the experiments is to determine how the pressures beneath the jet vary with velocity, turbulence intensity, air concentration, plunge pool depth and height of free fall.

Although the original design of test rig with an 8m/s capability would have been preferable, the smaller 5m/s rig which has been built is still capable of providing much useful information. Whatever size of laboratory rig were chosen, it would still be necessary to extrapolate the results to prototype conditions. Data on correlations between model and prototype for falling jets are not available, but several studies on pressure fluctuations due to turbulence in stilling basins have shown satisfactory agreement with the Froudian scaling criterion (e.g. see Lopardo et al (20)).

6 MEASUREMENTS

Not all the planned equipment has yet been installed in the test rig, and as explained above the air injection system remains to be added. The measurements that have or will be made in the tests comprise:

1. flow rate of water in jet (by means of BS-type orifice meter);

2. height of discharge level of jet above floor level;

3. depth of tailwater;

4. amount of flow turbulence in jet (root mean-square velocity fluctuation and spectral distribution);

5. total flow rate of air added to jet;

6. air concentration profile within jet;

7. pressure fluctuations at points on floor beneath jet (maximum, minimum mean and root mean-square values plus spectral distributions);

8. temperatures of water and air.

In the tests carried out to date, the velocities in the jet (item 4 above) have been determined using an electromagnetic current (emc) meter connected to an analogue tape recorder (RACAL 7-track type) and an ultra-violet (uv) chart recorder. Records are digitised by means of a Farnell DTS 12T digital storage oscilloscope, and spectral analyses are carried out using a Fast Fourier Transform (FFT) software package mounted on a BBC micro-computer. This computer system has a limited capacity since it is capable of storing only 1024 data values at one time, and does not have a smoothing facility for obtaining statistically reliable spectral estimates. As a result, for a particular test condition, the amount of energy measured at a given frequency can vary significantly between successive recordings. It is planned to overcome this limitation by analysing the analogue recordings using a more sophisticated PDP-based system available at HR.

Measurements of air concentration in the jet are made by means of an instrument developed at Nottingham University (see White and Hay (6)), and purchased specially for this research project. The device senses the passage of air bubbles by means of a very fine wire (typically 0.2mm in diameter), which projects slightly from the tip of a thin insulating tube. When the tip of the wire is in water an electrical circuit is completed, and a corresponding current flows. When the tip enters a bubble, the circuit is broken and the current suddenly changes. Instruments such as this are subject to errors due to surface tension, which prevents instantaneous wetting and unwetting of the tip. The Nottingham design overcomes this problem in a novel way by sensing the rate of change of the electrical current, and using this to convert the signal into a series of step-type waves. The electronics thus enable the instrument to behave as a simple on-off switch: on, when the tip is in water; off, when it is in air. Other advantages are that the gauge is not dependent upon the precise conductivity of the water, and that it can be calibrated by means of an internally-generated square-wave signal. The air concentration is obtained by measuring the proportionate lengths of time that the tip is in air and water. This calculation assumes that the air bubbles and water are travelling at the same velocity, which is usually valid for small bubbles in turbulent high-velocity flows.

The pressures on the floor are measured by means of flush diaphragm transducers manufactured by Western Sensors Limited. These have a diameter of 19mm, and use foil strain gauges and integral amplifiers to measure pressures up to 7.0m head of water, with a maximum output prior to amplification of 40mV. The transducers are mounted on a plate measuring 1.0m x 1.0m (see Fig 5). The transducers needed to be carefully waterproofed so that they could be fixed directly to the underside of the plate, but this arrangement avoided the requirement for tapping tubes; such tubes reduce the dynamic response of the system and, when studying aerated flows, can give false readings if they become partly filled with air.

Preliminary tests with the pressure transducers demonstrated that they required regular and careful calibration. It was found that the datum readings (for zero pressure) tended to drift with time, and that the sensitivities were affected by small changes in temperature. Initially, the calibration was carried out by placing a tube with a watertight seal over an individual transducer on the plate, and then applying a known static head. The datum reading was obtained with the transducer in air. This technique proved to be flawed, because the electrical current passing through the transducer heated it to a higher temperature when it was in air than when it was under water.

To minimise the temperature changes, a large box with a watertight seal is now placed on the measuring plate, and filled to two different, known levels. This method allows all the transducers to be calibrated simultaneously, and provides a large enough body of water to maintain a near constant temperature. The water in the box is drawn from the sump so that its temperature will be similar to that used in the tests. The calibrations are carried out before and after each set of measurements.

The pressure signals are recorded and analysed in the same way as the velocity measurements, using the digital storage oscilloscope and the FFT program. For the spectral analysis, it was found that a maximum sampling frequency of 200Hz was sufficient to register all the significant energy in the velocity and pressure fluctuations for jet velocities of up to 5m/s.

The depth of water in the plunge pool is measured by means of two pressure tappings, one near a corner of the pool and the other near the centre. The latter gives a more representative measurement of the water level at the jet, and can be used when the pipe is discharging below the surface. When the jet is falling freely into the pool, the central tapping fills with air, and it is necessary to use the one near the corner.

Despite the care taken in setting up and operating the system for measuring velocities and pressures, it is still producing some anomalies which require to be corrected before full confidence can be placed in the results. This should be borne in mind when considering the preliminary findings described in the next section.

7 RESULTS

Preliminary tests have been carried out to study the performance of the experimental rig and the measuring equipment over the likely range of operating conditions. Results from these tests are described herein, but it should be remembered that any conclusions can at this stage only be provisional. As explained in the previous section, it is planned that a more capable analysis program will be used in later experiments to provide fuller spectral and statistical descriptions of the results.

The first set of data concerns the degree of turbulence in the jet. The jet was discharged freely into air from a height of 1.08m above the floor, and the longitudinal velocities on the centreline were measured with the emc meter at the point of exit from the vertical pipe and at 400mm below it. Three records were analysed for each of three discharges to determine the mean velocity ($\bar{V}$) and the root mean-square value of the fluctuations about the mean (V_{rms}). The results are plotted in Figure 6 in terms of the variation of the turbulence intensity ($V_{rms}/\bar{V}$) with mean velocity. The values of $\bar{V}$ at the point of exit were compared with the average value (V_{av}), calculated from the discharge (measured by the orifice meter) and the cross-sectional area of the vertical pipe. At the two higher discharges, the differences between $\bar{V}$ and V_{av} were less than 5% of V_{av}, and at the lowest discharge the difference was within about 10% of V_{av}.

The changes in mean velocity along the centreline show that, for all three discharges, the kinetic energy head of the water increased by approximately 160mm-200mm after falling through a vertical distance of 400mm. This apparent loss in total energy is interesting because it is not accounted for by the relatively small increase in energy associated with the turbulent fluctuations. The results in Figure 6 show that, as the discharge in the jet is increased the absolute level of turbulence (V_{rms}) increases but the relative turbulent intensity ($V_{rms}/\bar{V}$) decreases. In future tests, it is planned to vary the amount of turbulence in the jet by placing mesh screens in the vertical pipe.

The rate of expansion of the jet when discharging freely into air was determined by analysing a series of high-speed photographs of the jet at velocities of V_{av} = 2.45, 3.15 and 4.26m/s; examples are shown in Plates 3 to 6. In each photograph, the edges of the jet were estimated by eye (taking the mean of the spatial variations, not the envelope of the maximum departures from the mean), and measured to obtain values of the average rate of expansion:

$$E = \tan^{-1} \{(B-B_o)/z\}$$

where z is the vertical distance below the point of exit, B is the total width of the jet at level z, and B_o is the value at the point of exit. Eight photographs of each velocity were analysed, and used to determine separate values of E for the long sides (B_o = 200mm) and the short sides (B_o = 67mm). The results are presented in Table 1.

Two competing factors influence the rate of expansion of the jet. Firstly, the sides of the jet diverge due to the effects of turbulence and air entrainment (see Fig 1). Secondly, the velocity of the water in the jet increases as it falls, and this tends to reduce its cross-sectional area. The greater the initial velocity of the jet, the more significant the first factor becomes. This explains the results in Table 1 which, for example, show that at V_{av} = 4.26m/s the short side of the jet expanded at an overall angle of E = 2.4°, but contracted at E = -0.2° at V_{av} = 2.45m/s. From Plate 5 (for V_{av} = 4.26m/s) and the corresponding values of E at z = 104mm and z = 564mm, it can be seen that the jet diverged relatively rapidly over the first 100mm, and then at a slower, nearly constant rate for the remainder of its fall. The jets tended to oscillate somewhat in position, but their mean widths remained fairly constant, as shown by the relatively small standard deviations in the values of E.

The next set of data concerns the pressures produced on the floor of the pool by a submerged jet discharging approximately 150mm below the water surface. Tests were carried out at two discharges (corresponding to average velocities in the pipe of V_{av} = 3.17m/s and 4.48m/s), and an average pool depth of $\bar{h}$ = 617mm. Figure 7 shows the mean pressures ($\bar{p}$) recorded by the transducers for records of 50s period sampled at a frequency of 20Hz. The pressures have been calculated relative to hydrostatic, so that the time-averaged static pressure acting at a point on the floor is $(\bar{p} + \rho g\bar{h})$.

The results appear to be consistent, with pressures decreasing fairly symmetrically around the sides of the jet, both in the longitudinal and transverse directions; the peak pressures in the centre of the jet increase roughly in proportion to the square of the average velocity. Also shown in Figure 7 are points indicating the range of pressures that occurred. In these first tests, only the difference between the maximum and minimum pressures in each 50s record was measured. In order to plot the results in Figure 7, it was assumed that the maximum fluctuations were distributed symmetrically about the mean values (but see later). Measurements were also made of the root mean-square pressure fluctuations; values of p_{rms} varied from about 90mm head of water in the region vertically below the jet to about 28mm far away from the jet at gauge 9B (see Fig 5).

Similar tests were made with the jet falling through air into the plunge pool. The vertical pipe was shortened so that it discharged at a level of 2.30m above the floor of the basin, and the depth of water in the pool was approximately the same as in the previous tests with the submerged jets ($\bar{h}$ = 585mm); the height of fall of the jet through air was therefore 1.715m. Measurements were carried out at three discharges corresponding to pipe velocities of V_{av} = 2.44, 3.15 and 4.24m/s; due to its fall, the velocity at which a jet entered the pool was greater than its initial value of V_{av}.

Air was entrained by the plunging jet both during its fall and at the point where it entered the pool (see Plates 7 and 8 for velocities of V_{av} = 2.44m/s and 4.29m/s respectively). The pressures exerted by the jet on the floor of the basin are plotted in Figure 8. The effects of the aeration and the increased distance travelled by the jet through water (585mm compared with 471mm for the submerged jet) can be seen by comparing the pressures shown in Figure 8 with the results in Figure 7 for the submerged jet. The mean pressures due to the plunging jets were considerably lower than those produced by roughly equivalent submerged jets. Thus, for a pipe velocity of about V_{av} = 3.2m/s, the submerged jet gave $\bar{p}$ = 580mm head of water at the position of the central gauge and the plunging jet $\bar{p}$ = 154mm, despite the fact that the velocity of the plunging jet would have increased to more than V_{av} during its fall. This indicates the significant beneficial effect which air entrainment can have on impact pressures in plunge pools.

Also shown in Figure 8 are the maximum and minimum pressures that occurred in each 50s record. Unlike the case of the submerged jets, the peaks were measured as absolute pressures and not just as differences between the maximum and minimum values. Therefore, the points in Figure 8 show how the pressures varied relative to the means. As can be seen, the maximum positive fluctuations within the jet were larger than the negative ones by a factor of about 3-4. This suggests strongly that the pressure variations do not follow a symmetrical Gaussian type of probability distribution. Comparison of Figures 7 and 8 shows that, although the plunging jets gave lower mean pressures than the submerged jets, they did produce significantly larger pressure fluctuations. Thus, for a pipe velocity of V_{av} = 3.2m/s, the maximum range of pressures at the position of the central gauge were Δp = 469mm for the submerged jet and Δp = 1327mm for the plunging jet. These various preliminary findings may have important implications for the design of aprons in plunge pools, but require checking by further measurements.

The final set of data concerns the distribution with frequency of the energy in the velocity and pressure fluctuations. Figure 9 shows typical plots of energy density for the turbulent velocity fluctuations in the centre of the jet when discharging freely into air with a pipe velocity of about $V_{av} = 3.2$m/s. At the point of exit, the energy is mainly contained in the frequency bands below 10Hz. However, after the jet has fallen through a distance of 400mm, the energy has become more evenly distributed and has significant frequency components up to 25Hz.

Typical spectra of the pressure fluctuations produced on the floor of the plunge pool by the submerged jets are shown in Figure 10. The results are for a pipe velocity of $V_{av} = 3.17$m/s and a mean pool depth of $\bar{h} = 617$mm. The plots show that, near the centre of the jet (transducer 3B, see Fig 5), there are strong components with frequencies $\leqslant 0.5$Hz but also significant energy in the bands up to about 15Hz. Close to the edge of the jet (transducer 5B), nearly all the energy is contained in the bands below 0.8Hz. Far away from the jet (transducer 9B), the fluctuations are very much smaller, but cover a range of frequencies up to 25Hz with a peak value at about 7Hz.

Corresponding results recorded by the same transducers for the case of the plunging jet with $V_{av} = 3.15$m/s and a mean pool depth of $\bar{h} = 585$mm are presented in Figure 11. Comparison with Figure 10 shows considerable differences. Near the centre of the jet, there is significant energy up to 10Hz but there are no strong components below 0.5Hz. The fluctuations at the edge of the jet are larger than in the centre, but cover the same range of frequencies with peaks at about 2-4Hz; this contrasts markedly with conditions at the edge of the submerged jet where the energy was concentrated below 0.8Hz. Far away from the plunging jet, the fluctuations are small and have a similar frequency distribution to those produced by the submerged jet.

As mentioned in Section 6, the values of energy density given by the current analysis program can be expected to vary significantly from one record to another; the results shown in Figures 9 to 11 are therefore only representative of the spectra that may occur. In later work it is planned to use a more capable analysis system which will give statistically stable estimates of the energy spectra.

8 CONCLUSION

The literature review has shown that adequate information is not yet available to enable designers to assess impact pressures in falling-jet energy dissipators. Questions concerning the trajectory and amount of air entrained in falling jets are, from an experimental point-of-view, best considered separately from the behaviour of jets entering a plunge pool. It was decided that the present experimental work should concentrate on measuring conditions in the plunge pool, particularly the impact pressures on the floor, as this was the aspect about which least was known. The test rig has therefore been built so as to investigate the relationship between the characteristics of the jet entering the pool and the pressures that it exerts.

The rig is designed so that jets falling freely through air and jets discharging just below the surface of the plunge pool can both be studied. The jet is produced by a rectangular nozzle measuring 200mm x 67mm, and is therefore more representative of prototype conditions than the circular jets used by previous researchers. Provision has been made for adding an aeration device to the jet nozzle so that the effect of air on impact pressures can be determined in a systematic manner.

Preliminary tests have been made to assess the overall performance of the equipment and the measuring system. Mean and fluctuating pressures on the floor of the basin have been analysed for freely-discharging and submerged jets with velocities between 2.4m/s and 4.5m/s. Provisional conclusions (which may need to be revised as a result of further work) are:

1. the cores of submerged non-aerated jets produce mean impact pressures which are approximately equivalent to the velocity head of the jet;

2. a free-falling jet, containing some entrained air, produces lower mean pressures than a similar submerged jet, but a larger range of pressure variations about the mean;

3. the positive pressure fluctuations resulting from free-falling jets are much larger than the negative fluctuations;

4. the turbulent energy in the core of the jet is distributed over a fairly wide range of frequencies (up to 15Hz in these initial experiments), but in the case of non-aerated submerged jets there are strong components at low frequencies (below 0.5Hz).

9 ACKNOWLEDGEMENTS

The report of the experimental study was produced by Mr J A Perkins and Mr R W P May, and the measurements were made by Mr I C Meadowcroft. The design of the instrumentation was supervised by Mr I E Shepherd, and the equipment was installed by Mr D Perrott. The literature review was carried out by Mr E Whitehead and Mrs P M Brown.

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TABLES

TABLE 1: Rates of expansion of jets discharging into air

Velocity V_{av} (m/s)	Level z (mm)	Expansion Rate E (degrees)			
		Long side		Short side	
		average	st. dev.	average	st. dev
2.45	104	3.3*	0.7*	2.3	0.8
2.45	564	1.1*	0.2*	-0.2	0.2
3.15	104	5.0	1.0	4.1	0.8
3.15	564	2.1	0.3	1.0	0.3
4.26	104	6.5	0.8	4.9	0.9
4.26	564	3.7	0.1	2.4	0.5

* Values calculated from six measurements and not eight as for others

FIGURES

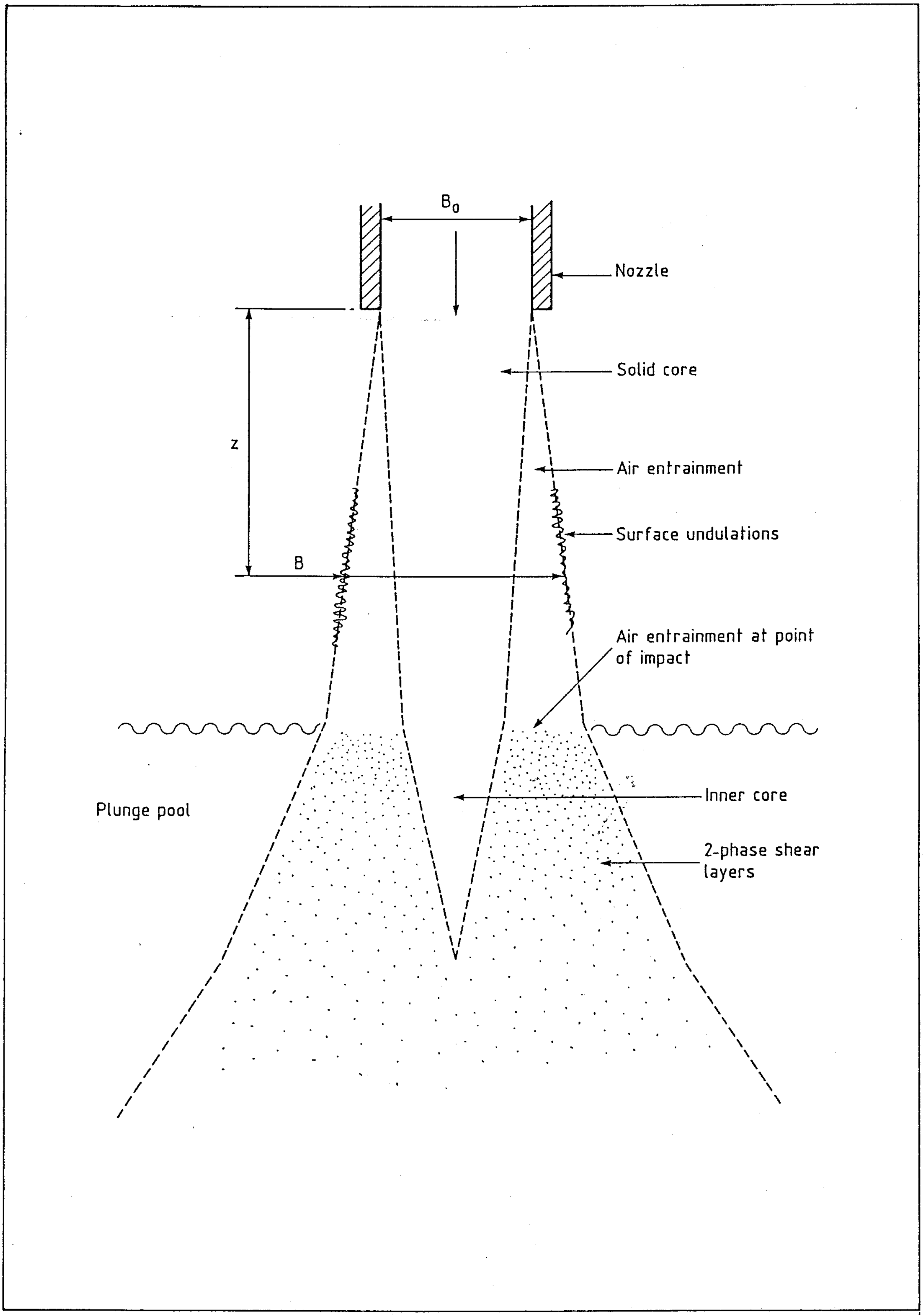


Fig 1 Schematic diagram of jet falling through atmosphere into plunge pool (after Ervine)

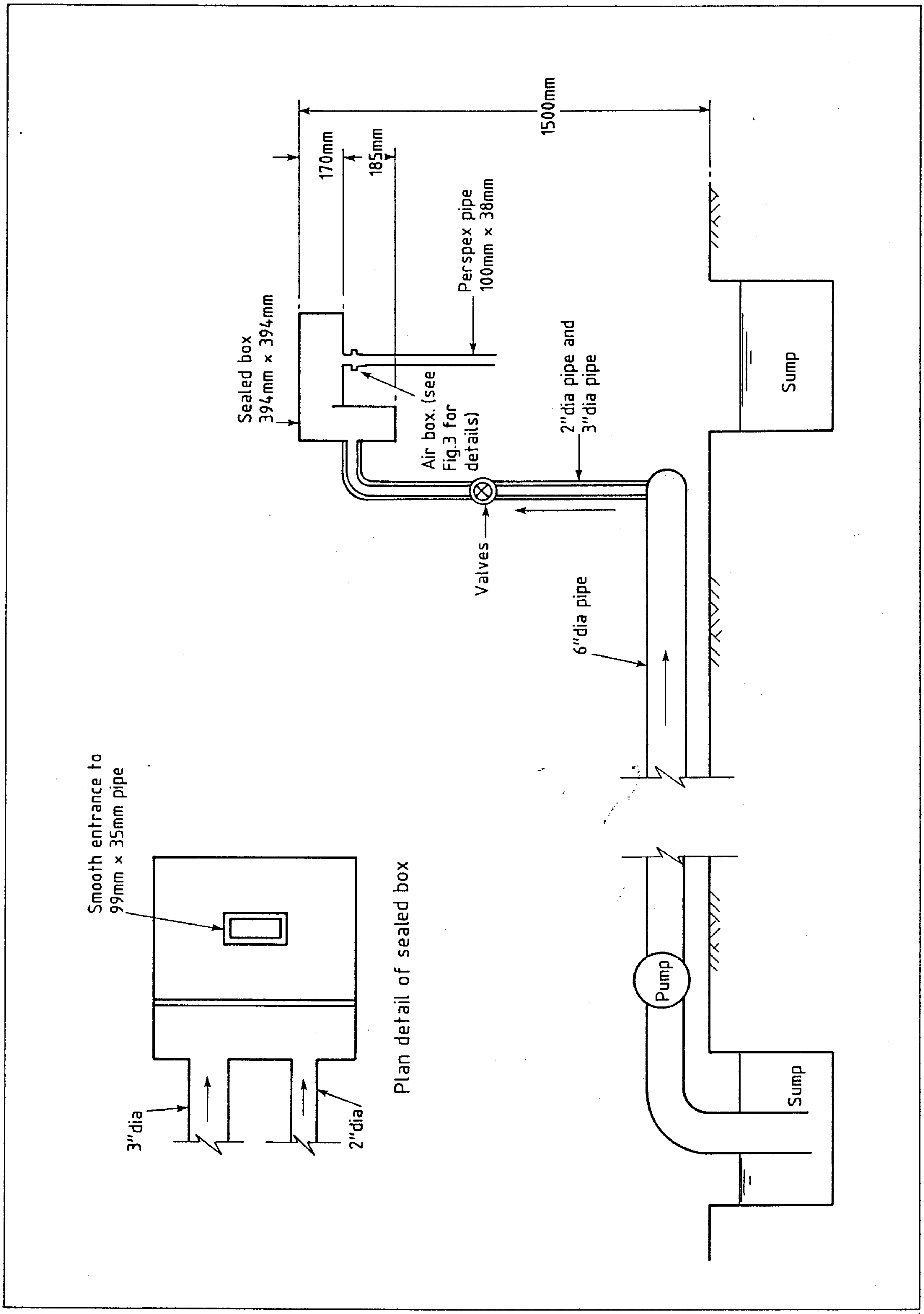


Fig 2 General layout of small scale test rig

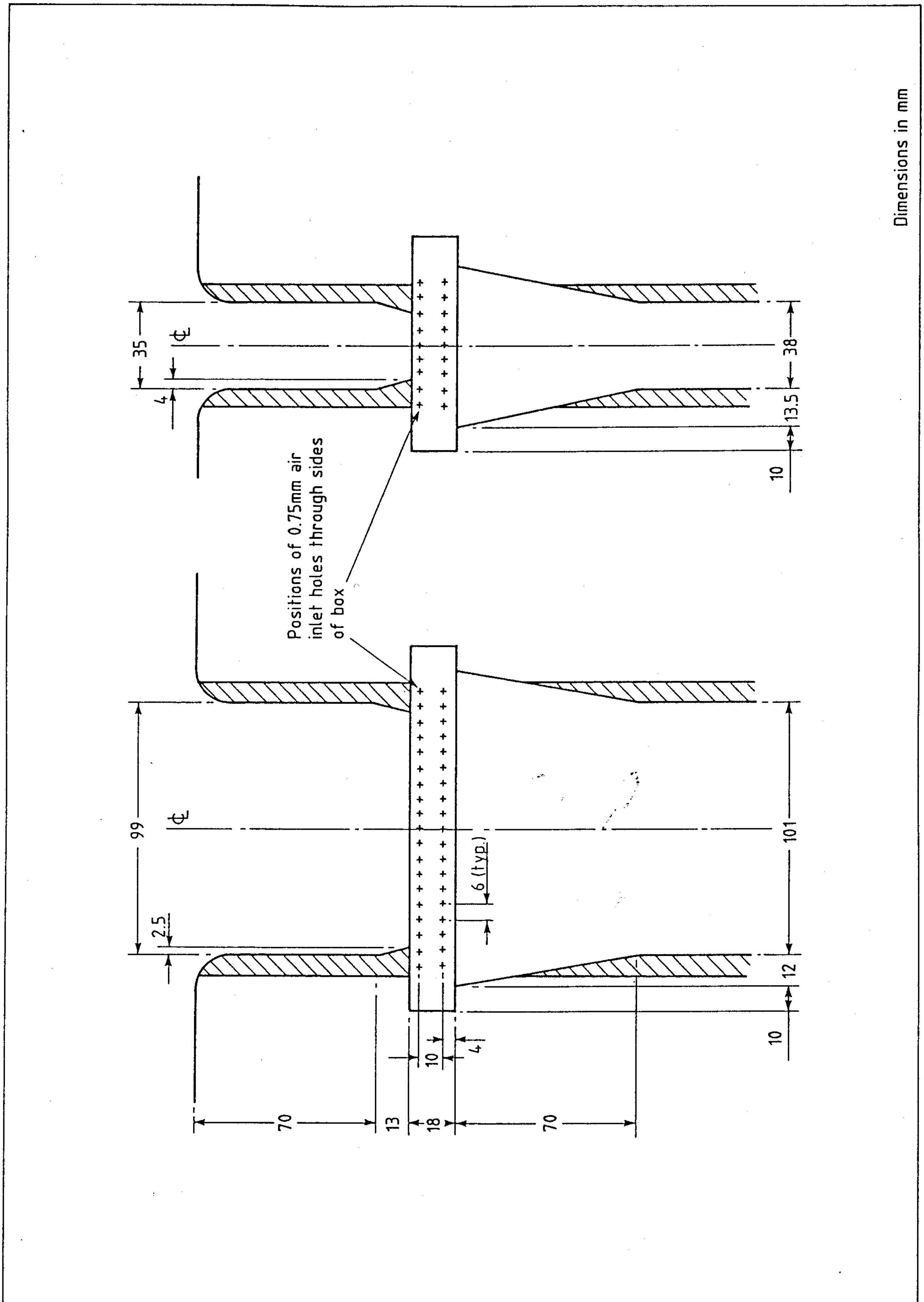


Fig 3   Details of modified air box

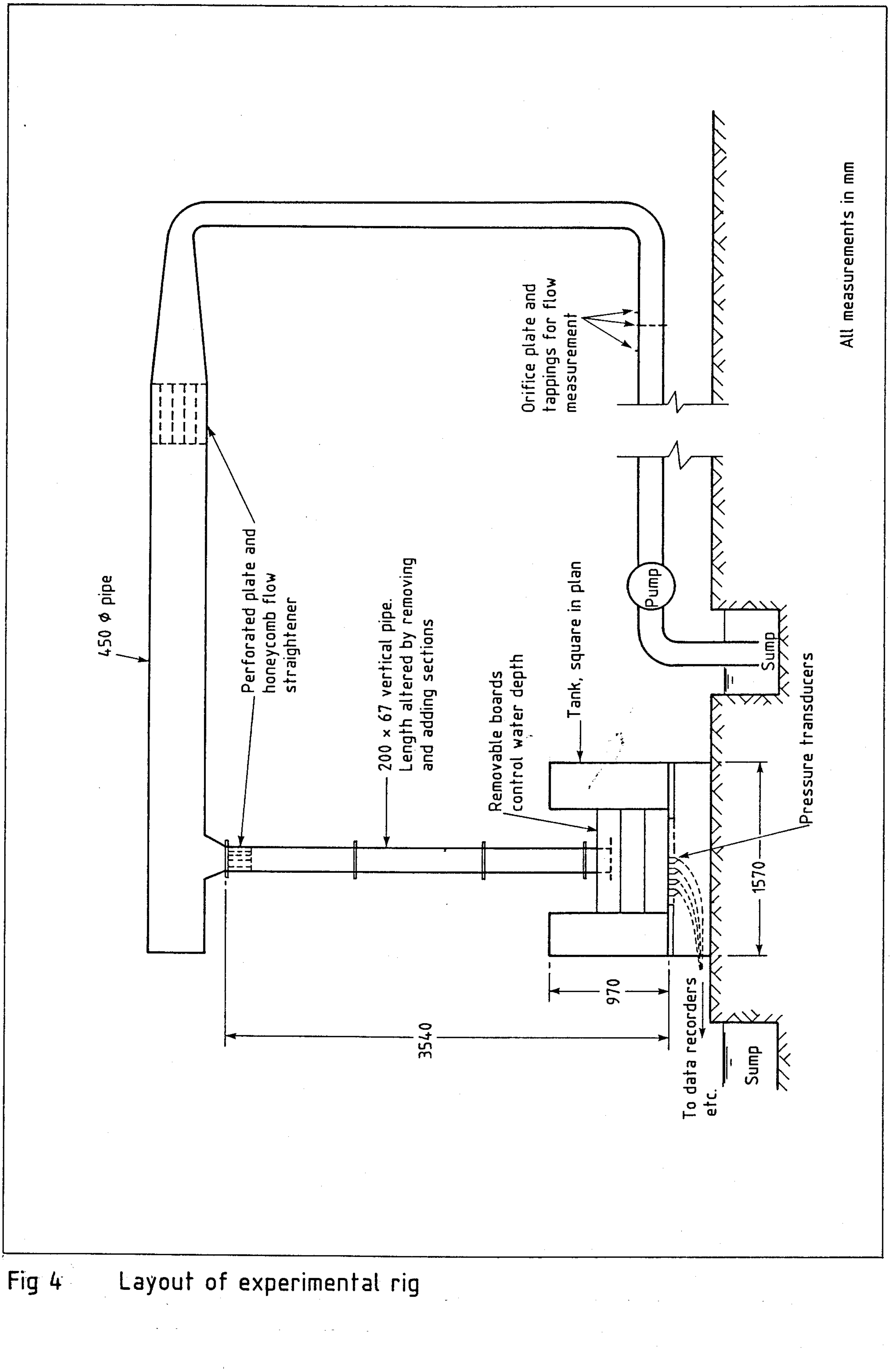


Fig 4 Layout of experimental rig

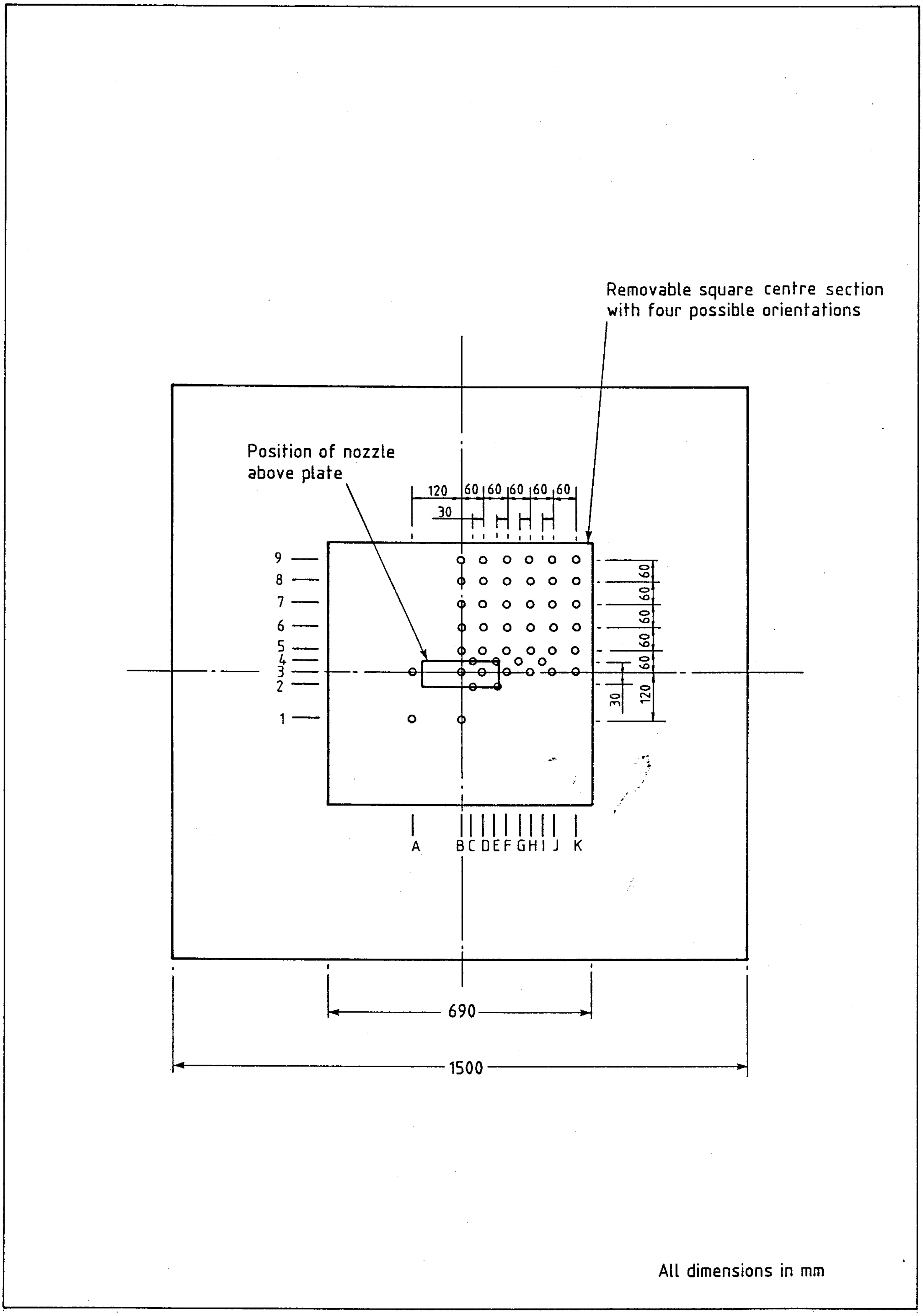


Fig. 5 Layout of pressure tappings

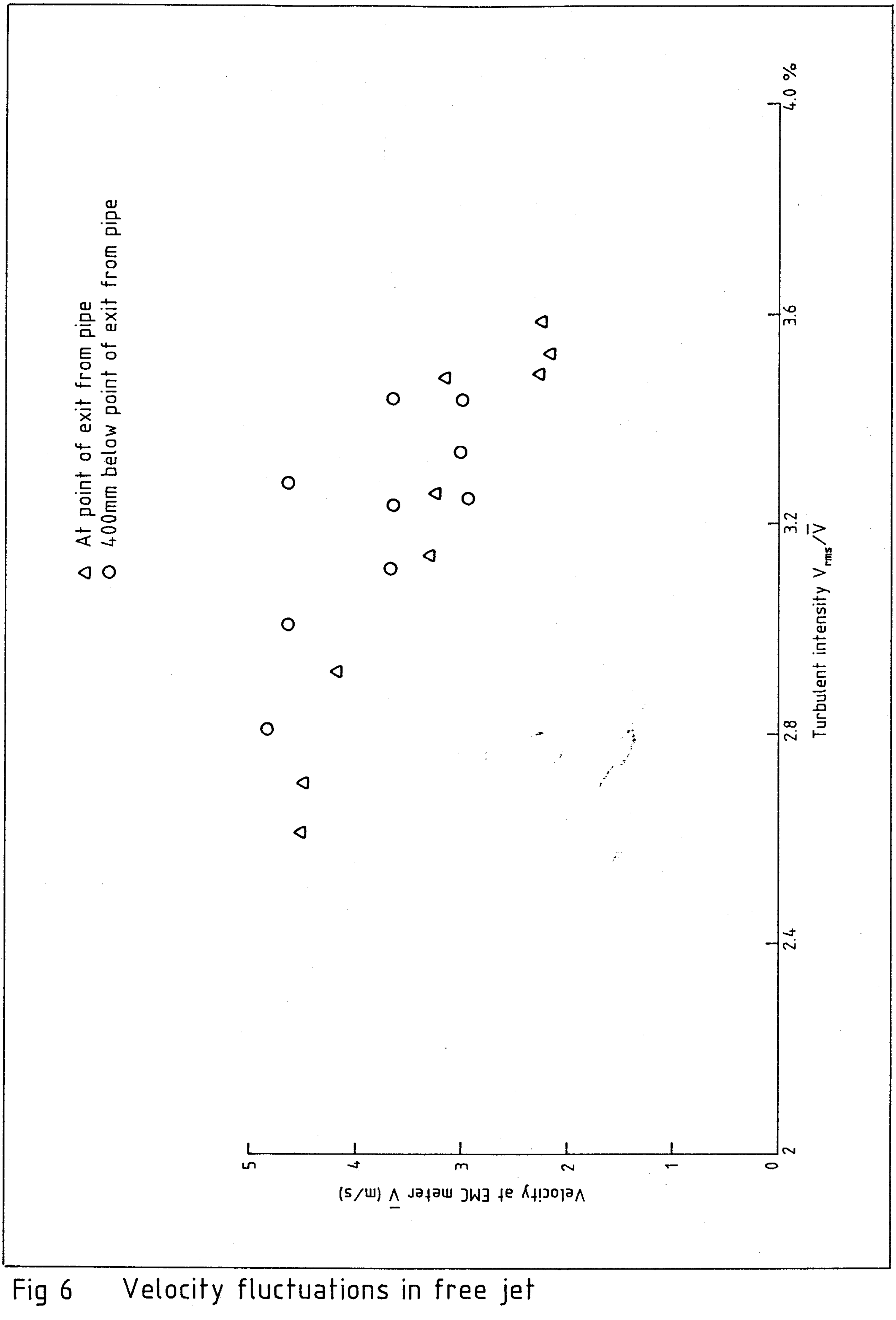


Fig 6 Velocity fluctuations in free jet

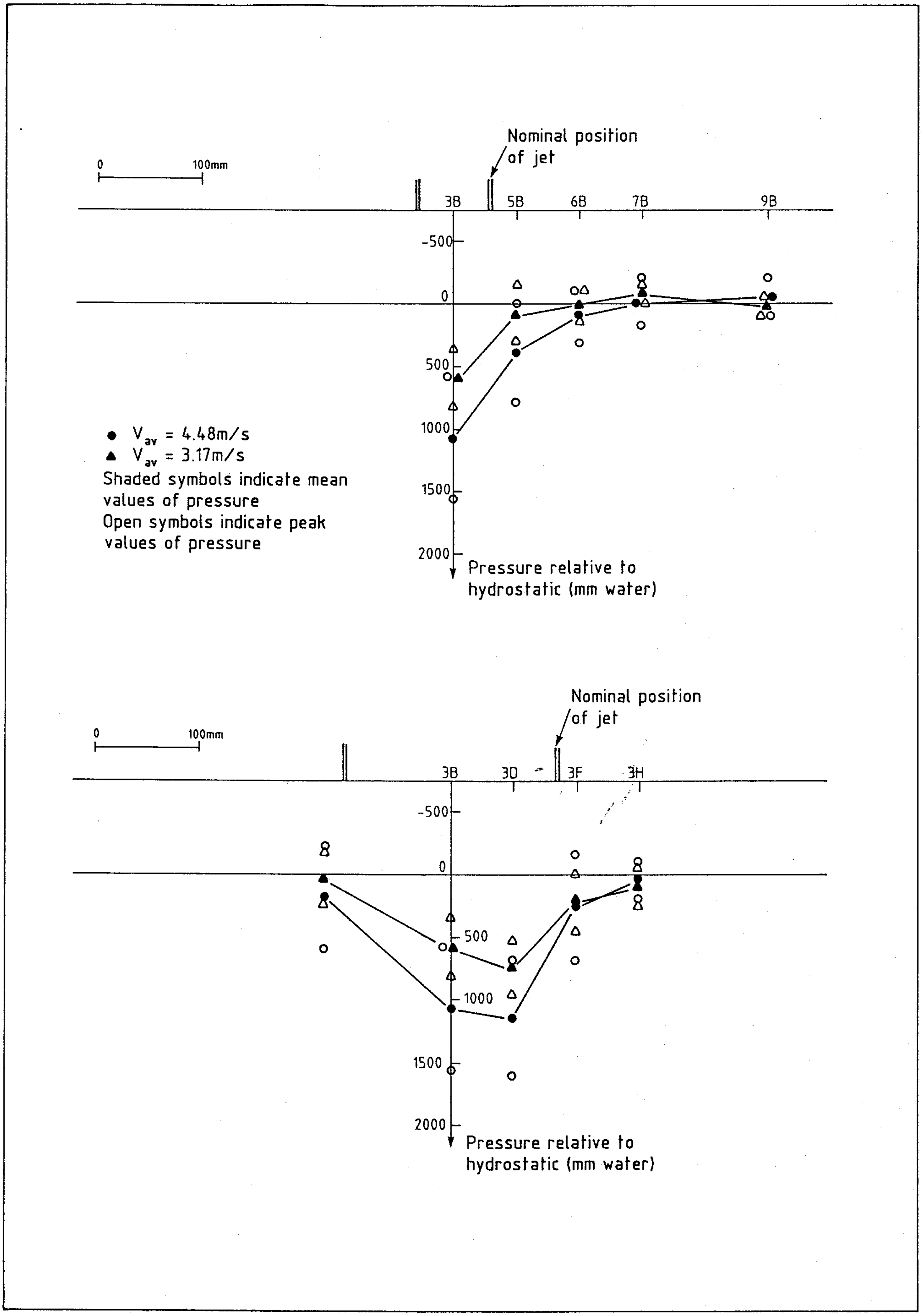


Fig 7 Dynamic pressures due to submerged jets

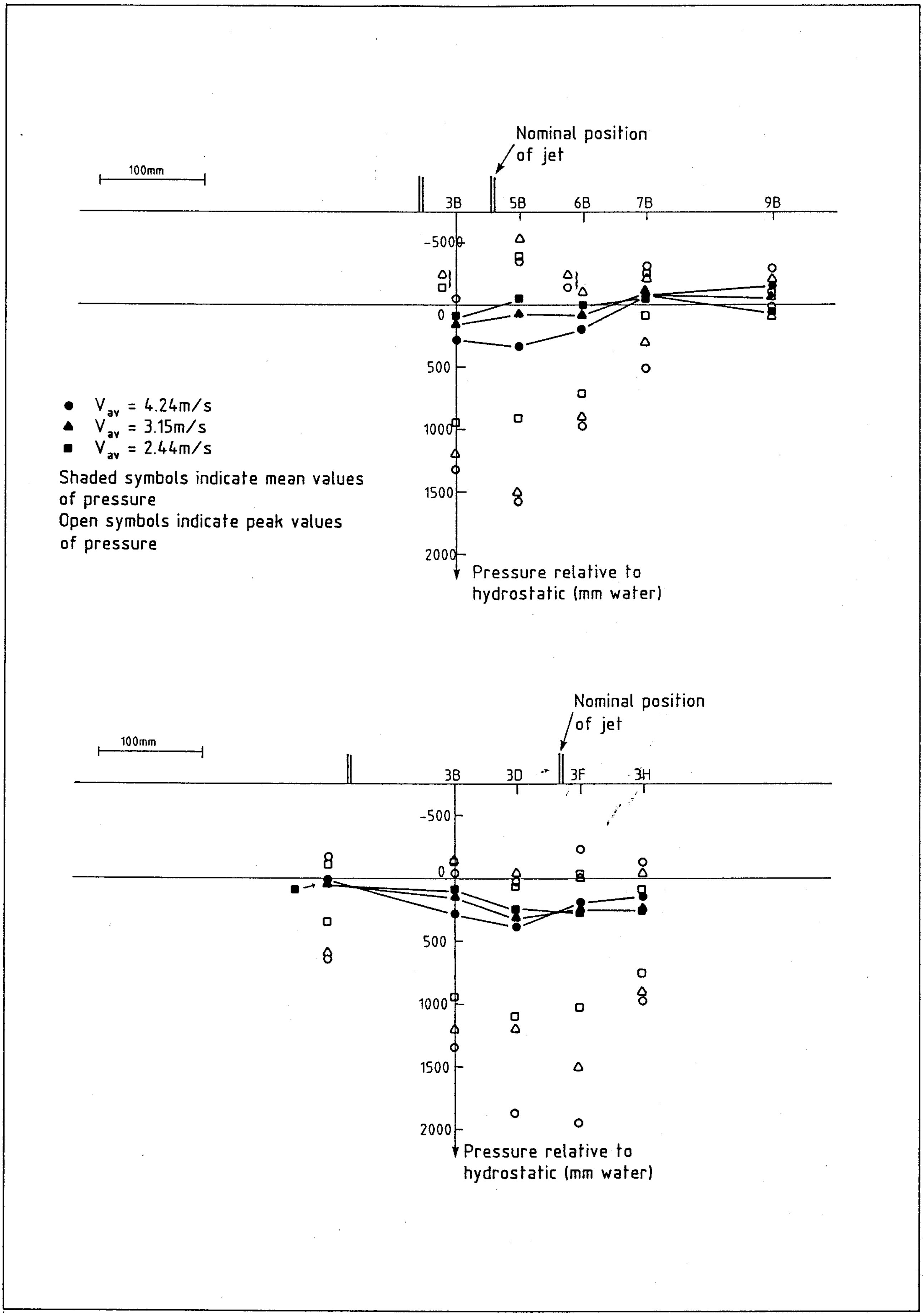
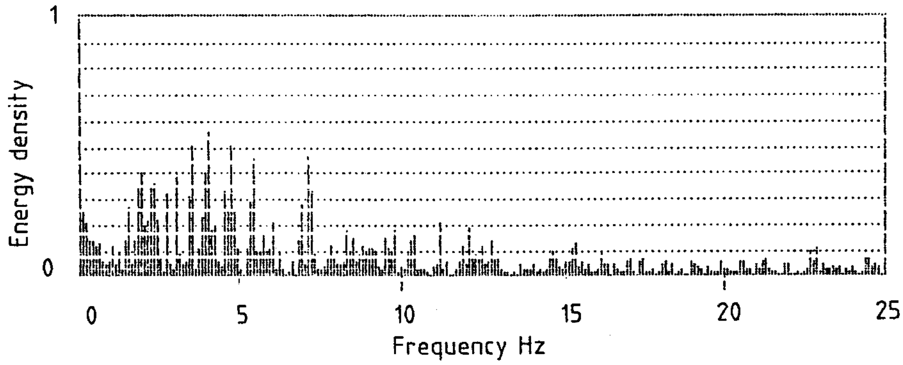
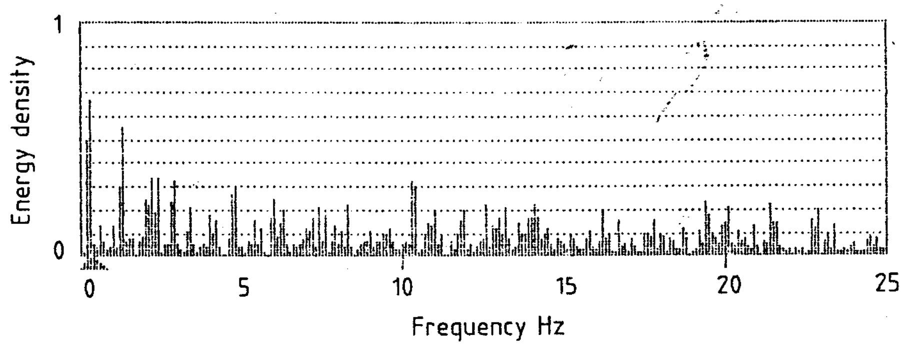


Fig 8 Dynamic pressures due to plunging jets



a) At point of exit from pipe
V_{av} = 3.21m/s V_{rms} =0.11m/s



b) 400mm below point of exit from pipe
V_{av} = 3.19m/s V_{rms} = 0.12m/s

Fig 9 Energy density spectra for velocity fluctuations in the centre of the jet

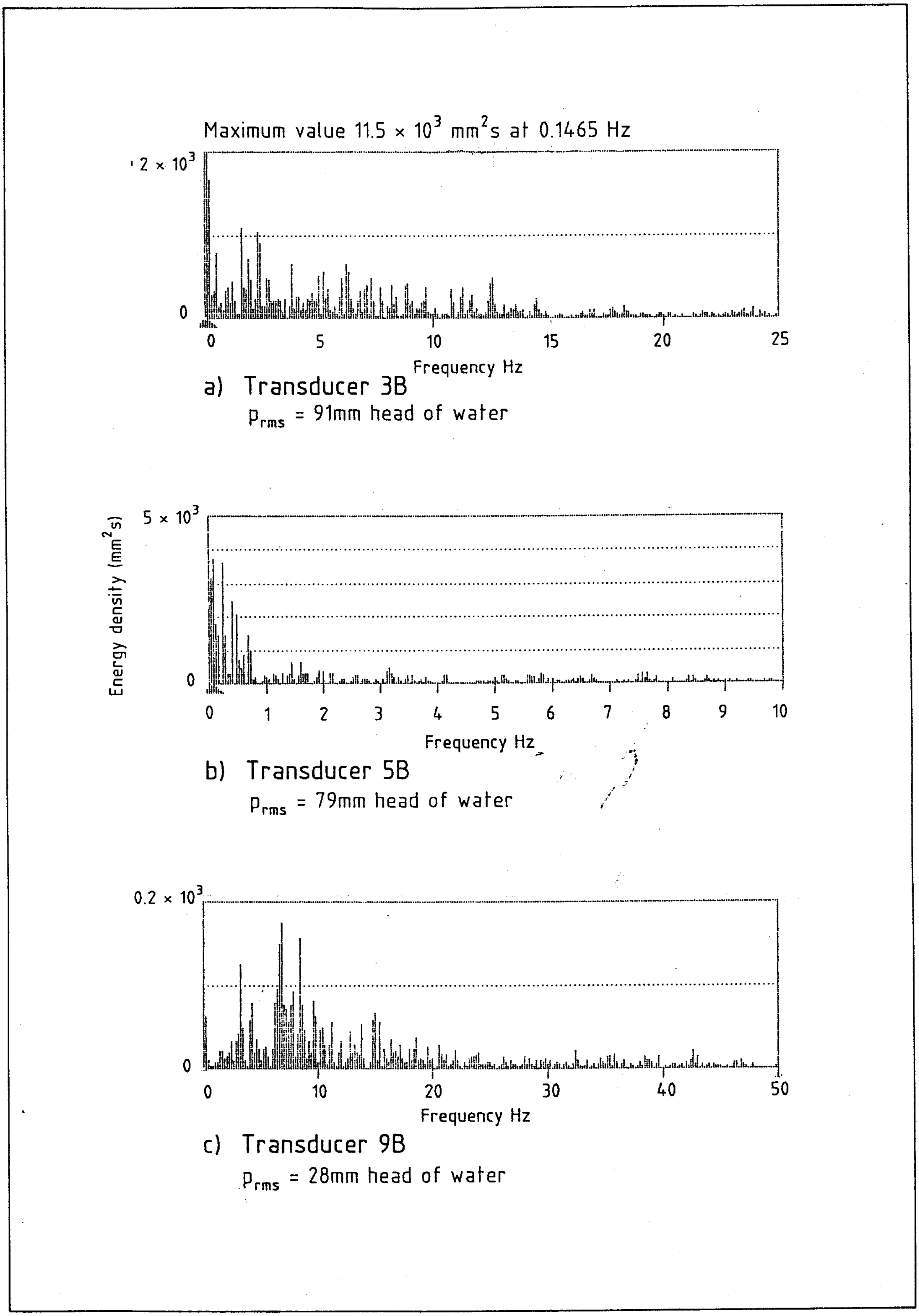
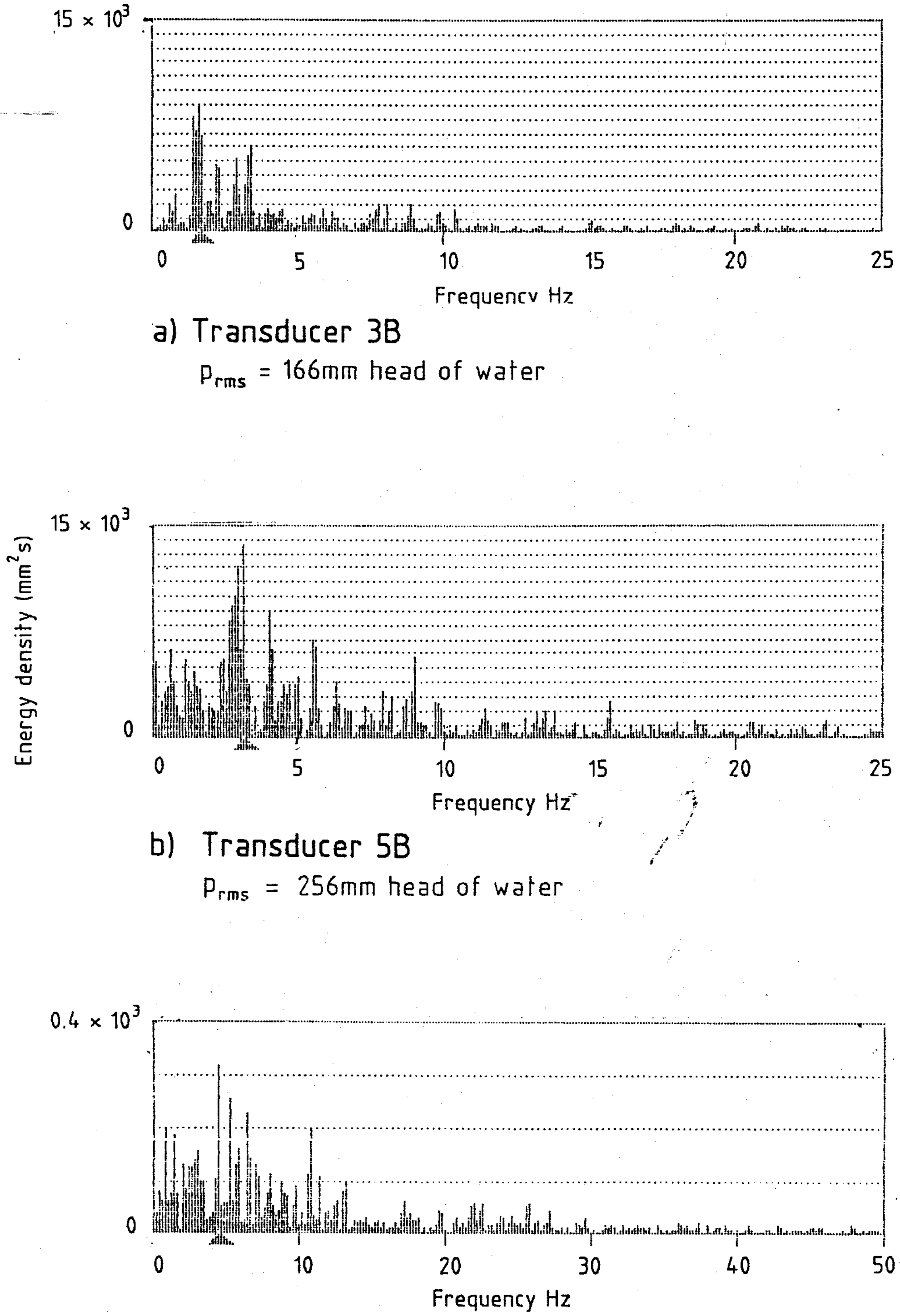


Fig 10 Dynamic pressure spectra for submerged jet. V_{av} = 3.17m/s



a) Transducer 3B
p_{rms} = 166mm head of water

b) Transducer 5B
p_{rms} = 256mm head of water

c) Transducer 9B
p_{rms} = 38mm head of water

Fig 11 Dynamic pressure spectra for plunging jet. V_{av} = 3.15m/s

PLATES

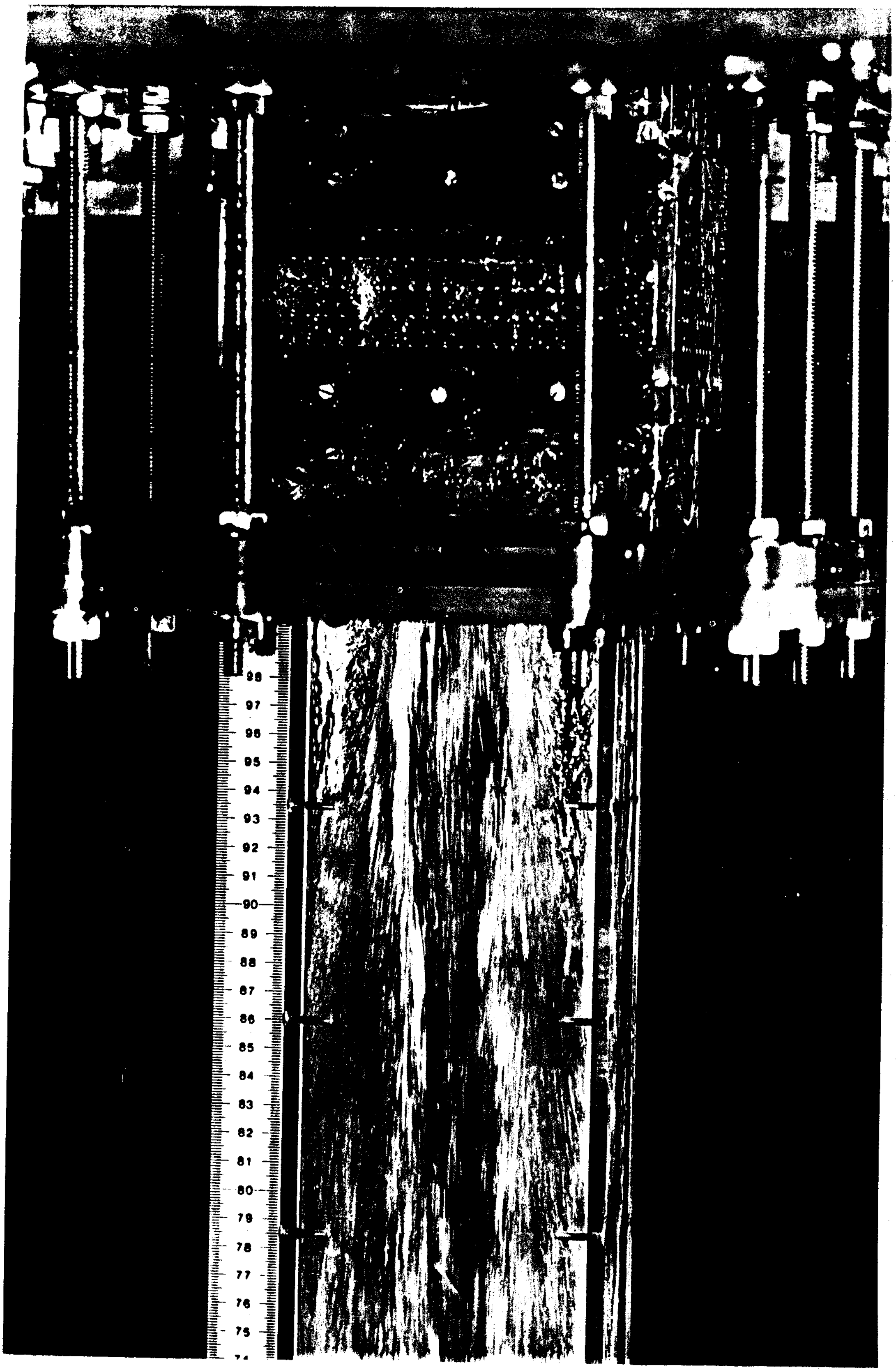


PLATE 1. Performance of model aerator: initial design

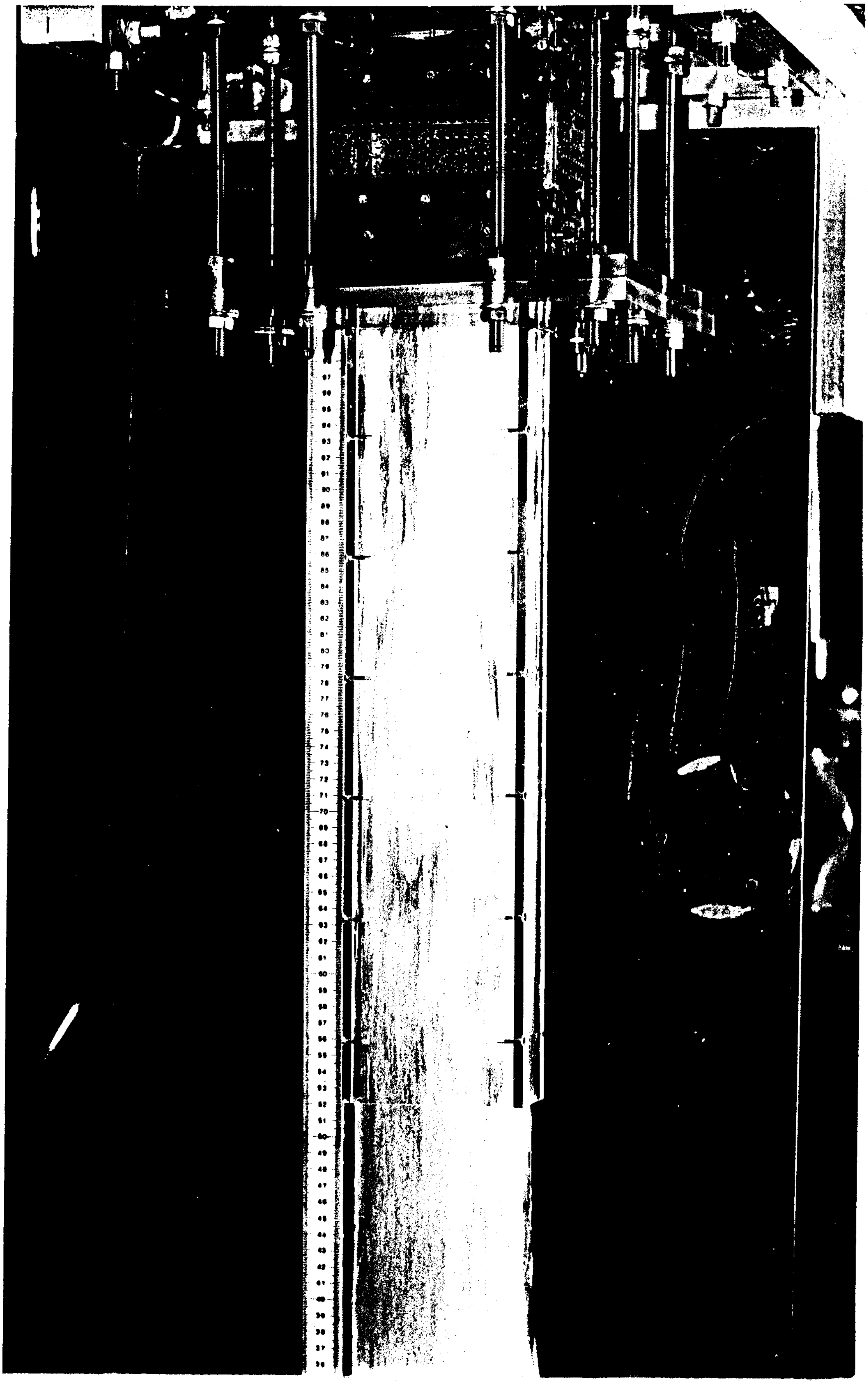


PLATE 2. ` Performance of model aerator: modified design

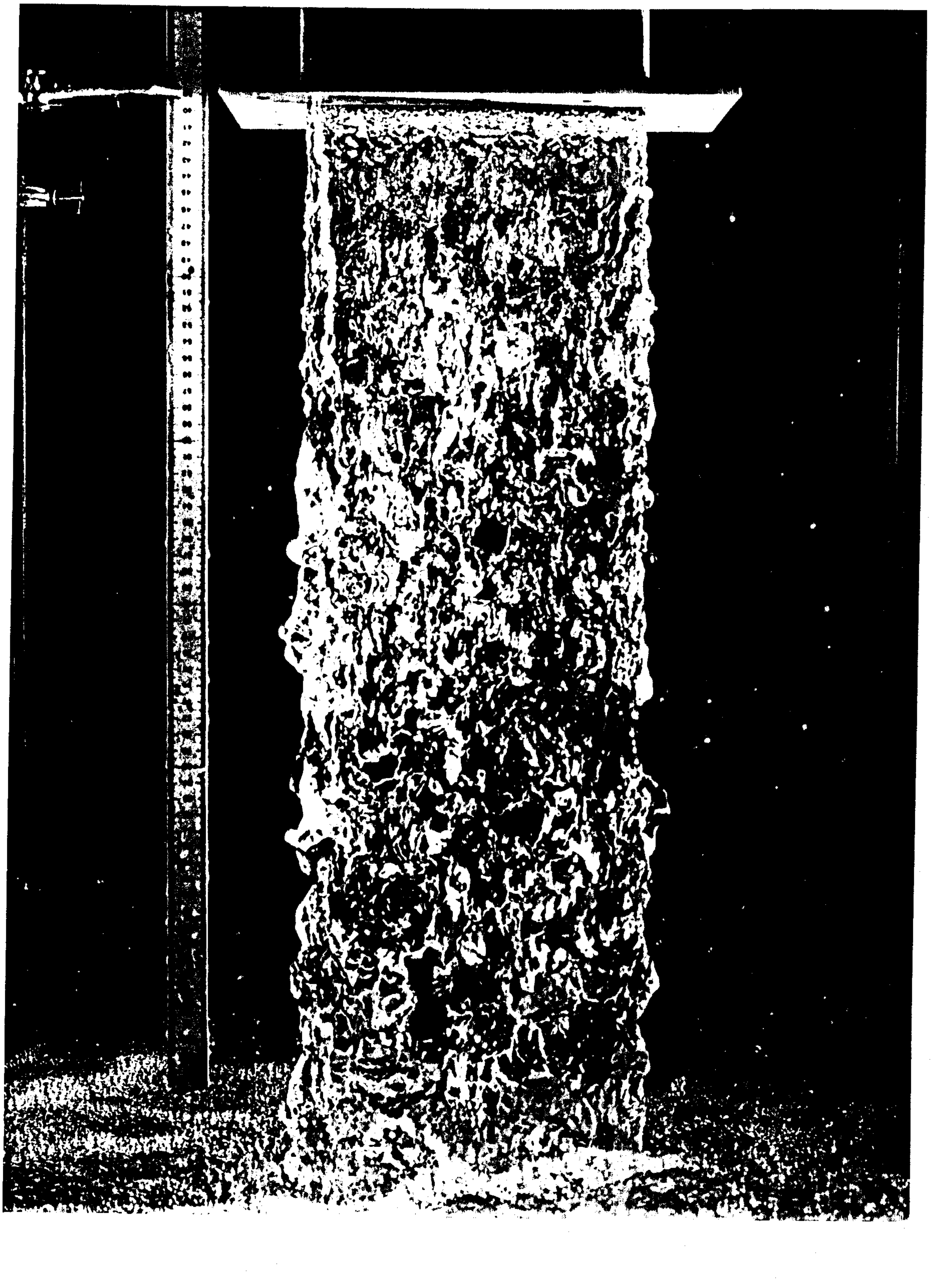


PLATE 3. Jet discharging from height of 1.08m at $V_{av} = 2.45m/s$: long side

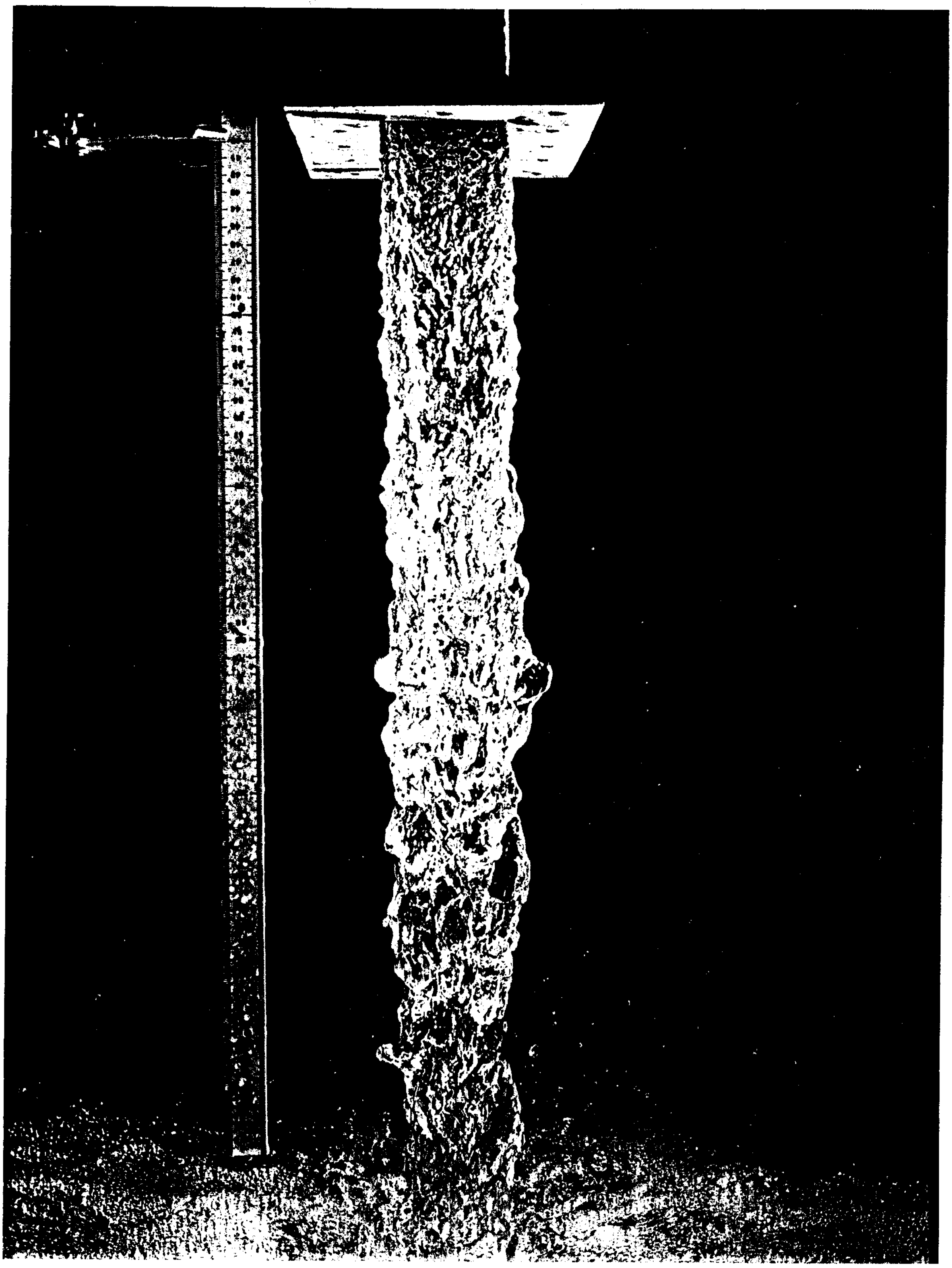


PLATE 4. Jet discharging from height of 1.08m at V_{av} = 2.45m/s: short side

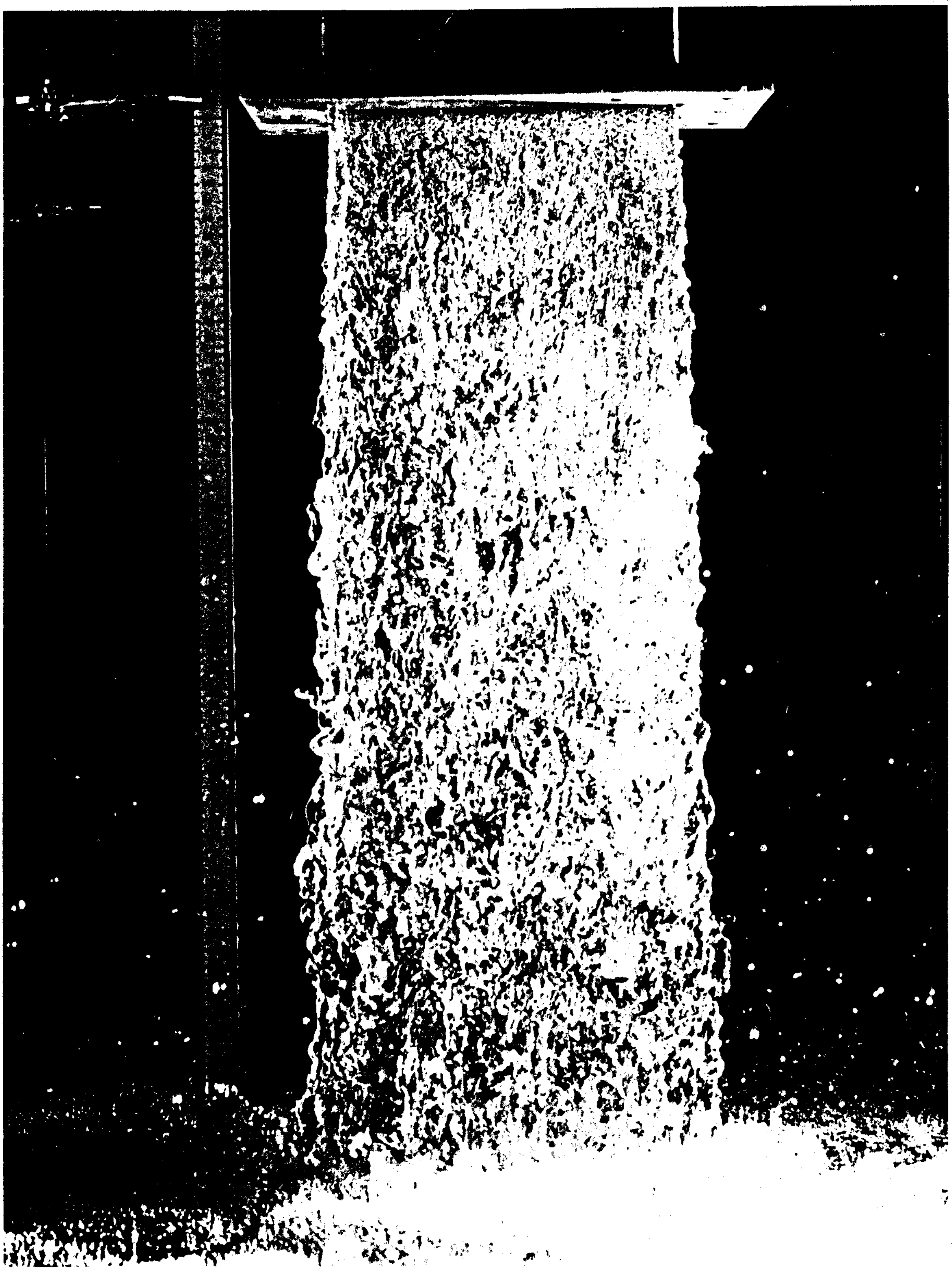


PLATE 5. Jet discharging from height of 1.08m at V_{av} = 4.26m/s: long side

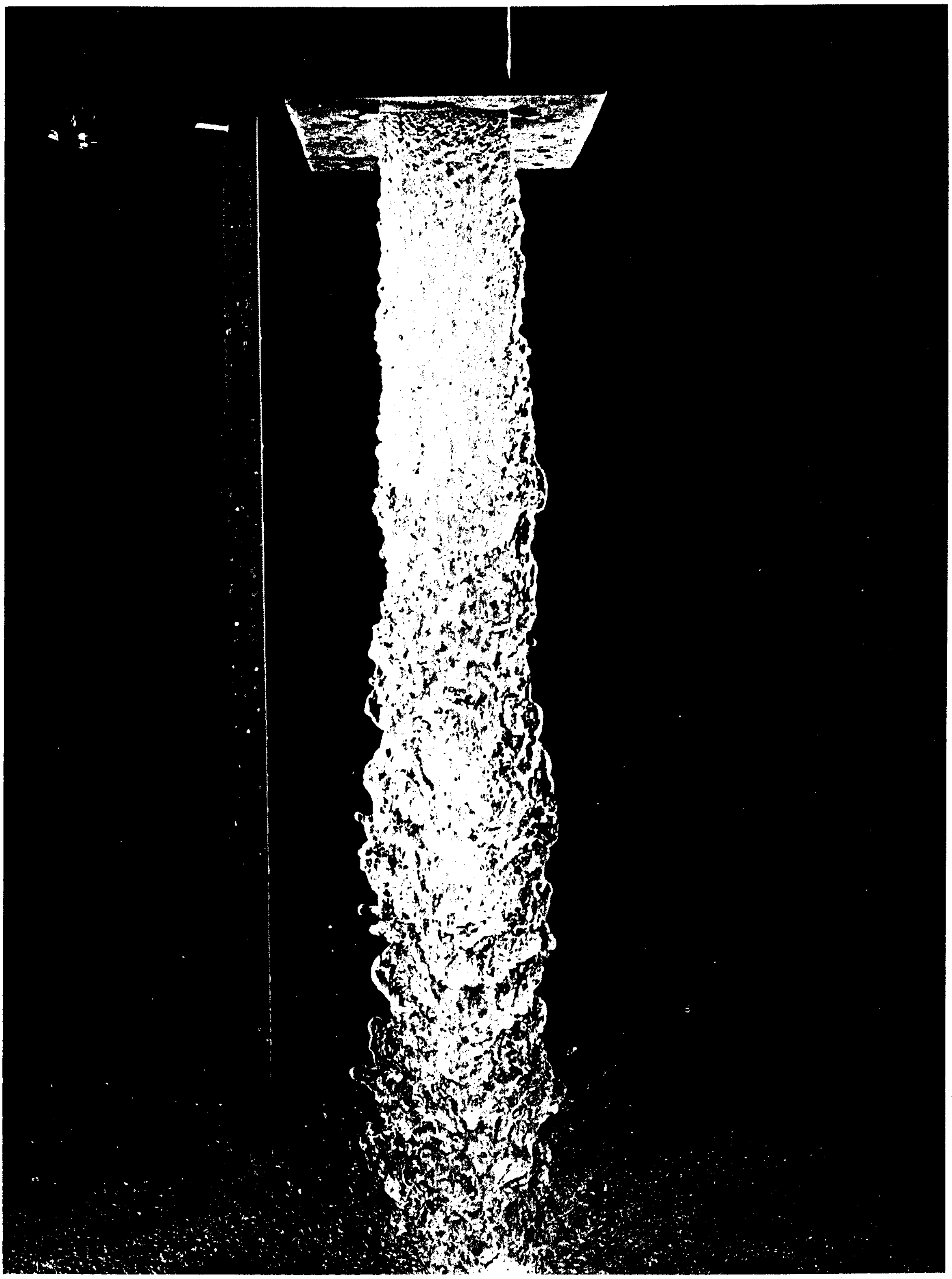


PLATE 6. Jet discharging from height of 1.08m at V_{av} = 4.26m/s: short side

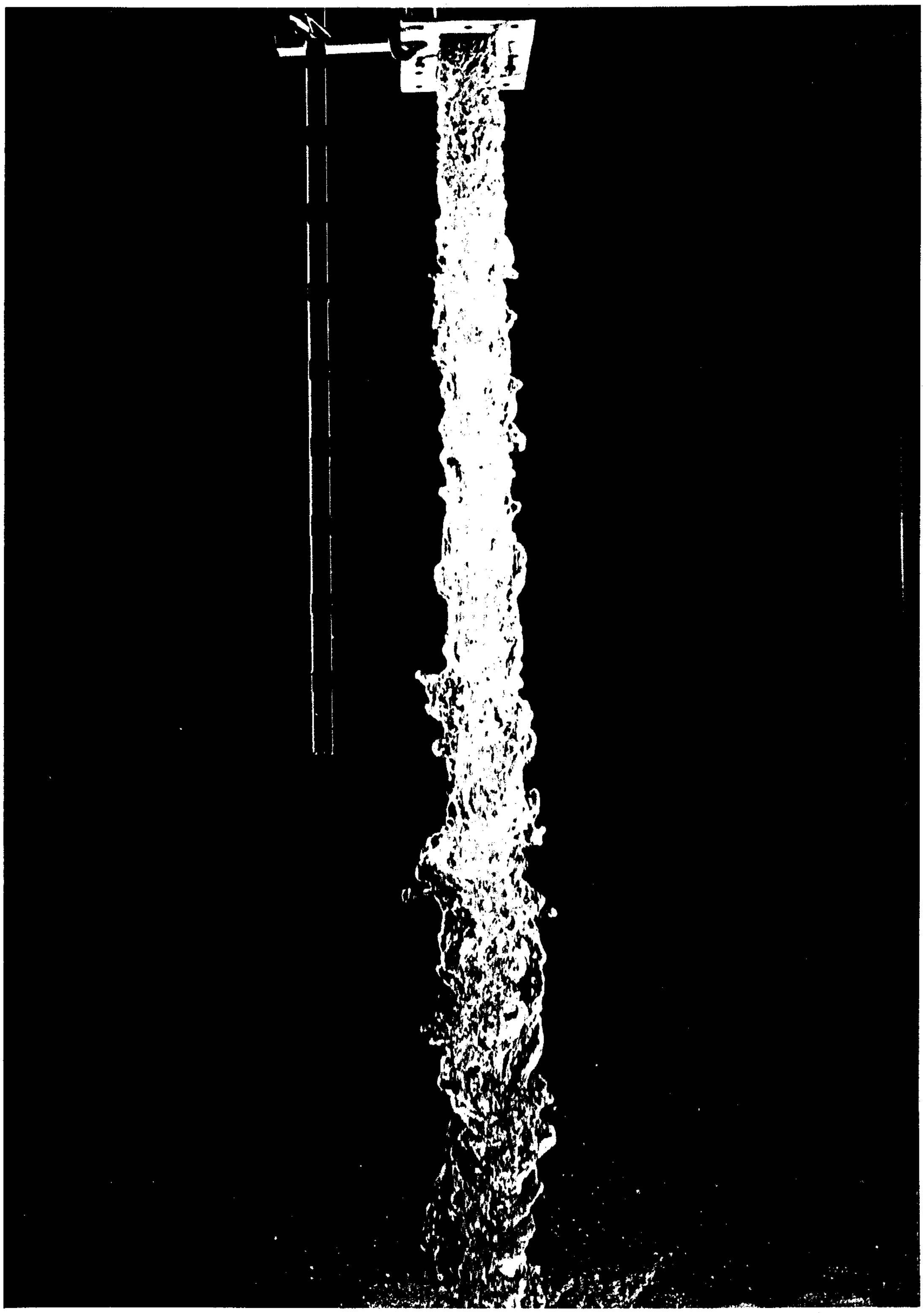


PLATE 7. Jet discharging from height of 2.30m at V_{av} = 2.44m/s: short side

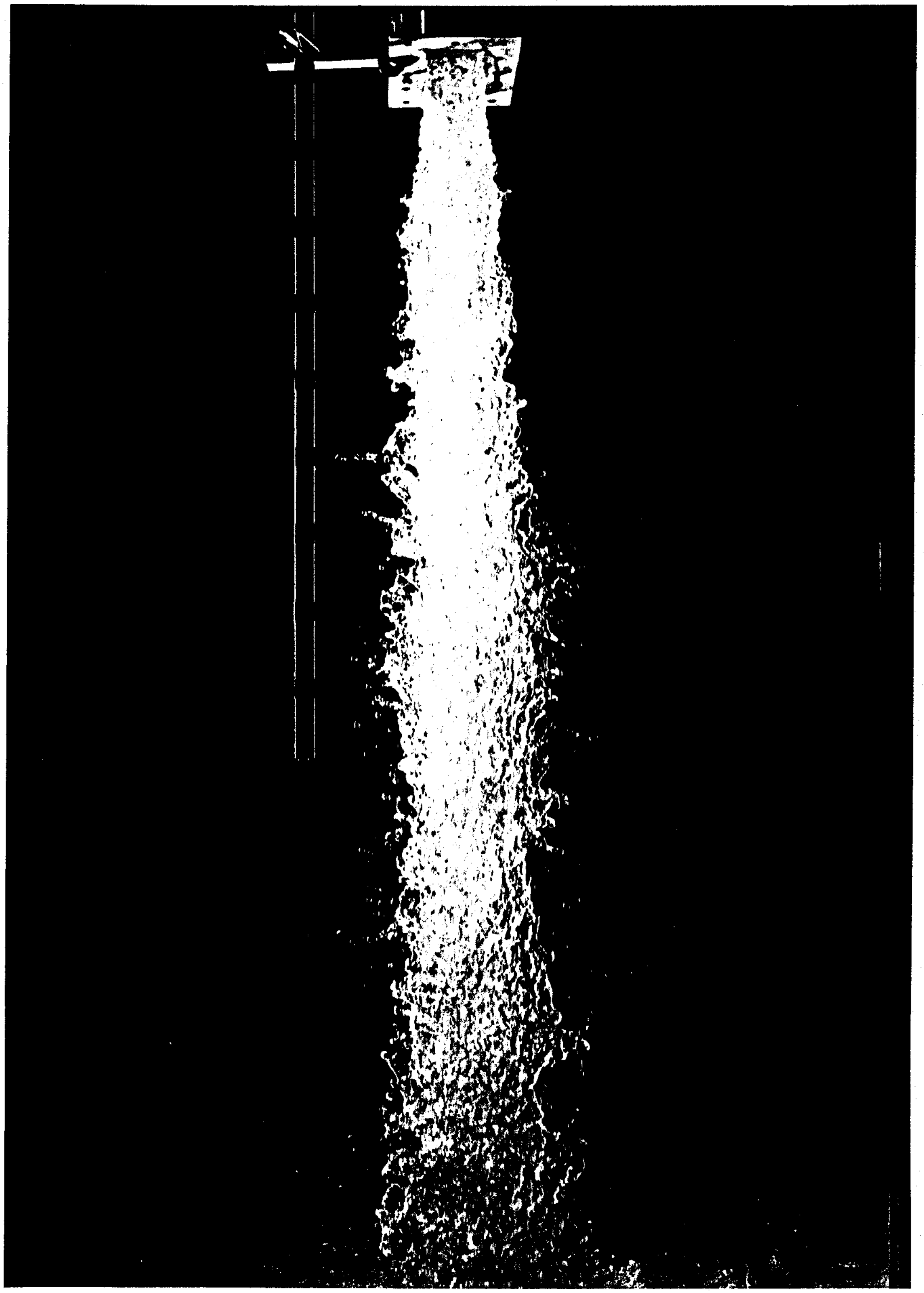


PLATE 8. Jet discharging from height of 2.30m at V_{av} = 4.29m/s: short side

APPENDIX A

APPENDIX A: LITERATURE SURVEY

A.1 Introduction

Many modern dams are of thin concrete arch construction. This design of dam is not normally compatible with hydraulic jump basins for flood energy dissipation and the usual methods used are ski-jump outlets or chutes, and vertical drops from the crest of the dam. The latter method is attractive because the structure is compact and means can readily be incorporated to break up the jet and dissipate substantial amounts of energy by air resistance. However, a negative feature of this method of energy dissipation is that it takes place close to the dam and it is essential to provide a protective apron under the jet. Existing dams using this method may or may not have water pools on the apron; there has been little information available as to the benefits of either approach. This review seeks out the available information on this subject and proposes steps to be take to augment it.

A.2 Scope of review

The range of information related to jets falling on fixed surfaces, and the influence of tailwater pool depth on the forces generated, is rather small. There is, however, a wider range of information on the scour developed by falling jets on erodible surfaces. There are features that are common to both situations and information gained on one has relevance to the other. Papers on the development of scour under falling jets are therefore included. Also included in the bibliography are a number of papers not specific to the topic under review but of background interest.

A.3 High-level jets

The heading refers to the jet from overflow crests or outlets high in a dam and therefore not under high pressure. The throw is relatively short and the jet on impact with the ground or apron below the dam will have a vertical or near vertical trajectory.

The principal papers that refer to these conditions are those by Ishikawa and Hausler and Hartung.

Ishikawa (1) addresses the question of forces on a fixed surface beneath a steeply falling jet and identifies two types of flow. Type A occurs when downstream tailwater depth is low and the flow is supercritical. Upstream flow is submerged and creates a pool behind the jet. This implies a sheet jet and two dimensional flow with very little space around the sides of the jet. Type B flow occurs when downstream depth is high and the flow is therefore submerged. The author makes assumptions on energy conservation and momentum balance to derive an equation for dynamic pressure on the fixed bed. Theory is compared with model tests and gives good agreement. The English version of this paper gives only a contracted form of the theory and no details of the model tests. A translation of the longer original version of the paper in Japanese is not yet available.

Hausler (2) (also Hausler and Hartung (3)) is mainly concerned with scour under a jet but deals with the form of a water jet in water as an analogy to the theory of free jet turbulence founded by Prandtl and tested in air. The author's conclusion is that dispersion is almost completely linear and that a core is formed that has the same velocity as the entry velocity to the tailwater. The boundaries of the core are also linear and converge with a half angle between 4 and 6 degrees depending on Reynolds No (4). Hausler assumes that the tangent of the half angle can be taken to be 0.1 (5.7 degrees) and that the core length is therefore 5 x diameter or width of the entering jet. He further states that at this depth in the tailwater, 20 per cent of a rectangular jet's energy will have been dissipated and 30 per cent of the energy of a circular jet. Since jet theory would only predict total dissipation at infinite depth, the author carried out experiments and predicted that in practice a circular jet would have almost completely dispersed at a water depth of 20 x diameter of jet, on entry to tailwater. Model studies by Cola (5) predicted a similar level of dispersion for rectangular jets at a depth of 40 x width of jet. It is not clear in references to rectangular jets which width dimension is being referred to but reasoning suggests it would be the smaller.

Hausler equates the length of a jet in unlimited water to the potential depth of scour under a jet and therefore to the depth of tailwater for zero pressure on the bed. For lower depths he states that if the bed is within range of the jet core (depth less than 5 x jet diameter) the peak pressure will equal the entering velocity head and the distribution will be Gaussian to a distance of one third of the water depth either side of the centre.

A.4 Scour under jets

Many equations have been proposed to calculate the depth of scour that will occur under the impact of a jet. A comprehensive review and assessment of these equations has been made by Mason and Arumugam (7). The scour depth in most of the formulae is the depth from the water surface, on the assumption that total water depth is the criterion for energy dissipation. Only one or two formulae assume that the proportion of total water depth that is above bed level, i.e. the tailwater depth, will influence the total water depth. The authors showed that the various formulae gave widely different results when tested against a wider variety of data than that used in the original development of a particular formula. Mason therefore proposed a formula in the form that appeared to be the most satisfactory.

This was:

$$D = K\, q^{x}\, H^{y}\, h^{0.15}/g^{0.3} d^{0.1}$$

where:

D = depth of scour
q = unit discharge
H = height from tailwater to reservoir level
h = tailwater depth
g = acceleration due to gravity
d = characteristic particle size (models)
= 0.25m (prototypes)
$K = 6.42 - 3.1H^{0.1}$
$x = 0.6 - H/300$
$y = 0.15 - H/200$

This equation does not relate directly to the problem of pressures on a fixed bed but is an alternative way of estimating the minimum depth of tailwater for dissipating the energy of a jet.

A.5 Aeration

All the foregoing papers on pressures on an apron, dispersion of a jet and scour under a jet assume no significant aeration of the jet. Ishikawa assumes the velocity and dimensions of the jet at entry to the tailwater. Hausler suggests ignoring air entrainment in order to make the results conservative or to assume a small dispersion in air and a slightly reduced core size on entry to the tailwater. He does not, however, give positive guidance on this point.

On the other hand there is a body of evidence to suggest that deliberate introduction of air into a falling jet can substantially reduce pressures/scour on impact.

Johnson (8) experimented with a vertical nozzle discharging onto a gravel bed. The nozzle was slightly below water level to exclude all uncontrolled air entrainment.

A measured amount of air was introduced to the jet such that the jet contained 50 per cent air at atmospheric pressure. When the unaerated jet was giving maximum scour depth, the aerated jet under the same tailwater conditions was scouring to only half the depth. A further test is also of interest. The unaerated jet was split into 32 fine jets of the same total area. The jets were parallel but the separation between the jets doubled the overall impact area. This had virtually no effect on the scour depth compared with the single jet.

A number of model tests of specific projects (e.g. 9 and 10) have shown that, despite the inability of models to entrain air on the scale of a prototype, marked gains in energy dissipation have resulted from the deliberate break up of the jet from an overspill crest. Although the details may differ, the principle normally used is that developed by Roberts (11) using splitters on the crest. McKeogh and Elsawy (12) showed that the turbulence intensity of a jet as it leaves a nozzle has a pronounced effect on the behaviour of the jet. Using small circular nozzles the authors investigated the "disintegration length" of a vertical falling jet and showed that the jet broke up into spray in as little as half the distance when flow in the nozzle was deliberately made turbulent. Horeni (13) has carried out a similar study for a rectangular jet. It may be therefore, that the beneficial effect of splitters on the crest, is due to an increase in turbulent intensity rather than the entrainment of air. When Roberts- type splitters are operating at low discharge it is usually seen that they divide the flow into individual jets without promoting a high degree of turbulence. Under these circumstances the energy dissipation is not notably higher than for a single jet. This is in line with both the observations of Johnson and of McKeogh and Elsawy.

Whether the effect of splitters is to break up the jet through turbulence or introduce air that is carried down the water column the effect is to carry entrained air into the downstream pool. Volkart (14) showed that falling droplets entrain air on impact with a pool in a study of air bubble entrainment in self-aerated flows using stroboscopic techniques.

It has been shown experimentally (Homma (15)) that when air is entrained in a jet, the jet disperses on entering a pool in a shorter distance than a non-aerated jet.

It is apparent that aeration of a jet both above and in the tailwater pool can potentially reduce the pressures on the bed of the pool by such an extent that to ignore aeration,in order to provide a safety margin,could lead to excessive over-design or to the rejection of a viable design option.

A.6 Conclusions

It is essential to carry out model tests on falling jet energy dissipators to ensure that flow conditions are satisfactory in every respect. The tested design will be the outcome of preliminary desk studies and given the cost of model studies and the time taken to execute them, radical variations are unlikely to be made unless the initial design is totally unacceptable.

It is therefore of great advantage if initial design options can be compared on a basis of sound knowledge of the behaviour of falling jets from outlet to tailwater pool to pool bed.

At present the information available is more qualitative than quantitative. Only one study has been found that specifically attempts to determine the forces on a concrete apron under a falling jet by theoretical means. The theory assumes that the velocity of the jet on entry to the pool is known and that the jet is coherent and not aerated. The effect of natural or deliberate dispersion or aeration of the jet cannot therefore be assessed. The remainder of the available information consists of isolated studies of individual aspects of jet behaviour.

There is a need to draw together these various aspects and relate them to the practical problem of designing effective and safe falling-jet energy dissipators. Implicit in this is the need to relate, as accurately as possible, model performance to prototype performance.

Particular questions to be answered are:

(a) The behaviour of rectangular or sheet jets in a tailwater pool. Most work has been done so far with circular jets. Occasional references to rectangular jets suggest that their behaviour may be quite different and this is the form most often occurring in practice.

(b) The characteristics of jets in pools with finite boundaries. Most work on jets relates to pools of unlimited extent.

(c) The effect of air entrained in the jet or by the jet on the dispersion within the tailwater pool.

(d) Characteristics of the jet on entry to the tailwater pool in terms of discharge, dimensions of jet at its origin and the height of fall. McKeogh and Elsawy related length of fall before jet broke up from natural instability to total discharge for circular jets. Horeni formed a similar relationship, using unit discharge, for a rectangular jet.

(e) The effect of turbulence on the break up of the jet.

(f) The effect of the introduction of air near the origin of the jet on the break-up of the jet.