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WATER RESEARCH LABORATORY

REPORT No. 46

Wind Induced Oscillations of Power Station Stacks

by

C. R. Dudgeon

OCTOBER, 1962

The University of New South Wales
WATER RESEARCH LABORATORY.

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Final Report to The Electricity Commission of New South Wales

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PREFACE.

This study forms part of a series of investigations undertaken by the Water Research Laboratory of the University of New South Wales at the request of the Electricity Commission of New South Wales. The study was commenced in July 1961 and completed in March 1962.

Throughout the course of the investigation close liaison was maintained with the Electricity Commission through engineers of the Commission's Project Development Section, Messrs. K. Watson, N. Lamb and A. Kugaevsky. Information on the progress of the study was made available through these officers.

The work was carried out at the Water Research Laboratory, Manly Vale, N.S.W., by Messrs. C.R. Dudgeon and T. Durkin. The Electricity Commission programme is under the direct supervision of Mr. D.N. Foster of the Laboratory Research staff.

H. R. Vallentine,
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Officer-in-Charge of the Water Research Laboratory.

October 1962.

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SUMMARY

Wind induced oscillations of welded steel smokestacks at Prymont Power Station, N. S. W., have led to local buckling and fatigue cracks near the base of at least one stack. Observed double-amplitudes of the tops of the 200 feet high stacks have been of the order of 2 to 3 feet.

This report deals with a survey of the relevant literature and theoretical aspects of the problem together with laboratory and prototype tests aimed at determining the interference or 'buffeting' effects of eddies in the wake from an upstream stack on those downstream.

Smoke trail tests carried out on the prototype yielded no quantitative information on interference but did give qualitative data on separation points and regularity of eddy shedding.

Model tests showed the effect of interference at sub-critical Reynolds numbers but the testing facilities available did not allow conditions dynamically similar to prototype conditions above critical Reynolds numbers to be achieved. However, for super-critical Reynolds numbers above 5×10^6 regular eddy shedding is known to occur as it does for sub-critical Reynolds numbers (below 2×10^5) and as the Pyrmont stacks oscillate in this super-critical range the prototype interference effects are unlikely to differ appreciably from those observed in the model.

The elastic response of cylinders to wind induced forces is not dealt with in this report but methods of suppressing the forces are considered.

The most direct means of eliminating periodic interference or 'buffeting' effects would seem to be to prevent the regular shedding of eddies from upstream cylinders. It is considered that the most practical method of suppressing the periodic shedding of eddies is to fit to the stacks spoilers of the type investigated by Weaver (18) and Scruton and Walshe (15).

The optimum spoiler system, according to the above investigators, would consist of four 'strakes' with heights of 6 to 10 pc. of the stack diameter wound helically around the stacks with a pitch of 12 stack diameters. However, Weaver's results suggest that in the case of the Pyrmont stacks a single 'strake' of the above dimensions fitted only between the middle and top catwalks might suffice.

A wind tunnel capable of proving these spoilers at Reynolds numbers of 5 x 10^6 and higher is unavailable locally and it is suggested that if tests at these Reynolds numbers cannot be arranged elsewhere, spoilers should be fitted in stages beginning with a single 'strake' over part of the length as described above and adding further 'strakes' if necessary.

An aesthetically acceptable solution might be to replace the existing cat-ladders by a spiral set of steps incorporating the spoiler.

For a comprehensive treatment of the elastic response of cylinders to periodic forces the reader is referred to Reference (18).

1. Introduction

1.1 The Prototype

At the time the design of Pyrmont Power Station smoke stacks was carried out, inadequate information was available on the dynamic behaviour of tall cylindrical structures subjected to wind loading. It was customary in engineering design to compute static wind loads and design the structure to withstand these with a suitable margin of safety.

While stacks were constructed of masonry or riveted steel which possessed sufficient damping properties, problems of wind induced oscillation were not serious. The postwar development of welded steel stacks of ever increasing height and very low inherent damping led to serious oscillation which caused the failure of at least one stack in the United States and difficulties with others: (2, 3, 10).

The Pyrmont installation shown in Fig. 1 consists of four welded steel stacks 91 feet in height, 13 feet in diameter and spaced at 55 feet centres on a line bearing N. 78° E. The stacks are mounted on heavy steel plate web girders incorporated into the structure of the roof of the building which is approximately 200 feet above the adjacent ground level.

In the winter months, strong westerly winds occur frequently and during these winds large amplitude oscillations of the stacks, in particular, No. 3, positioned second in line from the windward end, have been observed. Double amplitudes have been up to 2 to 3 feet. Local buckling and fatigue cracks attributed to this movement were found near the base of No. 3 stack.

1.2 Purpose of Investigation

The purpose of the investigation described in this report was to study the aerodynamic cause of the oscillations and, in particular, to ascertain whether any aerodynamic reason could be found to explain why the amplitude of oscillation of No. 3 stack was greater than those of the other stacks.

1.3 Associated Investigations

This investigation was one of a series initiated by the Electricity Commission to study all aspects of the problem. The overall structural problem was investigated elsewhere by means of water and wind tunnel tests on dynamic models of the stacks. The Commission also carried out strain, phase and amplitude measurements on the prototype.

2. Theoretical Aspects and Literature Survey

2.1 Flow Past a Single Cylinder

2.11 General

The earliest theoretical work on the flow past a cylinder dealt with the flow of an ideal fluid and is inapplicable to the present problem as separation effects are not accounted for.

The development of boundary layer theory by Prandtl and others in the early part of this century led to a better understanding of drag, lift, separation and the formation of wakes. The study by Strouhal, Von Karman and others, of the vortex streets behind cylinders immersed in a moving fluid yielded quantitative information on the periodicity of vortex shedding. This information has been extended by Kovasznay, Roshko, Ribner and Etkin, Relf and Simmons, Delany and Sorenson, and others.

The subject is still not fully understood, particularly the mechanism of vortex formation and shedding, and several recently published papers (4, 5 and 14) indicate that fundamental research work is still being actively pursued.

2.12 Mean Drag Coefficient and Strouhal Number

Fig. 2(a) shows a combined plot of the data at present available on the periodicity of vortex shedding and the mean drag coefficient for flow past a long stationery cylinder with its axis at right angles to the direction of flow.

(i). Drag and Lift Coefficient

The temporal mean drag force on a body immersed in a flowing fluid is given by the expression:

$$D = C_D \, A \, \tfrac{1}{2}\rho V^2$$

where D = mean drag force

C_D = coefficient of drag

A = area of the body projected normal to the flow

ρ = fluid density

V = approach velocity of the fluid

The values of C_D are usually plotted against Reynolds number and give the drag force averaged with respect to time, yielding no information on fluctuating forces. However, a plot of instantaneous C_D versus time will indicate a mean positive value with cyclical fluctuations about this mean. A corresponding equation can be written for the "lift" or lateral forces, C_D being replaced by C_L. For a cylinder the mean value of C_L is zero but a plot of C_L against time will also show cyclical fluctuations about this mean. The cyclical lift fluctuations are greater than those of the drag.

In both cases the regularity of the cyclical fluctuations depends on the Reynolds number of the flow.

(ii) Strouhal Number and Reynolds Number

The Strouhal number, $S = \frac{nd}{V}$ and the Reynolds number, $\mathbb{R} = \frac{Vd}{\nu}$ are dimensionless numbers which allow the relationship between the variables affecting the period of vortex shedding to be plotted on a single curve for all cylinders.

n = frequency of vortex shedding

d = cylinder diameter

ν = kinematic viscosity of the fluid.

Recent work by Roshko (14) has allowed the curves of Fig. 2(a) to be extended to Reynolds numbers of 10^7.

(iii) Vortex Street

Fig. 2(b) shows the pattern of vortices which develop in the wake of a cylinder. The geometry of this pattern depends on the conditions of flow.

This pattern is important in the study of the interference of the wake from an upstream cylinder with the pressure distribution and resultant forces on downstream cylinders.

2.13 Variation of Flow Characteristics with Reynolds Number

Several important characteristics of the flow around a cylinder are reflected in the C_D and $\frac{1}{S}$ curves, viz:

(1) For extremely low Reynolds numbers (less than about 0.1) the flow approximates to that of an ideal fluid with stagnation points on the

centre line at both the front and the rear of the cylinder and streamlines symmetrical about the centreline of the flow.

(2) For Reynolds numbers above 1, separation points become apparent on both sides of the cylinder and move forward around the cylinder with increasing Reynolds number until they stabilise at positions approximately 85 deg. from the forward stagnation point. Between Reynolds numbers of 1 and approximately 2.5×10^5 flow in the boundary layer is laminar right up to the separation points.

The C_D and $\frac{1}{S}$ curves are smooth and without sudden changes over this range.

(3) As the Reynolds number increases above 2.5×10^5, turbulent flow commences in the boundary layer upstream of the separation points and, as a result of the consequent increase in the rate of transfer of momentum from the body of the flow into the boundary layer, the flow is able to cling to the surface longer and the separation points shift towards the rear of the cylinder to about 110 deg. from the forward stagnation point. This shift is reflected in the C_D and $\frac{1}{S}$ curves by a sudden drop in the value of C_D and increase in the value of $\frac{1}{S}$. For other conditions constant, this decrease in S of approximately 100 pc. means a doubling of the frequency of eddy shedding. A narrowing of the wake is associated with an increase in shedding frequency for stability considerations.

(4) Recent work of Roshko (14) indicates that a further increase in Reynolds number results in a gradual increase in C_D and decrease in S, to values which tend to stabilise at approximately 0.7 and 0.26 respectively for Reynolds numbers between 3×10^6 and 10^7. This change is associated with a slight return of the separation points towards the front of the cylinder.

It should be noted that the frequency given by S is a predominant frequency and not necessarily the only frequency present in the wake. In all cases it would be better to consider a frequency spectrum with a dominant frequency shown to a greater or less extent for various Reynolds numbers. (See Para. 2.17).

2.14 Effect of Cylinder Roughness on Vortex Shedding

An increase in the roughness of the surface of the cylinder leads to a reduction in the value of Reynolds number at which turbulence appears in the boundary layer. The sudden rearward shift of the separation points and thus the sudden drop in the C_D curve occur for a lower Reynolds number than the value 2.5×10^5 mentioned in Para. 2.13.

2.15 Effect on Vortex Shedding of the Turbulence Level of the Approaching Air Stream

Large scale turbulence in the air approaching the cylinder has the same effect as cylinder roughness, that is, it promotes the early onset of turbulence in the boundary layer.

2.16 Vortex Shedding and Movement of the Separation Points

For a given value of Reynolds number, the separation points are not in fixed positions on each side of the cylinder but oscillate backwards and forwards as eddies are shed alternately from each side. Observation of the separation points during this investigation has shown that although the vortex shedding might be regular in time, the upstream and downstream limits of the separation points vary from cycle to cycle.

2.17 Regularity of Vortex Shedding

At very low Reynolds numbers (up to approximately 40) at which separation points first become apparent, vortices are present at the separation points but none are shed (13). When shedding first commences, the process is very regular and remains regular over the range of Reynolds numbers from 40 to 150. For higher Reynolds numbers, irregular shedding accompanies the formation of regular vortices. The irregularity increases until at Reynolds numbers between about 2×10^5 and 4×10^5 no distinct periodicity of vortex shedding can be detected. It has been found that a predominant frequency can be found again for Reynolds numbers beyond 3.5×10^6.

When the irregular fluctuations become significant the fluctuations downstream from the cylinder must be analysed as spectra, rather than single frequency phenomena. It would be more general to consider a spectrum of frequencies for all Reynolds numbers.

2.18 Effect on Vortex Shedding of Cylinder Length - Diameter Ratio and End Effects.

Wind tunnel experiments (5, 17) have shown that coefficients of drag and frequencies of vortex sheddings are affected by the cylinder length to diameter ratio and the nature of the boundaries at the cylinder ends. In addition, it has been found that if the diameter of the cylinder is reduced at an end, the frequency of vortex shedding on the cylinder may correspond to that for the reduced diameter.

Variations in conditions along the length of the cylinder have been found to be particularly important when the boundary layer is in a state of transition from laminar to turbulent flow.

2.19 Effect of Cylinder Oscillation on Vortex Shedding

Wind tunnel tests (9, 18) have indicated that the periodic forces acting on a cylinder are increased if the cylinder is allowed or forced to oscillate with an appreciable amplitude. This "self-amplification" must be due to the superposition on the stream velocity, V, of an oscillating velocity which may have components both in the direction of and at right angles to the direction of flow, depending on the locus of motion of the cylinder. This motion is equivalent to an oscillating circulation around the cylinder.

If the cylinder oscillates around a circular path of radius A under the influence of fluctuating lift and drag forces in a wind of velocity V with a period T, the resultant wind velocity relative to the cylinder is:

$$V_r = \sqrt{\left(V + \frac{2\pi A}{T}\cos\theta\right)^2 + \left(\frac{2\pi A}{T}\sin\theta\right)^2}$$

where θ is the angle between the resultant and the direction of V and varies between $\pm \tan^{-1} \frac{2\pi A}{VT}$

Typical values for Pyrmont stacks are:-

V = 60 feet per second

T = 1 second

A = 1 foot

Then the resultant wind velocity is $\sqrt{(60 + 2\pi \cos\theta)^2 + (2\pi \sin\theta)^2}$ swinging between $\pm$ 8.3 deg. from the direction of V.

The velocity in the V direction would vary between 60 $\pm$ 6 ft/sec.

The component in the lateral direction would be $\pm$ 6 ft/sec.

If the flow pattern relative to the resultant velocity remained constant (i.e. if the pattern were able to follow the $\pm$ 8.3 deg. swing) and the vortex shedding mechanism were unaffected, the velocity swing would lead to an oscillating lateral force of $\pm$ sin 8.3 deg. p.c; i.e. $\pm$ 0.15 p.c. However, this would oppose the motion and lead always to air damping. This does not agree with experimental observations and the conclusion which may be drawn is that the cylinder oscillation leads to a periodic distortion of the flow pattern and asymmetrical motion of the separation points. This in turn leads to an increase in the magnitude of the periodic forces.

Model tests carried out during this investigation indicated that separation points could not be forced to move upstream as fast as downstream and it is suggested that the periodic distortion of the flow pattern is due to this fact. A small change in frequency of eddy shedding also accompanies the oscillation. This has been attributed (13) to the fact that the wake width becomes wider and for stability the frequency of eddy shedding must increase.

When the cylinder is elastic and free to oscillate in response to the impressed forces, the degree of self-amplification depends on the damping characteristics. Structural damping is not considered in this report.

2. 2 Flow Around Cylinders in Line

The Pyrmont stacks are spaced a sufficient distance apart for interference effects with winds blowing across the line of the stacks to be of no consequence. Some published information (7) is available on this subject but has not been actively pursued in this investigation.

Published information on interference effects for flow parallel to a number of cylinders in line is very limited. Some early work was carried out on flow patterns for an ideal fluid but this does not allow for separation effects.

Laird (7, 8) has carried out experimental and theoretical work on the forces on a number of cylinders in a stream. The experimental work, which consisted of drag and lift measurements on cylinders abreast and in line, was followed by a free streamline analysis of the effect of vortices in the flow approaching a cylinder. The study was related to the design of pile supports for marine structures and has no direct application to the stacks problem for the following reasons:-

(1) The test cylinders were oscillating in the fluid at the end of a long pendulum to reproduce the type of motion experienced by the fluid around piled structures subjected to wave action.

(2) Tests were carried out only at low Reynolds numbers.

(3) The theoretical work does not account fully for the effects of separation around the cylinder.

The important variables influencing the interference between cylinders are the spacing and the angle between the flow direction and the line of the cylinders.

By altering the shape, orientation and magnitudes of the pressure distribution around a cylinder, vortices moving downstream alter the periodic forces from those which occur on a cylinder in undisturbed flow. The effect is frequently referred to as "buffeting". The cylinder spacings and the angle of attack of vortices clearly affect the amount of distortion the normal flow pattern is subjected to.

Hydrodynamic theory has difficulty in dealing with the problem because of separation; and model work is difficult because of the large wind tunnel test sections required to accommodate a number of cylinders at various spacings and orientations.

The angle of attack yielding maximum interference effects is subject to some doubt. Ozker and Smith (10) published a polar plot of amplitude of oscillation against wind direction for the second of a series of three stacks on a power station in Detroit, U. S. A. The plot was based on prototype observations and showed a maximum amplitude for winds parallel to the line of the stacks. However, the published information reveals that the maximum wind velocity experienced happened to occur along the line of the stacks and does not preclude the possibility that a greater amplitude would have occurred for the same wind acting at a small angle to the line of the stacks. There is also the possibility that the maximum amplitude for the third stack, say, might occur for an angle of attack different from that producing maximum amplitude of the second.

3. The Model

3.1 Testing Channel

To enable flow patterns around cylinders in line to be observed, a water model was built as shown in Figure 3.

The test section consisted of a rectangular channel 4 feet long, 30 inches wide and nine inches deep covered by a perspex top to prevent the formation of surface waves. A gravel baffle and rectangular approach section preceded the test section which was followed by an outlet section and tailwater gate used to maintain the hydraulic grade line slightly above the perspex roof of the test section.

3.2 Model Stacks

Four 3 inch diameter perspex tubes were fitted in line in the test section to represent the four Pyrmont stacks. The tube spacing was made geometrically similar to the prototype spacing at a scale of 1:52.

3.3 Dye Injection

Each cylinder was fitted with a dye injecting device as shown in Fig. 3. These consisted of fine stainless steel tubes which could be rotated around the cylinders to inject dye at any desired position. Protractors were fitted to allow the angular position of the injectors to be measured accurately.

The injectors were designed to allow the oscillating separation points to be observed and their limits of movement measured.

3.4 Model Reynolds Numbers

The maximum Reynolds number at which the model could be operated was limited by the maximum discharge available. This was approximately 2 c.f.s., giving an approach velocity of 1.1 ft. per sec. and a Reynolds number of 2.2×10^4. This Reynolds number compared with a prototype value of 4.9×10^6 for a 40 m.p.h. wind and 7.3×10^6 for a 60 m.p.h. wind.

It will be observed from the C_D and $\frac{I}{S}$ versus IR curves that the conditions of operation of the model and prototype are completely different, the model boundary layer being laminar and the prototype layer turbulent. The model could not thus be relied on to yield dynamically similar results and was mainly of interest in yielding qualitative flow patterns.

To overcome the limitations of the model, prototype tests were attempted to allow a comparison of model and prototype results. (See Para. 7).

4. Model Tests

Tests on the model were carried out only at the maximum Reynolds number attainable (2.2×10^4) as nothing was to be gained by testing at lower Reynolds numbers when prototype Reynolds numbers were much higher.

The direction of flow was restricted to that along the line of the cylinders because the restricted width of the test section prevented the four cylinders being skewed to any appreciable angle without wall effects being encountered.

Frequencies of eddy shedding for all four cylinders were observed for a number of cylinder spacings. In addition, the movement of the separation points were observed and movie films of dye trails from the cylinders were taken and later analysed to determine phase relationships between vortices shed from the four cylinders.

5. Prototype Tests

Smoke bombs were made from a mixture of zinc dust and carbon tetrachloride with a suitable filler to reduce the reaction temperature.

These bombs were ignited with fuse lighters and hauled up the prototype stacks both in the wake and at the stagnation point to allow flow patterns around the stacks to be observed for various wind conditions. Movie films of the trails were taken and later analysed.

6. Model Test Results

6.1 Eddy Shedding Frequency

The frequencies observed agreed closely with those predicted by the curve, (Fig. 2a). It was noted, however, that the shedding was not completely regular and eddies were shed occasionally at random. This observation agrees with the findings of Roshko (13) who found that some eddies were shed irregularly for Reynold numbers above 150.

No difference in frequency of eddy shedding was observed for any of the four stacks although at the upstream point on the second cylinder there sometimes appeared to be flow direction reversals at twice the frequency of eddy shedding.

6.2 Flow Pattern

It was found for the cylinders in line that instead of the approximately parallel sided vortex trail which forms the wake from a single cylinder, the vortices moved away at an angle to form a divergent wake. The angle of spread increased more rapidly beyond the second cylinder, indicating that the third and fourth cylinders were not as subject to interference from their neighbours as was the second. This would explain the second cylinder being subjected to greater periodic forces for flow in this particular direction.

6.3 Movement of Separation Points

The lateral force component on a cylinder can be expected to vary with the extent of oscillatory movement of the stagnation point and separation points for these mark the point of maximum pressure and the limits of the reduced pressure zone in the wake respectively.

Fig. 4 shows the measured fluctuations of the stagnation point and separation point positions. It is clear that the fluctuations on the second cylinder in line is the greatest in the three cases in which more than two cylinders were present and that the closer the cylinder spacing, the greater the swings measured. There would be a lower limit to the spacing to which the latter comment would apply as for very close spacings the cylinders would commence to act as one body.

In general, with the above proviso, the results indicate that the closer the spacing, the greater the fluctuating lateral forces. There appears no reason to believe in the existence of a critical spacing equal to the spacing of vortices in the vortex trail.

7. Prototype Test Results

Very little significant information was obtained from the prototype tests largely because of the difficulty of obtaining any required set of wind conditions. Observations were made under three sets of conditions:-

(a) Wind approximately 20 m.p.h. across the line of the stacks.
(b) Wind approximately 30 m.p.h. across the line of the stacks.
(c) Wind approximately 30 - 45 m.p.h. along the line of the stacks.

In the first case, the smoke bombs provided sufficient smoke for the wake to be observed and the paths of shed eddies followed, but as the wind was across the line of the stacks, the effect of the wake from one stack on others downstream could not be observed. The smoke showed clearly the positions of the separation points which indicated turbulent boundary layer. The period of shedding was difficult to estimate as regular shedding was interspersed with a good deal of irregular shedding, but the period of regular shedding that was observed agreed approximately with that predicted from Fig. 2a. The occurrence of some irregular shedding agrees with Roshko's findings (13,14).

In the second case, large movements of the stacks were observed when the wind approached 40 m.p.h. Once again, separation points could be observed and indicated a turbulent boundary layer. Eddy shedding was more regular than that observed for the 20 m.p.h. wind but some irregular shedding was still present. This agrees once again with Roshko's findings.

For both of these cases the irregularity of eddy shedding was much more pronounced than in the model tests.

In the third case the wind velocity was so high that the smoke output of the 2 pound mixture bombs was insufficient to allow the wake to be traced as far as the downstream stacks. The test thus yielded no information on the effect of the upstream stack on those downstream. However, separation points were clearly marked and pointed to a turbulent boundary layer with predominantly regular vortex shedding.

In all cases, an interesting point noticed was the strong updraft in the wake immediately behind the stack.

The catwalks and ladders attached to the stacks did not appear to affect the flow under the conditions experienced. However, Humphries' wind tunnel experiments (5) would lead one to expect the catwalks to exert a controlling influence on lengthwise variations in the flow at transition Reynolds numbers, by assisting the formation of transition 'cells'.

7.1 Prototype Oscillations for Wind Directions Nearly Parallel to the Line of the Stacks

The motion of the stacks was observed over a period when the wind was backing from approximately north-west to south-west with gusts up to 45 m.p.h.

An important observation was that when the wind was along the line of the stacks, the stack second from windward (No. 3) moved through a large amplitude while the windward stack (No. 4) was quiet and the remaining two (Nos. 1 and 2) oscillated but not as violently as No. 3.

When the wind was slightly off the line of the stacks, however, the third stack from windward (No. 2) appeared to have the greater amplitude.

8. Suppression of Periodic Forces on Cylinders

This discussion considers only the suppression of forces and does not cover all the methods of suppressing associated mechanical oscillations. These include alteration of the structural properties of the cylinders.

8.1 Alteration of Cylinder Diameter

This would not be practicable in most cases but when diameters of new structures are chosen, consideration should be given to the effect of diameter on the Reynolds numbers at which the structure will operate as well as its effect on structural stiffness.

8.2 Roughening Cylinder Surface

In certain cases where the resonant vibration condition occurred for Reynolds numbers just below the smooth cylinder critical value of $2.5x10^6$ it might be advantageous to roughen the cylinder surface to encourage an early transition to a turbulent boundary layer. Over a limited range of velocities the vortex shedding would then be almost aperiodic. This would not be the case for the Prymont installation as the resonant condition occurs at supercritical Reynolds numbers.

8.3 Provision of Splitter Plates

It was found by Roshko (13) that the introduction of a Splitter Plate behind a cylinder divides the flow and prevents the regular shedding of eddies. The application of this method to structures would not be practicable except in cases where the wind came always from the same direction, as winds acting at right angles to the plate would cause very large drag forces requiring prohibitively strong construction.

8.4 Provision of Perforated Shrouds

Price (12) carried out experiments in which he placed a perforated shroud around an oscillating cylinder and found that the oscillations were suppressed to some extent.

8.5 Boundary Layer Removal

A method of preventing boundary layer separation is to suck off, through slots, the stagnating fluid in the boundary layer before it has an opportunity to separate from the surface. Experiments with specially shaped aerofoils revealed that the power requirements were excessive and this would be even more so for cylinders. This together with the complexity of ducting required, would render the method impracticable.

8.6 Provision of Spoilers

Various types of spoiler may be attached to structures subject to wind induced oscillation to disrupt the regular vortex formation and thus reduce the magnitude of periodic forces.

The most promising type suggested to date has been tested by Weaver (18) and Scruton (et alia) (15, 19, 1, 16). They wound spoilers in a helical pattern around cylinders and measured the effectiveness of various configurations in reducing wind induced forces and oscillations. Scruton used rectangular section "strakes" while Weaver used cylindrical windings. Both types worked effectively.

The optimum height of spoiler, pitch of winding and number of starts were determined by both investigators and the results agree reasonably well. Suppression of forces was found to be greatest for the following winding characteristics:-

Height of spoiler	-	6 to 10 pc. of the cylinder diameter
Number of starts	-	4
Pitch of winding	-	approximately 12 cylinder diameters.

Weaver quotes a reduction of the lift coefficient of approximately 75 pc. for a single start helix compared with an 85 pc. reduction for a four start helix under the same flow conditions. A single start helix might thus be sufficient in the case of the Pyrmont stacks and would be less costly to construct and possibly more acceptable aesthetically, particularly if it could be incorporated into a spiral set of steps to replace the existing cat-ladders.

An important point to note is that these spoilers have not been subjected to model tests at Reynolds numbers as high as those at which the Pyrmont stacks oscillate and that their efficacy at these high Reynolds numbers has not been proved. In fact, Weaver (18) states specifically that he would not recommend the spoilers for Reynolds numbers above 4×10^5 as his optimisation was carried out only for Reynolds numbers up to this value. He also states that for these high Reynolds numbers the forces are erratic for plain cylinders and that some of his tests showed no alteration of the force fluctuations when spoilers were added.

However, the tests referred to by Weaver fall in the aperiodic range defined by Roshko between Reynolds numbers of approximately 2×10^5 and 5×10^6 and do not demonstrate that the spoilers would not suppress the periodic formation of vortices that Roshko found became re-established at a Reynolds number of approximately 5×10^6 at which the Pyrmont stacks oscillate.

Scruton and Walshe (15) and Woodgate and Maybrey (19) do not mention in their publications the range of Reynolds numbers over which their tests were carried out. It is probable that these tests were carried out below supercritical Reynolds numbers. Subsequent drag measurements by Cowdrey and Laws (1) on cylinders fitted with strakes were made at Reynolds numbers between 8.5×10^4 and 3.8×10^6. However, no observations of vortex shedding were reported.

Two further points of interest arise from Weaver's results. The first is that a large number of small diameter windings was found to increase the magnitudes of periodic forces. The second is that a helix wound around a cantilevered cylinder for only 20 p.c. of its length, reduced oscillations to approximately 10 p.c. of the base cylinder value. The optimum length over which the winding extended was quoted as approximately 40 p.c. This finding suggests that for the Pyrmont stacks a system of spoilers over part of the length might be the most economical solution.

9. Conclusions

1. Model tests showed that for subcritical Reynolds numbers the wake from the upstream cylinder of a line of cylinders parallel to the flow affects the separation of flow around the downstream cylinders, causing a greater swing of separation and stagnation points and thus greater fluctuating lateral forces.

This effect was found to be greatest for the cylinder second in line and to increase as the cylinder spacing was decreased. A limit would occur when the two cylinders began to act as one unit. No data were obtained for winds acting at an angle to the line of the stacks.

2. The best method of reducing the interference quoted in 8.1 would appear to lie in suppressing the regular shedding of vortices from the upstream cylinder.

3. The most practical known means of suppressing regular vortex shedding is to provide helical "spoilers" in the form of flat plates with an upstand of 6 to 10 p.c. of the stack diameter wound with a pitch of approximately 12 stack diameters around the stacks. It is possible that a single start spiral wound over only a portion of the length of each stack would suffice.

There is no proof that this system of spoilers would be satisfactory for supercritical Reynolds numbers, but in this range where regular vortex shedding is known to occur there is no apparent reason why the spoilers should not act as they do for subcritical Reynolds numbers.

No wind tunnel is available locally for testing at Reynolds numbers of 5×10^6 and higher. Unless tests can be arranged elsewhere, the following procedure would appear to be warranted:

(i) Construct only one spoiler over the distance between the top and middle catwalks of No. 4 stack. This spoiler should be positioned with its centre point at the south-western end of the line of centres of the stacks.

(ii) Await observation with south-westerly winds above 40 m.p.h.

(iii) Should oscillation still occur, add further spoilers until the optimum value of four is reached

(iv) Add spoilers to other stacks as necessary.

This procedure would be justified by Weaver's findings that a single spoiler is only about 10 to 15 p.c. less effective than four spoilers and that for a cantilevered cylinder windings over 40 p.c. of the cylinder length yielded optimum suppression of oscillations.

For Pyrmont, and for future stacks, an aesthetically acceptable solution might be to replace the existing vertical cat ladders by helical ladders incorporating a single spoiler.

(v) It should be noted that the elastic response of a cantilevered cylinder to forces generated by vortex shedding has not been considered in detail in this investigation. The effect of strakes has been shown to depend on the structural damping characteristics of the cylinder (15, 19) and a knowledge of these characteristics is required before the efficacy of strakes in damping oscillations can be guaranteed. If the structural damping is very low, the maximum amplitude of oscillation may not be reduced sufficiently.

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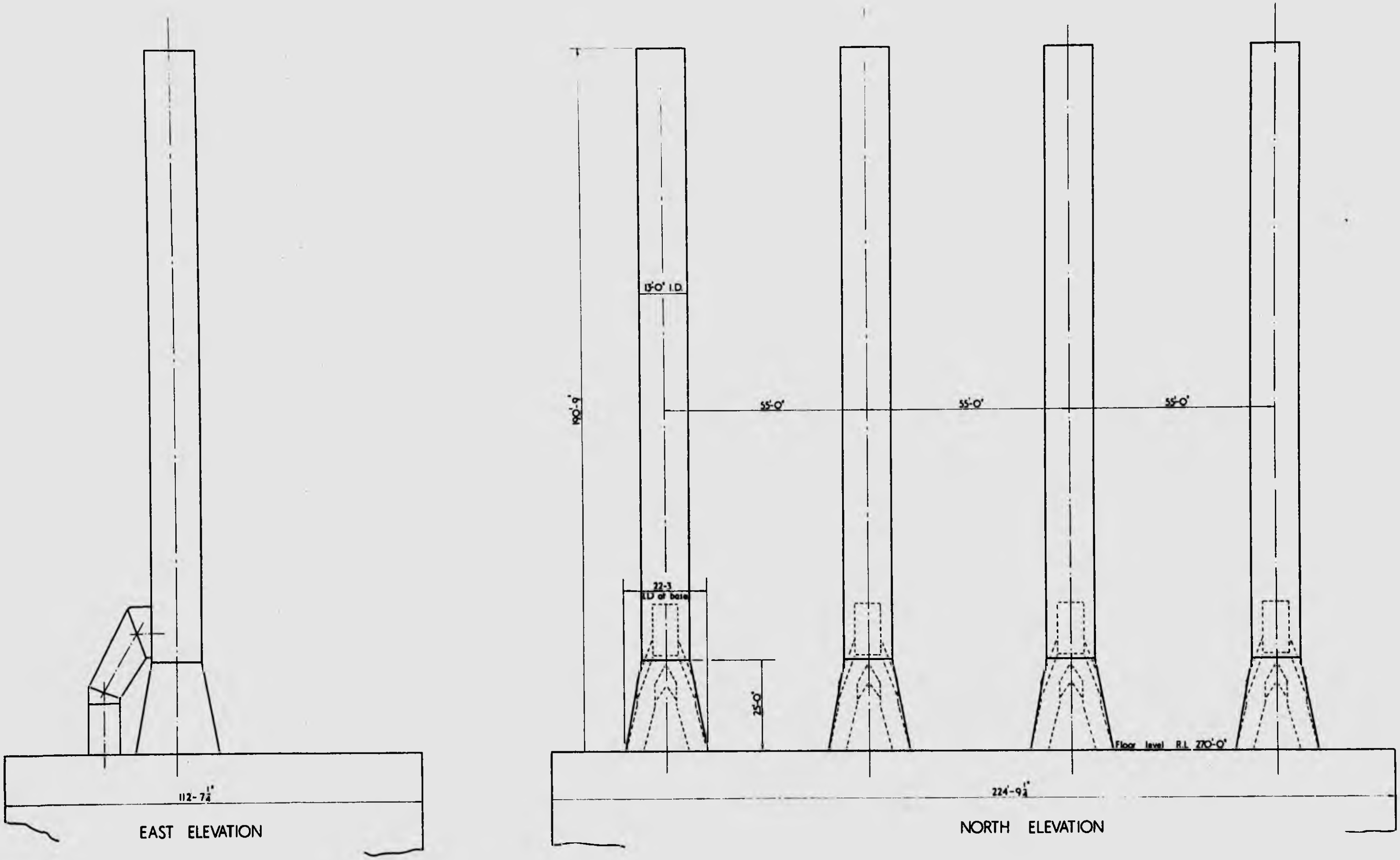


FIGURE No. 1.

THE UNIVERSITY OF NEW SOUTH WALES
WATER RESEARCH LABORATORY

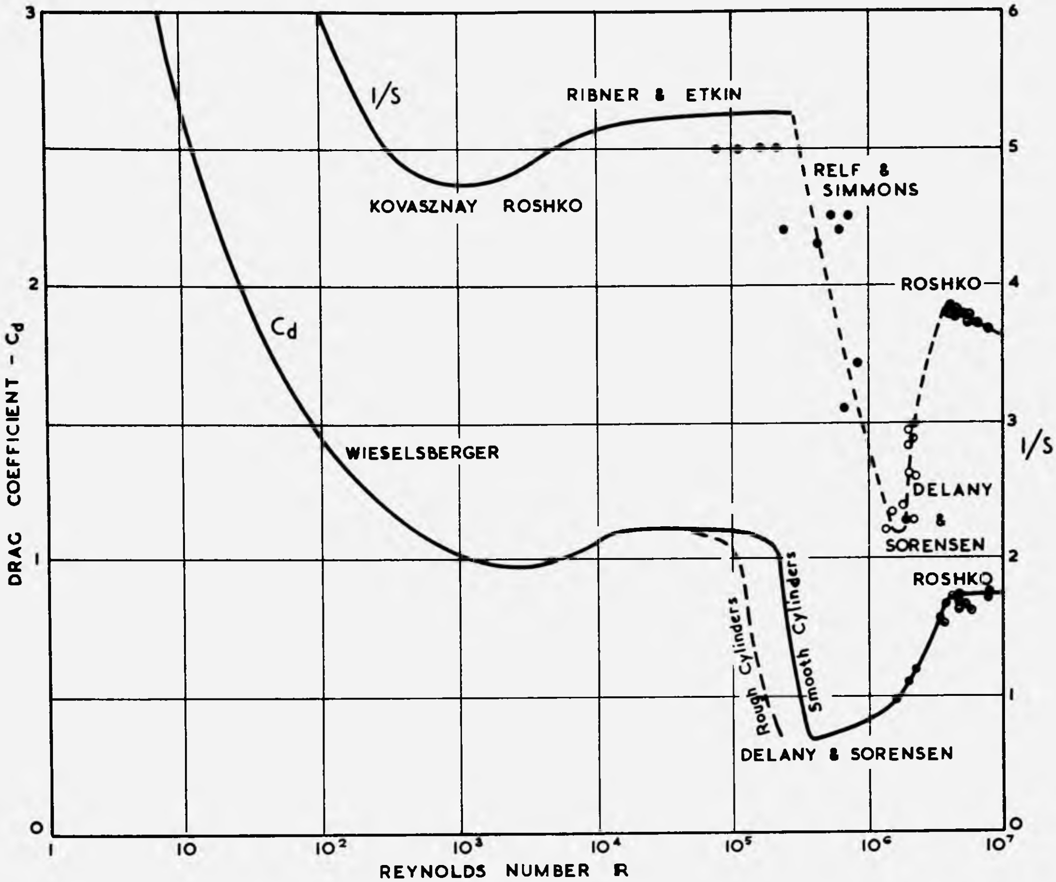
The Electricity Commission of N.S.W. Project 7.2

PYRMONT POWER STATION
LAYOUT OF STACKS

Scale: [illegible] = 1 foot
Drawn:
Traced: P.A.
Checked:

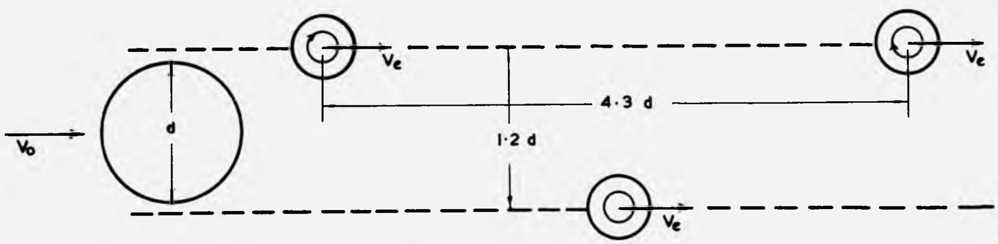
Date: 19.2.62

CE-C-2446



DRAG COEFFICIENT & RECIPROCAL OF STROUHAL NUMBER

Fig. 2a.



KĀRMĀN VORTEX TRAIL

Fig. 2b.

FIGURE No. 2.

THE UNIVERSITY OF NEW SOUTH WALES WATER RESEARCH LABORATORY		
The Electricity Commission of N.S.W. Project 7·2	Scale: —	Date: 16·3·62
Flow Around a Cylinder of Infinite Length Drag Coefficients and Vortex Spacing	Drawn: T. Durkin	
	Traced: P.A.	
	Checked:	

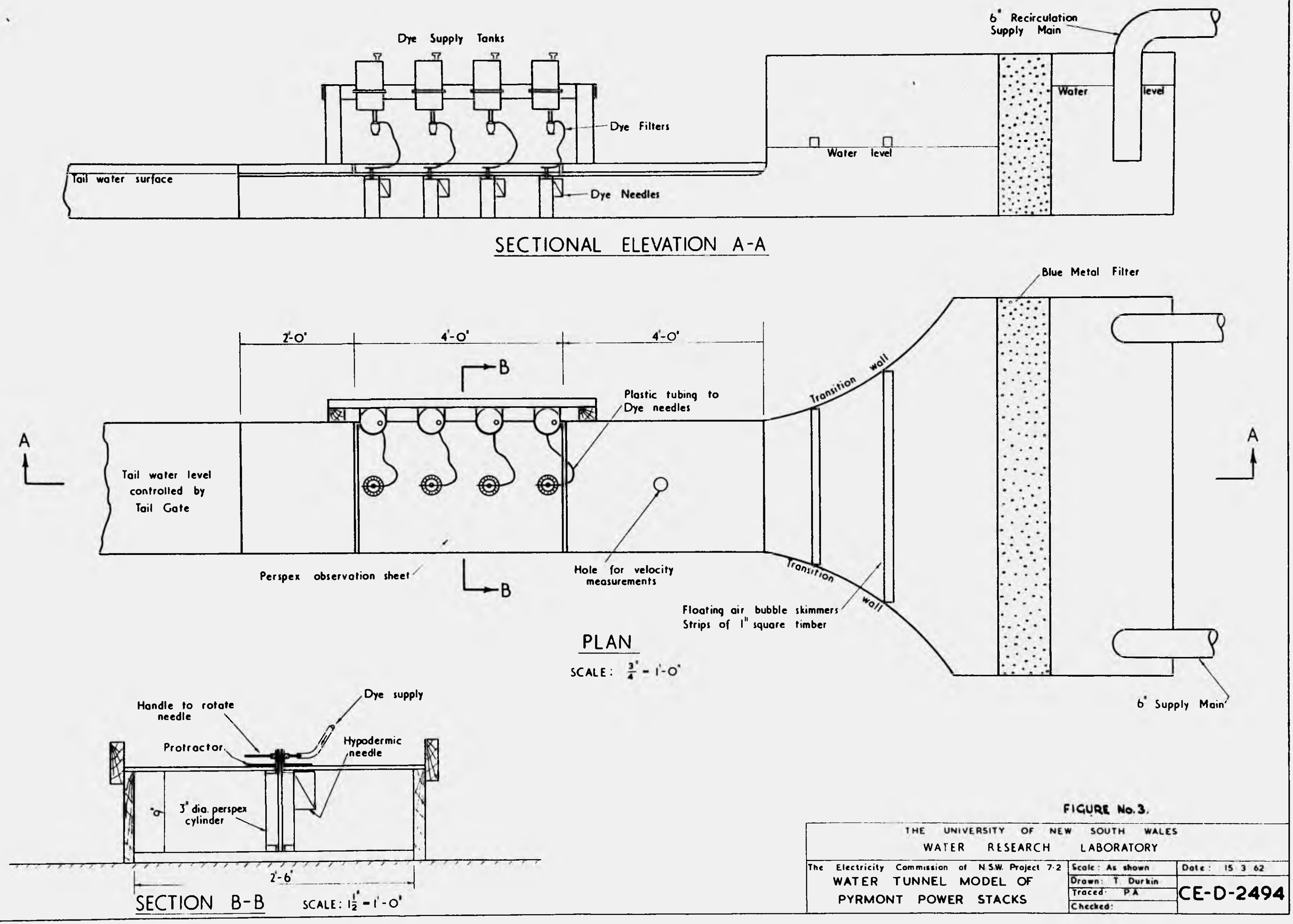
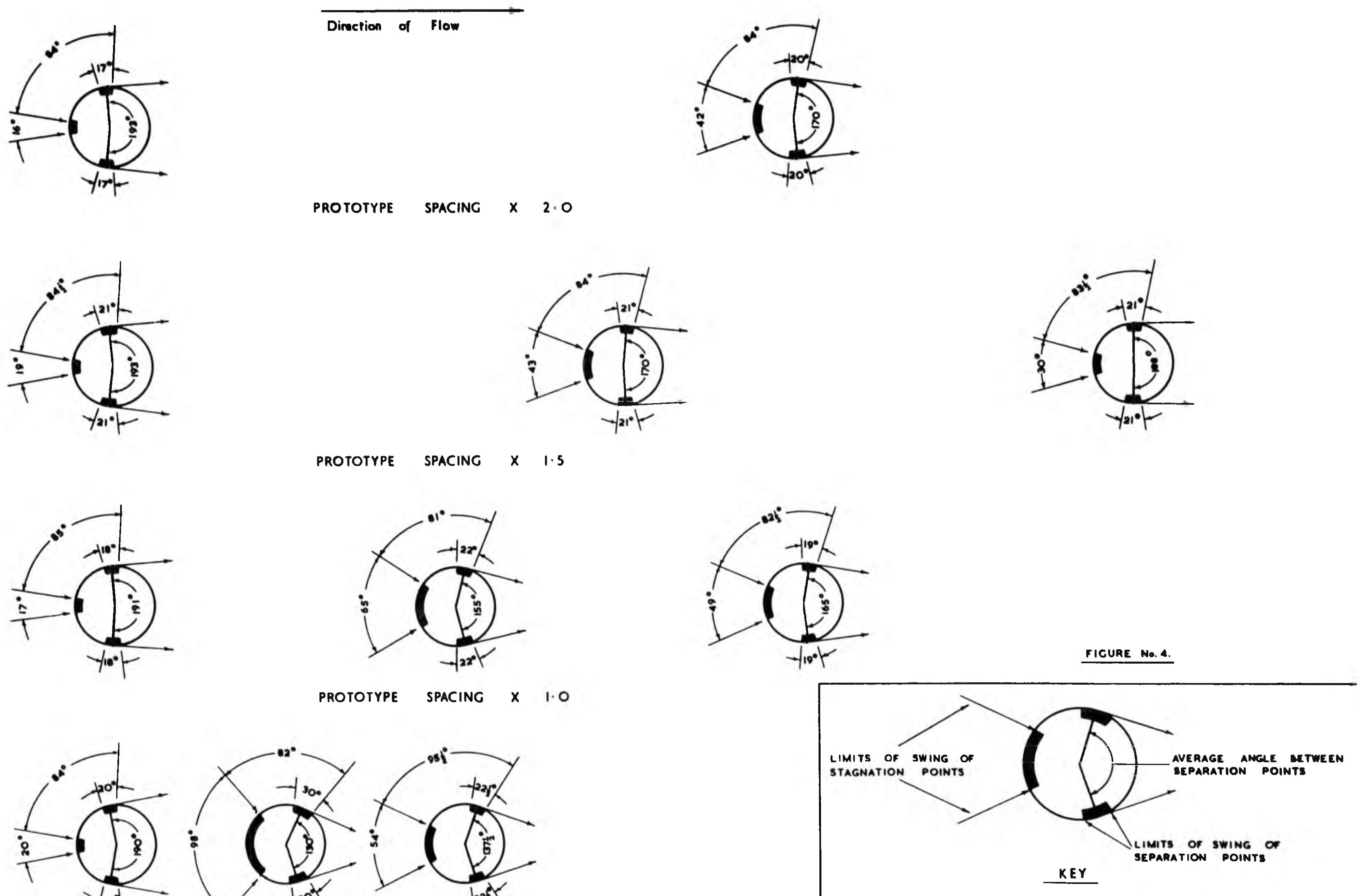


FIGURE No. 3.

THE UNIVERSITY OF NEW SOUTH WALES
WATER RESEARCH LABORATORY

The Electricity Commission of N.S.W. Project 7·2	Scale: As shown	Date: 15 3 62
WATER TUNNEL MODEL OF PYRMONT POWER STACKS	Drawn: T. Durkin	CE-D-2494
	Traced: P.A	
	Checked:	



THE UNIVERSITY OF NEW SOUTH WALES
WATER RESEARCH LABORATORY

The Electricity Commission of N.S.W Project 7·2
PYRMONT SMOKE STACKS
RELATION BETWEEN STACK SPACING AND POINTS OF STAGNATION AND SEPARATION

Scale:
Drawn: T. Durkin
Traced: P. A.
Checked:

Date: 24·1·62

CE-D-2445