THE NEW SOUTH WALES UNIVERSITY OF TECHNOLOGY

School of Civil Engineering

HYDRAULIC RESEARCH STATION

KING STREET,

MANLY VALE, N.S.W.

LAKE MACQUARIE POWER STATION
N.S.W.
HYDRAULIC INVESTIGATION OF CIRCULATING WATER INTAKES AND PUMP PITS

REPORT No.2

TO THE

ELECTRICITY COMMISSION OF N.S.W.

BY

R.T.HATTERSLEY

MAY 1958

TELEPHONE XJ 0261

The New South Wales University of Technology

SCHOOL OF CIVIL ENGINEERING

HYDRAULIC RESEARCH STATION
KING STREET,
MANLY VALE, N.S.W.

LAKE MACQUARIE POWER STATION, N.S.W.

HYDRAULIC INVESTIGATION OF CIRCULATING WATER PUMP INTAKES

REPORT NO. 2

TO THE

ELECTRICITY COMMISSION OF N.S.W.

By

R.T. HATTERSLEY A.S.T.C. A.M.I.E. (AUST.)
SUPERVISING LECTURER IN CIVIL ENGINEERING

MAY 1958.

https://doi.org/10.4225/53/578714209e14f

CONTENTS

PART 1.

PREFACE.

oooOooo

APPENDICES.

oooOooo

D R A W I N G S.

Item	Title	Electricity Commission No.
1.	Lake Macquarie Power Station Circulating Water System	K.61003L
2.	No.1 Turbo-Alternator Circulating Water Conduits Pumps & Wells	LM.97479B
3.	No.2 Turbo Alternator Circulating Water Conduits Pumps & Wells	LM.97980K
4.	Nos. 1 B and 2 A Turbo-Alternator Arrangement and Details of Director Plates	LM.101198C/1
5.	No.2B Turbo Alternator Arrangement & Details of Director Plates	LM.101901 C/1
6.	Channel Junction between Units 2 & 3. Baffle Plates	LM.102836C
7.	Pump Pits 3A & 3B	LM.102898 B/2
8.	Nos. 4, 5 & 6 Turbo Alternators Arrangement of Circulating Water Conduits and Pumps	LM.92278 B/4
9.	No. 4 Turbo-Alternator Baffles in C.W. Conduits	SK.1107
10.	No. 5 Turbo-Alternator. Bulkheads & Water Directing Vanes	LM.105131 B/

oooOooo

PART 1.

PREFACE.

1. INTRODUCTION.

The investigations covered by this report were carried out in the Hydraulic Laboratories of the School of Civil Engineering at the request of the Electricity Commission of New South Wales. Model tests were directed in the first instance to the improvement of the hydraulic entrance conditions to the condenser circulating water pumps of plant already in service and subsequently to the modification of the design of inlet channels of plant under construction at the Lake Macquarie Power Station, Wangi, Newcastle, New South Wales.

2. AUTHORITY AND ACKNOWLEDGMENTS.

Undertaken by kind permission of the Vice Chancellor of the N.S.W. University of Technology, Professor J.P. Baxter, O.B.E., B.Sc., Ph.D. A.M.I. Chem. E., F.R.A.C.I., M.I.E. Aust. the work has proceeded with the encouragement of Professor C.H. Munro B.E., F.R. San I., M.I.E. Aust., Professor of Civil Engineering and with the considerable assistance of the staff of the School of Civil Engineering.

Acknowledgment is also made of the assistance afforded by Mr. H.W. Duncan, Deputy Chief Engineer of the Power Station Construction Division of the Electricity Commission of N.S.W. and members of the staff of the Division, in particular Mr. R.W. Lofts who has arranged for the timely supply of much data used in the investigation, The help and assistance of Mr. A.B. Jones, Resident Engineer and Mr. J. Neilson, Power Station Superintendent Lake Macquarie Power Station, and their staff at site inspections and tests and Mr. A.B. Hoore of the Transmission Division for advice and arrangements for the printing of the typescript is appreciated.

3. DESCRIPTION OF PUMPING PLANT.

The first section of the Lake Macquarie Power Station will contain three turbine alternators of 50 M.W. rating and three turbine alternators of 60 M.W., the condensing plant of which is equipped with two axial flow pumps per turbine. The pumps for units 1 to 3 are each designed to handle 18,500 gallons of water per minute against a gross head of 20.5 feet. Those for units 4 to 6 inclusive are designed for a flow of 24,250 g.p.m. against a gross head of 22 feet.

The pumps for units 1 to 3 are arranged with vertical spindles in individual open pits approximately seven feet square in plan.

The open pits are built directly on the side of a distribution channel 5 feet in width and of water depth varying 5 feet to 9 feet from invert to the free surface of the water, according to tide movement and draw-down produced by flow to the pump suctions.

The pumps for units 4 to 6 were initially planned with suctions in the open distribution channel, the width of which varied from 12'9" near the pumps to 8' - 0" in between units.

The channels are fed by two lateral channels which enter the distribution channels at right angles.

Details of the general arrangement of the pumps and supply channels are shown on the Electricity Commission Drawings:-

K61003L	Circulating Water System Arrangement
LM97479B	Circulating Water Conduits No.1 Unit
LM97980K	Circulating Water Conduits No.2 Unit

Copies of the drawings are attached to this report.

PART 11

MODEL TESTS AND DESIGNS.

4. INTERIM REPORT NO.1

When the first turbine alternator was put into service in October 1956, the operation of the circulating water pumps was unsatisfactory. Air entrainment at the pump suctions was extensive and immediate remedial measures were essential to preserve the life of the condenser tubing and accordingly investigations were directed to the finding of a temporary solution to the problem of air entrainment which would not entail loss of the plant from service.

A system of baffles was devised as explained in detail in Interim Report No.1 forwarded to the Electricity Commission in May 1957. Interim Report No.1 should be read in conjunction with this report. In addition to the baffles recommended in Interim Report No.1 two slots were cut nine inches wide in the step before pumps 1A, 1B, 2A and 2B, to minimise unsteadiness produced by the flow over the sharp edge of the step.

5. REMEDIAL MEASURES NO.2 UNIT.

The second unit became available for service in May of 1957 and showed evidence of air entrainment and vibration of the pumps worse than No.1 unit.

It was realised that the conditions of entry to the pumps of No.2 unit would suffer by reason of a higher mean velocity in the distribution channels feeding the pumps. The mean velocity approaching pump No.2B was approximately 5.1 feet per second. Diversion of flow into No.2 Pump Pits under such conditions produced a turbulent broken surface in the pit with a high rate of swirl at the entrance to pump.

Calculations showed that if the type of baffle adopted for No.1 B pump was to be used for 2A and 2B, the by-passed flow to No.1 unit would pass over the horizontal baffle plate at near critical velocity with an average surface level in the distribution channels at RL.9650. The height of vertical baffle "F" (Refer Interim Report No.1) was reduced for No.2 to achieve a compromise between the possibilities of surface disturbances accompanying flow near critical depth over the baffle and poorer distribution of flow which would result at the pump bell if the flow under the baffle was unduly restricted.

The baffles modified in this way were fitted to both Pumps 2A and 2B - refer to drawings Nos. LM.101198C/1and LM.101901 C/1 for details.

The behaviour of the flow over the baffles was observed in the prototype with both Units 1 and 2 in operation and the surface levels in the supply channels varying from R.L. 99.5 upstream of No.2B Pump to R.L. 98.5 at No.1 A Pump.

Air entrainment for all pumps was reduced. Vibration was reduced to a satisfactory point for all pumps except No.1A which was found to have a broken impeller. Subsequent replacement of this impeller resulted in restoration of satisfactory conditions at Pump 1A.

Measurements of entrained air were taken by officers of the Commission and the results are included in Appendix 2 together with similar readings taken before the baffles were inserted.

The surface level in the distribution channels was artificially lowered to R.L.97.00 by restricting flow at the penstock in the main supply channel and further observations were made on the flow conditions over the baffles.

Air entrainment was noted to increase and surface conditions over the baffles were as predicted, indicating that operation with channel surface levels below R.L. 96.5 would not be feasible with the temporary baffles in position.

6. CHANNEL JUNCTION BETWEEN UNITS 2 AND 3.

The junction of the lateral channel supplying the distribution channel to Units 1, 2 and 3 is approximately 40 feet upstream from the entrance of No.2B Pit. During the test at low surface level, particular note was taken of the effect of the Tee-junction on the flow conditions approaching Pump 2B. With a velocity of approach in the vicinity of 5 feet per second, a standing wave formed on the opposite wall of the distribution channel and evidence of violent separation was apparent about the right angled corner of the entrance to the distribution channel. The combination of wave and separated flow produced intense air entrainment accompanied by swirling flow co-axial with the channel.

The co-axial swirl prevented much of the air entrained at the channel junction from rising to the surface and it was consequently swept into the intake of Pump 2B.

To effect a temporary contol of flow at the junction, a horizontal baffle plate was recommended and is as shown on E.C. Drawing No. LM.102836C.

Further recommendations concerning channel junctions are contained later in this report, vide page 10.

7. PUMP PITS NO.3 UNIT.

Construction of the channels and pits for No.3 unit were completed in advance of the remainder of the plant, the initial design of No.3 Pits conformed closely to that of No.1 and No.2 units with the exception of a slightly lower distribution channel inlet velocity.

An investigation was therefore made into the possibility of modifying the shape of the pits in so far as the superimposed structure permitted. This showed that a cutaway at 2'-9" radius was the maximum radius that could be permitted without expensive modification to the supporting structure. Drg. LM.102898 B/2

Following studies made of the distribution and lateral channels to units 1 and 2, it was also noted that it would be highly desirable to take water for No.3 unit from the lateral channel feeding Units 4, 5 and 6 in preference to that feeding units 1 and 2 so that levels in the channel feeding these units would not be depressed below R.L. 96.50 at No.2 unit. For the same reason, flow could not be taken past No.3 pit to supply unit 4 etc. unless at least two units of the group 1 to 3 were out of service.

It was therefore assumed that No.3 unit could be fed from either side but that flow past either pit 3A or 3B would be unlikely to exceed the flow of one pump for No.4 unit viz. 65 c.f.s. The need to cope with flows from either left or right necessitated a symmetrical design for the pit entrance.

Under these conditions the approach velocities to the pits would be moderate and rounding of the corners of the pits by cutting away the existing concrete to a radius of 2' - 9" offered a means of reducing separation of flow at the pit entrance to a tenable extent.

The model pump pits were then constructed upon these assumptions and to eliminate unsteadiness noted in tests of units 1 and 2 over the step into the pump pit the floor of the pump pit was filled to R.L. 91.00 leaving the clearance from pump bell to floor at 0.5 X the bell diameter following recommendations by Iversen Ref. 3.

A series of tests was then devised to control swirl at the pump entry. A central pier was designed which provided the best solution but resulted in the production of eddies of low strength on the downstream face. These produced air entraining vortices at levels below R.L. 96.00 The vortices were localised in the wake of the pier and were entirely controlled by inserting horizontal beams at R.L. 94.00. A further pair of beams was inserted at R.L. 96.00 to improve conditions for inlet channel water surface levels above R.L. 97.00.

7. PUMP PITS NO. 3 UNIT (cont'd).

Further tests after inclusion of the beams showed that the inflow to the pump model remained clear of air entrainment to R.L. 94.5. At this point a weak vortex formed at the rear of the pit. R.L. 94.5 also corresponds to the level of the impeller and the redesigned pit therefore inhibited air entrainment down to a surface level at which the impeller could not be expected to be self priming or free of cavitation.

Notwithstanding the satisfactory performance of the model pit, tests were made to control the weak vortex formation by artificially roughening the pit wall and the tests showed that roughness protuberances of moderate size were sufficient to control the phenomenon in the model. It was decided to roughen the rear wall of the pit as an extra precaution, between R.L. 93.5 and 96.5 by means of conical projections 1¼" in height x 1½" base width spaced at 3" centres (Refer Dwg. LM.102898 B/2 and Photo, Appendix (iii).

Comparative results of the air entrainment tests on the modified pits are shown in Appendix (ii).

Velocity measurements were made by current meter in the completed pits and the results for No.3A pit with channel surface levels at R.L. 97.5 and for No. 3B pit with channel surface levels at R.L. 100.00 are shown in Appendix(iv). No. 3B pit is adjacent to a bulkhead and therefore receives water from the supply channel without interference from flow proceeding further downstream.

The results for No. 3A pit show the effect of flow to No.3B pit in distorting the inlet flow pattern to Pump 3A. The prototype velocity patterns which are reproduced in Appendix (iv) were found to be in agreement with the model patterns.

The velocities and directions of flow recorded in the prototype flow exemplify the difficulties associated with diversion of channel flows into pump pits constructed on the side of the distributing channels.

The results for No.3A pit were obtained at distribution channel surface levels of R.L. 97.5, the level being artificially reduced by means of the inlet penstock at the screening chamber.

No evidence of air entraining vortices at the rear of the pump casing appeared for either pump 3A or 3B as the surface levels were lowered to R.L. 97.5. (Minimum permitted level during test).

8. UNITS 4, 5 and 6 - DESCRIPTION OF INSTALLATION.

Units 4, 5 and 6 were in various stages of construction at the time No.1 unit was placed in service and the intake channel designs were modified by the Electricity Commission.

Instead of an arrangement of pits placed at the side of the channels, the pumps were placed directly in the channels which were enlarged in the vicinity of the pumps evidently with the object of reducing the velocity of the water passing the pump barrels. The lateral channel from the screen chamber entered the supply channel adjacent to No. 5 unit but the walls of the lateral channel were turned in a radius of 13' - 0" on one side and 9' - 9" on the other side to meet the walls of the supply channels at the tee-junction. The curvature of the walls provided an improvement as compared with conditions at the tee-junction feeding units 1, 2 and 3. However, the benefit of the smoother curves in the junction was found to be more than offset by excessive channel velocities and the close proximity of the No. 5A pump to the tee-junction.

The general arrangement of this section of the plant is shown on E.C. Drawing No. LM. 96558 K/2.

The work of construction of the channels for units 4 and 5 was well advanced at the time investigations were concluded on No. 3 unit. Furthermore, the Commission's officers were anxious that hydraulic model investigation of the proposed pits for Tallawarra Power Station should be expedited to enable the initial designs to be formulated in advance of construction work.

8. UNITS 4, 5 and 6 - DESCRIPTION OF INSTALLATION (cont'd.)

A critical examination of the conditions of flow likely in the channels for units 4, 5 and 6 at Lake Macquarie Power Station led to the conclusion that although the design of the channels had been altered and the obvious defects of the Nos. 1 and 2 unit pits had been avoided, there still remained the possibility that the channels were prone to the vortex formation of the quiescent type. The quiescent type of vortex core occurs in near stagnant surface conditions in open channels or dead ends where surface circulation of low strength is set up in the vicinity of re-entrant corners or obstructions in the channel.

Such regions of surface circulation in association with the descending and convergent currents towards a pump entrance are the pre-requisites of deeply penetrating air entraining vortex cores.

It was therefore decided that work would be advanced as far as practicable on the construction of the model for Tallawarra Power Station and at the same time by a change of scale from $\frac{1}{8.73}$ to $\frac{1}{18.86}$ model casings already constructed for Nos. 1 and 2 units at Lake Macquarie and for Tallawarra Power Station could be used for investigations on Lake Macquarie Units 4, 5 and 6. Such time as became available pending the supply of vital information concerning the Tallawarra pumps and screens would be used to examine in the smaller scale model behaviour of the channels for units 4, 5 and 6 at Lake Macquarie.

9. NO. 4 PUMP PIT - DESIGN.

The pumps for unit No. 4 were arranged in a supply channel 12' 9" wide. Supply to these pumps would come from either end i.e. from the direction of unit 4 with the penstock gate between these two units open or from the channel junction near No. 5 unit (Refer Dwg. LM.92278 B/4 . Furthermore, it would be most likely that to control the flow to No.3 unit the penstock gate would be either wholly or partly closed. Under this latter condition the end of the channel near Pump 4A would become stagnant.

Model trials were accordingly arranged to test for the presence of air entraining vortices under these conditions and it was found that air entraining vortices occurred at Pump 4A for water surface levels below R.L. 97.00 at equal Froude Numbers with prototype and at higher levels with slight increase in flow above Froude parity.

Pre-entry swirl as measured by a vortometer was also present of varying magnitude and unsteadiness.

Similar conditions applied to No. 4 B with No. 4A out of action. It was therefore clear that modification of the channels would be necessary if air entrainment were to be avoided. As the flow through the No.4 unit pit could be either left to right or right to left according to circumstances, modifications to the pits should preferably be symmetrical.

To inhibit the pre-entry swirl at the pump inlets, which were originally placed off-centre in the channels, the model channel walls were curved towards the pumps and designed to achieve a mean velocity near the pump barrels over the range of normal operation not less than 1 foot per second nor more than 4 feet per second.

To cater for the shut-down of the penstock between units 3 and 4 or an adjacent pump which would result in a stagnant dead end, horizontal baffles were devised to prevent the entrance of air entraining vortices to the pump bells. Refer Dwg. SK.1107.

It was further proposed that the training walls should be constructed in cement rendered brickwork for ease of construction and the baffles in reinforced concrete. This form of construction could be readily arranged within the confined space of the pits as built. Model tests of the modified training walls showed that air entrainment could be obviated with channel levels as low as R.L. 89.5 provided sufficient flow occurred past the pump casing to break up the "Karman" vortex trail in the wake of the casing and to wash vorticity infected surface water away from the pump environs.

9. NO. 4 PUMP PIT - DESIGN (cont'd.)

Prototype velocities of the order of 1 foot per second or greater are calculated to be sufficient to achieve this purpose provided the depth of submergence of the pump bell was sufficient to ensure priming. The upper limit of velocity of approach would be dependent on the surface wave pattern produced about the pump casing.

In view of the smallness of scale for these tests (18.9 to 1), the results are to be regarded conservatively and accordingly tests were conducted over a wider range of flows up to 2½ times the prototype Froude Number at which flows surface conditions and air entrainment were adequately controlled in the model. To control air entrainment for the case of one pump only running when a near stagnant surface would exist at the downstream region, horizontal baffles as shown on Dwg.No. SK.1107 were prescribed to be inserted at R.L. 92.00.

The baffles which are constructed in reinforced concrete and permit the free withdrawal of the pump, are intended to ensure air free suction conditions at the pumps with channel surface levels as low as R.L. 93.00 (Design Level 96.00).

10. NO. 5 PUMP PIT - DESIGN.

The pumps for unit No.5 are arranged in an open pit which near pump 5A forms the junction with a lateral channel the second of two channels connecting the screen chambers to the distributing channels.

The walls of the channels at the junction which are vertical are constructed at approximately 9'.9" radius adjacent to pump 5A and 13 foot radius adjacent to the inlet to No. 4 unit pump.

A model was constructed of portion of the lateral channel and the distributing channel for units 5 and 6 and an off-take was provided in the end adjacent to No. 4 unit to enable flows to No. 4 unit to be simulated. See photograph Appendix (V) for model arrangement.

At the outset it was realised that separating flow occurring against the channel walls at the junction would affect the intake of pump No. 5A.

Tests were conducted in the model covering the range of flows for all combinations of flow to or past unit No. 5 with units 4 and 6 in and out of service. The extent of separated flow was traced by dye injection in the flow from the vicinity of the tangent point of the channel wall of the lateral channel extending across the channel junction in the direction of pump No. 5A with strongly established reversed flow extending from the tangent point of the distribution channel upstream towards the point of separation. A wake also formed downstream of pump No. 5A. The cast-off eddies proceed downstream along the far wall to the vicinity of pump No. 5B where air entraining vortices formed at channel surface equivalent levels below R.L. 95.00 for flow at the corresponding Froude Number with No.6 unit flow equal to zero. Flow proceeding from the central portion of the lateral channel was also noted to create a rolling formation on the opposite wall of the distributing channel which added further vorticity in the water proceeding to the pump intakes. Evidence of the effect of the separating flow at the channel junction was shown by unsteady behaviour of the vortometer placed in the model pump throat.

It was noted that when flows to unit No.6 were introduced, air entrainment ceased at the No.5B pump suction at surface level R.L. 95.0 but the increased rate of flow intensified the unsteadiness of the swirl at the pump suction.

Tests were then carried out to split the flow at the channel junction in order to control the separation and enshrouding walls were also devised for pumps 5A and 5B to control the wake behind each, to suppress the formation of vortices, and to minimise the swirl at the pump intakes.

10. NO. 5 PUMP PIT - DESIGN (cont'd.)

The optimum form of these features as found by the tests are as shown on the Electricity Commission's Drawing No. LM.105131B.

Air entrainment was found to be eliminated in the model to surprisingly low levels of R.L. 89.00 prototype equivalent surface level at Pump 5A and R.L. 91 for Pump 5B with no flow to unit 6A and 6B. The level of the suction bell lip was R.L. 88.33. These conditions were obtained at the corresponding Froude Number. Increasing the model flow to twofold resulted in accentuating wave action near the pump bells and air was entrained at levels below R.L. 91, pump 5A and R.L. 92.5 pump 5B.

Design level for the channel is given by the Electricity Commission as R.L. 96.00 and it is considered that the above results indicate that air entrainment should be eliminated in the prototype for all water surface levels above the design level.

Reviewing the results of the model tests for unit 5, the low levels at which air entrainment occurred are to be treated conservatively in view of the scale ratio used. However, air entrainment when it did occur was primarily caused by wave action about the pump bell and not by the agency of vortex formations which were absent.

Wave formation is represented in a model operated at the corresponding Froude Number with little distortion, and for this reason it is not expected that the pronounced discrepances due to scale effect noted by Iversen Ref. 3 would apply in this case.

11. FURTHER INVESTIGATION - LAKE MACQUARIE INSTALLATIONS, UNITS 1 and 2.

At the close of the series of tests conducted on the Pump Pits for No.5 unit, at the request of the Commission, consideration was given to the possibilities of modifying the sub-surface structure of the channels adjacent to No.1 and No.2 units with a view to providing a permanent re-design of the pump pits (the baffles of No.1 unit and No.2 unit were designed as temporary palliatives only). Furthermore, when the time arises for all four units 1, 2, 3 and 4 to draw water from the distribution channels, the channel surface levels at units 1 and 2 will be depressed below R.L. 96.5. Below this level the steel baffles will not be fully effective. Furthermore, investigation has shown that the baffles cannot be satisfactorily adapted to the conditions for channel surfaces below R.L. 96.5 due to the high approach velocities in the channels ruling when the surface levels are lowered.

Preliminary tests have also shown that pits similar in form to those for No.3 unit modified to suit the difference in channel invert level and the blind end near No.1A pit would be suitable for No.1 unit.

For No.2 unit, however, the limitations referred to earlier in this report with respect to No.3 pits and entrance cross flows, prohibit the use of this design for No.2 unit and it appears inevitable that extensive modification of the channel walls on the approach side to each pit will be necessary to obtain satisfactory results.

Tests in respect to units 1 and 2 were left in abeyance until such time as the prospect appeared of having these units out of service for a sufficient time to enable the alterations of the channel walls to be carried out.

12. FURTHER INVESTIGATION, UNIT NO. 6.

At the request of the Commission, tests on pump pits for Unit 6 were also left in abeyance to enable investigations to be implemented for the design of the pump pits at Tallawarra Power Station which work is now in progress.

It is anticipated that investigation of the Lake Macquarie items now in abeyance will be resumed at the conclusion of the Tallawarra tests.

PART 111.

COMMENT AND RECOMMENDATIONS.

13. TYPES OF PUMP PITS TESTED.

The range of tests conducted in respect of Units 1 to 5 have dealt generally with two types of pit, viz. those with side entry and those in which the pump is located within the channel itself.

Pits for No.3 unit may be regarded as typical of the side entry type while those of units 4 and 5 are examples of the 'in-channel' type.

14. PUBLISHED DATA.

Incidence of vortices in pump sumps has been studied in detail by various authors, notably Denny, Markland Pope, Brewer, Ref. 7, 8, 11, whose results have shown the effects of swirl as a predisposing condition of vortices in certain cases and also that concentric swirl about the pump suction eliminates vortices vide Ref. 7, P. 105.

These authors have not concerned themselves with the effect of vorticity at the suction bell as affecting the performance of the pump, a factor which is significant in the case of the axial flow pump with vertical axis, inasmuch as the usual installation entails placing the impeller as close as practicable to the entrance bell in order to obtain the necessary submergence of the impeller with minimum construction costs for the channels and pits.

15. CHARACTERISTICS OF FLOW IN APPROACH CHANNELS GENERALLY.

The tests conducted for Nos. 1, 2 and 3 units have amply demonstrated the importance of recognising the influence of the channel approaches as affecting swirl at entry to the impeller.

Studies of flow patterns on approach to pump bells in this series have also demonstrated the wide variation possible in a pit of given configuration between surface, intermediate and ground layers in the fluid.

Surface flows on approach to a pump casing are characterised by circulation and eddying ranging between tranquil and disturbed according to the disposition of the boundary surfaces with respect to the pump casing, the uniformity of flow at the bell mouth and the presence of downward flows near the centre of a zone of circulation.

16. VORTEX FORMATIONS.

It is of particular importance to note that the formation of smoothly walled vortex core is dependent on the continuance of tranquil conditions. Various authors have noted the periodic life of such phenomena and also the settling time necessary for establishing the essential quiescent condition for a vortex to form where the strength of the initial circulation is low.

A vortex formed in this way is easily broken but may appear in another position, if the means of breaking the vortex is static e.g. a vane or baffle. A quiescent vortex, however, once formed, may penetrate to a considerable depth below the surface and is therefore a vexatious cause of air entrainment.

Vortices show astonishing properties of propagation through a fluid under tranquil conditions and have been noted to propagate from dead-ends or backwaters for several feet below the surface but immediately disappear when a disturbance of small energy produces turbulence or cross flow.

16. VORTEX FORMATIONS (cont'd.)

In practice, channels on approach to pump positions rarely present hydraulically perfect surfaces and as a result small disturbances created by channel irregularities are sufficient to render such vortex formations unstable. Special efforts by constructors of pits to produce hydraulically smooth surfaces in the vicinity of the pump intake are wasted, especially if the pump is located in a closed sump or deadend.

It is important, however, to ensure that the wall profiles in approach channels and pits are correctly aligned to eliminate regions where extensive boundary layer separation will occur at normal rates of flow. Re-entrant corners and pockets should also be avoided.

The authors, ref. 7 & 8 have studied vortex formations in sumps of various types and have plotted results showing the incidence of air entraining vortices with various conditions of submergence, swirl and bell mouth designs but have laid no emphasis on the effect of vorticity at the pump inlet.

It is clear from the principle of conservation of momentum that vorticity introduced into the water by flow over badly formed approach channel surfaces will persist at the pump intake if the length of the approach path is short.

For axial flow pumps in particular, vorticity will have effect on the performance of the pump and the predisposition to cavitation.

The effect of vorticity at the pump intake was found to be a factor in the rough running and vibration of pumps 1A, 1B, 2A and 2B. Furthermore, it will be seen that correction of the channel intakes to minimise the vorticity and unsteadiness in evidence at the pump intake will automatically weaken vortex formations which may remain in the surface layers. These surface vortex formations of low energy content can be easily controlled by one or more of the following means:-

(a) By artificially inducing turbulence of a homogeneous nature e.g. weak vortices residual at the rear of No.3 unit pits were completely controlled by artificially roughening the walls at the rear of the pit below R.L. 96.5 with truncated conical projections 1¼" in height spaced 3" apart. See photograph Appendix (iii).
This method is suitable where the solid boundary surfaces confine the flow closely and the velocity of flow is sufficient to propagate the turbulence.

(b) By preventing downward flows towards the bellmouth in regions where surface circulation is obvious or imminent by the use of submerged horizontal fins, e.g. entrance No. 3 pits.

(c) By artificially producing upward currents of relatively small intensity where vortex formation is imminent by the use of baffles.
This method was adopted in the case of temporary baffles for units 1 and 2.

(d) By ensuring sufficient cross flow to wash vortices formed in surface wakes downstream before a vortex core can generate. A theoretical treatment to determine velocities for the control of vortices in a Karman Wake is given in Appendix (ix). Experimentally the velocities found satisfactory to effect this form of control were found to be very small, of the order of 0.5 foot per second in prototype.

The measurement of the residual vorticity at the pump intake in this investigation was effected by observing the revolutions of a four vane pivoted wheel mounted with axis vertical in the throat of the model pump casing at the approximate position of the impeller, hitherto called a vortometer.

16. VORTEX FORMATIONS (cont'd.)

Experimental evidence supported the theory that elimination of vorticity at the pump inlet would also produce controllable surface conditions and this was verified throughout these investigations.

17. APPROACH CHANNEL DESIGNS.

The study of the channel forms to combat the production of extraneous vorticity has revealed the importance of properly proportioning the water way areas to ensure that the velocities occurring under normal conditions are between the restricted limits which have been found essential.

These limits may be described in the following ways:-

(a) Velocities in the approach channel to a pump should not be less than 0.5 feet per second.

(b) Mean velocities should not exceed about 3 to 4 feet per second in any part of a straight approach channel in order to ensure that surface waves will not be a cause of surface air entrainment.

(c) Velocities in curved channel approaches should be low enough to reduce separation of the boundary layer against the channel walls to a tolerable extent. The region over which separation may extend will be determined by the actual design of a sump and the proximity of the separated flow or eddies to the pump intake.
A theoretical discussion of the phenomenon of separation and associated theory applied to this instance is given in Appendix (viii).

Uniform channel flow is essential for ideal approach to a pump. Serious disturbance of uniform channel flow occurs at channel junctions or sharp changes in alignment. Excessive velocities at these points will cause air entrainment by wave action. Channel velocities should preferably be reduced at junctions and bends to not more than 2 feet per second depending on the radius of wall curvature. If necessary, training walls should be inserted, see Dwg. No. LM.105131 B

Channel junctions should be remote from the pump pit or intake leaving sufficient length for flow conditions to stabilise.

18. PUMP ARRANGEMENT.

The type of pump pit which is discussed under this heading is dependent on the assumption that the pump is of axial flow or mixed flow design with vertical shaft and is self priming under all conditions of operation.

This type of pump is common in modern power stations because the large discharge possible with relatively small moving parts and casings enables high capacity plant to be built into small space within the power plant foundations. For this type of installation, the driving shaft is conveniently vertical and the motor is placed at floor level at the top of the pump column.

The simplest form of inlet to a pump of this kind is a bellmouth placed immediately below the impeller.

19. SUBMERGED TUNNELS VERSUS FREE SURFACES.

Various alternatives to the above arrangement such as scoop intakes or submerged tunnels and chambers have been suggested. The former produces a poor distribution of flow at the impeller and the latter if arranged at the end of a submerged duct tends to accumulate air released in the approach flow which is

19. SUBMERGED TUNNELS VERSUS FREE SURFACES,(cont'd.)

entrapped against the tunnel roof and eventually is drawn into the pump intake. Air is entrained by wave action at intakes or by circulating water screens preceding the pumps. The air is retained in the form of fine bubble suspensions. The rate of rise of these bubbles may be as low as 7 cm per sec. for bubbles 0.4 mm diameter (see table in appendix vii). The small bubbles do not readily break the surface "skin" of the water and are carried beneath the surface "skin" until they coalesce forming bubbles of sufficient size to break through to the atmosphere. It is therefore desirable that the approach channels and pits have free surfaces to enable as much air as possible to be released before the pump suctions are reached.

This series of tests has shown that provided the pits are properly designed, free surfaces can be retained in the approach channels and pump pits without incurring air entrainment at the pump suctions.

20. BELLMOUTHS - PUMP INTAKES.

Denny in a paper (Ref. 8) refers to the use of bellmouths and conical inlets and their relation to air entrainment with the conclusion that within the limits of the common proportions for pump suction bells the shape of the bell has little effect on the incidence of air entraining vortices. The observation is also made that air entrainment is least likely when the sump is as small as possible and in a communication on the above paper Rigby refers to a satisfactory sump with direct approach and in which the back of the sump "had been wrapped around the bellmouth."

The basis of design of axial flow pumps is established upon axi-symmetric conditions of flow and upstream diffuser blades if present are usually arranged on the assumption of zero whirl at the bell entrance.

The geometry of sump and approach channels is then nearly ideal when

(a) flow occurs with zero swirl. For axial flow pumps handling water, the simple approach with a horizontal axis is not feasible having regard to the practical problems of channel construction,motor and drive arrangement. Even so, it would not be free of the danger from vortex penetration from the free surface unless submergence of the upper edge of the bell was considerable.

(b) flow occurs over the lip of the bellmouth with uniform distribution around the circumference.

For pumps having vertical axes, the geometry of the pit is then such that the flow is guided to the bell entrance in such a way that the two conditions are satisfied.

Condition (a) will be satisfied if the approach to the pump is from a straight sided channel and the pump axis is placed at the centre line of the channel. The effect of velocity distribution in channel boundary layers will then be symmetrical about the pump bell.

Condition (b) will be met if the flow passing the sector of the bell closest to the approach channel is taken from the ground layers and the flow passing the rear sectors is taken from the intermediate and upper layers and passed around the pump casing and downwards under controlled limits of velocity.

The disposition of the walls with respect to the bell and casing will then be determined by proportioning passage areas to pass the several portions of the flow at the optimum velocities. These proportions can be readily determined b...

Note: Test carried out since the printing of this report in respect of No.6 Unit showed that an elliptical wall gave better results for a straight channel approach.

... layer adjacent to the pump casing. Refer to Item No.7, E.C. Dwg. No. LM.102898 B/2 and Appendix (x) entrapped against the tunnel roof and eventually is drawn into the pump intake. Air is entrained by wave action at intakes or by circulating water screens preceding the pumps. The air is retained in the form of fine bubble suspensions. The rate of rise of these bubbles may be as low as 7 cm per sec. for bubbles 0.4 mm diameter (see table in appendix vii). The small bubbles do not readily break the surface "skin" of the water and are carried beneath the surface "skin" until they coalesce forming bubbles of sufficient size to break through to the atmosphere. It is therefore desirable that the approach channels and pits have free surfaces to enable as much air as possible to be released before the pump suctions are reached.

This series of tests has shown that provided the pits are properly designed, free surfaces can be retained in the approach channels and pump pits without incurring air entrainment at the pump suctions.

20. BELLMOUTHS - PUMP INTAKES.

Denny in a paper (Ref. 8) refers to the use of bellmouths and conical inlets and their relation to air entrainment with the conclusion that within the limits of the common proportions for pump suction bells the shape of the bell has little effect on the incidence of air entraining vortices. The observation is also made that air entrainment is least likely when the sump is as small as possible and in a communication on the above paper Rigby refers to a satisfactory sump with direct approach and in which the back of the sump "had been wrapped around the bellmouth."

The basis of design of axial flow pumps is established upon axisymmetric conditions of flow and upstream diffuser blades if present are usually arranged on the assumption of zero whirl at the bell entrance.

The geometry of sump and approach channels is then nearly ideal when

(a) flow occurs with zero swirl. For axial flow pumps handling water, the simple approach with a horizontal axis is not feasible having regard to the practical problems of channel construction, motor and drive arrangement. Even so, it would not be free of the danger from vortex penetration from the free surface unless submergence of the upper edge of the bell was considerable.

(b) flow occurs over the lip of the bellmouth with uniform distribution around the circumference.

For pumps having vertical axes, the geometry of the pit is then such that the flow is guided to the bell entrance in such a way that the two conditions are satisfied.

Condition (a) will be satisfied if the approach to the pump is from a straight sided channel and the pump axis is placed at the centre line of the channel. The effect of velocity distribution in channel boundary layers will then be symmetrical about the pump bell.

Condition (b) will be met if the flow passing the sector of the bell closest to the approach channel is taken from the ground layers and the flow passing the rear sectors is taken from the intermediate and upper layers and passed around the pump casing and downwards under controlled limits of velocity.

The disposition of the walls with respect to the bell and casing will then be determined by proportioning passage areas to pass the several portions of the flow at the optimum velocities. These proportions can be readily determined by observing the behaviour of flow in a model but it is not possible to determine them accurately otherwise. The pit walls, thus determined, will then be found to be arranged in approximately parabolic form and the passage between the pump barrel and the pump wall will in fact be convergent, a form of passage which adequately controls separation at the boundary layer adjacent to the pump casing. Refer to Item No.7, E.C. Dwg. No. LM.102898 B/2 and Appendix (x)

20. BELLMOUTHS - PUMP INTAKES (cont'd.)

For pumps which are not placed on the centre line of the channel, the extent to which pre-entry swirl and vorticity can be eliminated at the intake will depend on the extent to which the guiding channel walls can be shaped to eliminate separation of the boundary layer against the walls. The phenomenon of separation is the principal agency by which vorticity is produced in the approach flow.

The curvature of the walls of the pump pits for units 3, 4 and 5, refer drawings LM.102898B/2, SK.1107, LM.105131B', have all been examined during model tests on this basis.

Horizontal subsurface control baffles may be necessary as shown on drawing LM.102898 B/2 where separation cannot be entirely controlled in the proximity of the pump entrance. The horizontal members prevent the upper layers of approach flow having any vertical velocity component in the region where separation is in evidence. Air entraining vortices are thus inhibited.

21. EFFECT OF PUMP DESIGN ON SUBMERGENCE REQUIREMENTS.

For a given discharge and head, there remains a considerable range of choice for a pump designer to determine impeller diameter, hub size and pitch of blading. As a result, manufacturers of pumps for power station condenser cooling water service, have in the past offered a variety of pump designs. Details of pumps which have been supplied for some N.S.W. Power Stations are shown in Appendix (xi).

The range of mean velocity of the water at the pump intakes is from 14.5 feet per sec. to 20.9 feet per sec.

In conducting this series of model tests, observations of pressure at the lip of the bellmouth showed that as the pressure at the bellmouth lip approached atmospheric pressure with increase in flow or reduction of submergence, air entrainment was imminent. The reduction in pressure is evidently a function of the velocity change occurring at the lip of the bell.

Time has not permitted detailed investigation of this aspect but it is noteworthy that the average entrance velocity for Lake Macquarie Units 1 and 2 is highest of any of the pumps tabled in Appendix (xi) and is only approached by the pumps at Pyrmont "B" Power Station. Both stations have suffered from air entrainment.

Until further investigation is made on this aspect and a definite conclusion drawn, it would seem prudent to specify that the average inlet velocity at the throat of the pump should not exceed 15 feet per second.

22. CONCLUSIONS.

This series of tests has demonstrated that the performance of axial flow pumps is vitally affected by the design of the approach channels and pump pits.

Depth of submergence is not a reliable criterion for satisfactory design of an axial flow pump pit for the prevention of air entrainment.

To the extent of the tests carried out in this investigation the design of pit evolved gave protection against air entrainment down to channel surface levels at which submergence of the axial flow pump impeller is governed by the need to control cavitation.

Model tests with scale factors of the order of 1 to 10 give satisfactory results when the tests are directed in the first instance to the study of flow patterns.

The design of pit resulting from model studies of flow patterns with the object of reducing vorticity of the pump intake, also mitigates air entraining tendencies to the stage where simple control measures are effective.

References.

1.	STEPANOFF A.J.	1948	Centrifugal and Axial Flow Pumps (Chapman & Hall).
2.	WORSTER R.C.	1948	British Hydro Mechanics Research Association Technical Note No.1 July 1948. "On the Rising Velocity of Air Bubbles in Water."
3.	IVERSEN H.W.	1953	Trans A.S.M.E. Vol. 75 No.4 p.635 "Studies of Submergence Requirements of High Specific Speed Pumps", also discussion p.639.
4.	FRASER W.H.	1953	Trans A.S.M.E. Vol.75 No.4 p.643 Hydraulic Problems Encountered in the Intake Structures of vertical-wet Pit Pumps and Methods leading to their solution.
5.	BRKICH A.	1953	"Power" February 1953 p.90 "Rid Vertical Pump Intake Design of Guess with Model Tests."
6.	DENNY D.F.	1956	"Fluid Handling" January 1956 p.2 "Air Entraining Vortices in Pump Sumps."
7.	MARKLAND E. and POPE J.A.	1956	Proc. Inst. Mech. Engineers Vol.170 No.2 p. 95 "Experiments on a Small Pump Suction Well with Particular Reference to Vortex Formations.
8.	DENNY D.F.	1956	Proc. Inst. Mech. Engineers Vol.170 No.2 p. 106 "An Experimental Study of Air Entraining Vortices in Pump Sumps", see also discussions.
9.	BONNINGTON S.T. and DENNY	1956	Research Report No.526 Feb.1956. British Hydromechanics Research Assoc. "Some Measurements of Swirl in Suction Pipes."
10.	PONOMAREFF A.I.		Report to Westinghouse Coy. on performance of Axial Flow Pumps.
11.	BREWER D.	1957	Vortices in Pump Sumps Commonwealth Engineer Sept. 2nd 1957 p.50.
12.	WISLICENUS G.F.	1956	Critical considerations on Cavitation Limits of Centrifugal and Axial Flow Pumps Trans. A.S.M.E. Nov.1956 p.1707.

oooOooo

APPENDIX II.

LAKE MACQUARIE POWER STATION UNITS 1, 2 and 3 AIR ENTRAINMENT TESTS.

Condition	Percentage Air Entrained							
	Pump 1A	Pump 1B	Pump 2A	Pump 2B	Pump 3A	Pump 3B	Pump 4A	Pump 4B
Before modification		0.06	0.15	0.43	-	-		
After modification with baffles Units 1 and 2 in operation Channel Level at No.1 Unit R.L.987	Nil	Nil	0.001	0.002	-	-		
Do. Channel Level R.L.97.5	-	-	-	0.004	-	-		
Do. Channel Level R.L.96.7	-	-	-	0.02	-	-		
After modification Units 1, 2 and 3 In service	-	-	.007	0.08	Not tested	Not tested		
After modification Units 1 and 3 and 4 In service	-	-	-				Nil	Nil

Unit No. 3 under construction

Appendices III, IV, V, VI, X are not in the original print copy.

APPROXIMATE RATES OF AIR BUBBLE RISE IN WATER.

Bubble Dimension cm.	Rate of Rise cm/sec.	Law of Rise.
0.02	2	Stokes
0.03	4	"
0.04	7	"
0.05	10	Stokes and Miyagis
0.075	13	Miyagis
0.1	15	
0.2	20	"
0.4	28	
0.6	24	"

Note: Bubbles in excess of 0.6cm. deform and rate of rise cannot be approximated readily by simple formulae

THE PHENOMENON OF SEPARATION AND ITS RELATION TO MODEL BEHAVIOUR

Separation of the boundary layer is a common agency by which vorticity is produced in approach channels feeding power station pumping plant layer at places in the approach channels close to the pump intakes.

The phenomenon of separation is discussed in most modern treatises on fluid dynamics and the mechanism by which it occurs is well known and established. A description of it is repeated here in preparation for further development of theoretical argument concerning the behaviour of flow in model approach channels.

A fluid possessed of viscosity flowing in a conduit will be observed to attain maximum velocity at a distance from the solid boundary. For well established two dimensional flow (e.g. in a long rectangular deep channel with a free surface) the surface flows will be observed to occur with a velocity distribution which is of complex form for all flows for which the Reynolds Number ($\mathbb{R} = \frac{v \times d}{\nu}$) is greater than approximately 3000.

For water flowing in cooling water conduits of the commonly encountered proportions in Power Stations, the boundary layer is turbulent.

Recent authors have attempted to evaluate velocity distribution in turbulent boundary layers and solutions have been evolved which are semi-empirical. Much of this work has been summarised in the following publications:-

(a) Clauser - Journal of Aero. Sciences February 1954 No. 2 p. 91

(b) Hama - Trans. Society of Naval Architects and Marine Engineers Vol. 121, 1956 p. 1219.

(c) Ross - Trans. A.S.C.E. Vol. 121, 1956, p. 1219

The velocity distribution may be described with respect to y = distance from the boundary in the manner shown in Fig. A below.

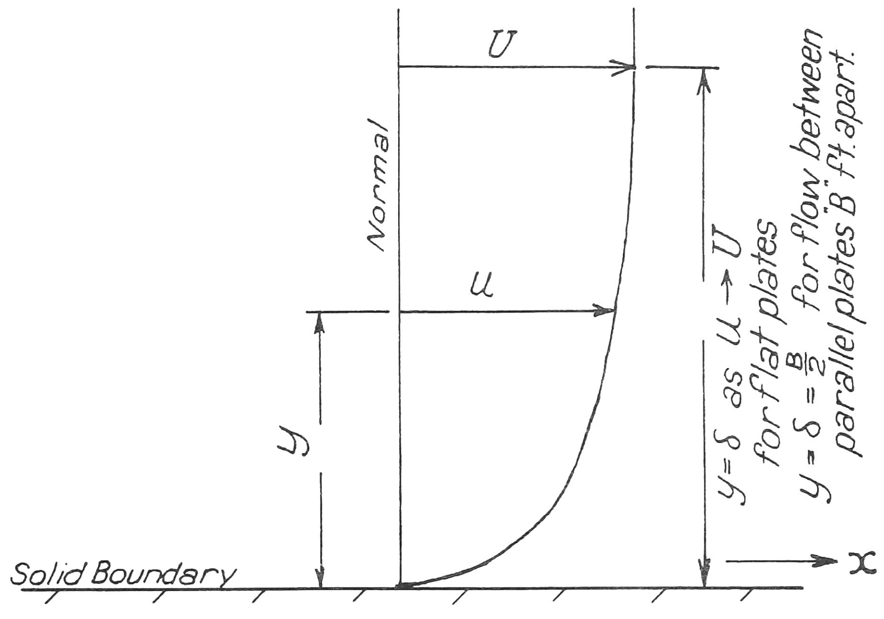

Fig. A.

When flow of the form in Fig. A approaches a channel transition, bend or other change in form which results in a change in pressure with variation in (x) any layer at a distance (y) will be accelerated or retarded according to the nature of the pressure change.

Where widening or opening of the channel occurs the pressure gradient will be adverse i.e. will act to produce a reduction of velocity. Thus, filaments near the wall will be retarded as will filaments in the main flow and for straight transitions the pressure difference will vary with "x" but remain substantially constant with "y".

Flows near the boundary will therefore tend to reverse in direction and the point of separation is said to occur when $\left(\frac{\partial u}{\partial y}\right)_{y_o} = o$

Continuance of flow beyond this point results in propagation of reverse flow and extension of the region of reverse flow until a vortex forms, i.e. circulation is complete. The vortex and portions of the separated fluid now possessed of vorticity are swept into the main body of flow. Refer Fig. B.

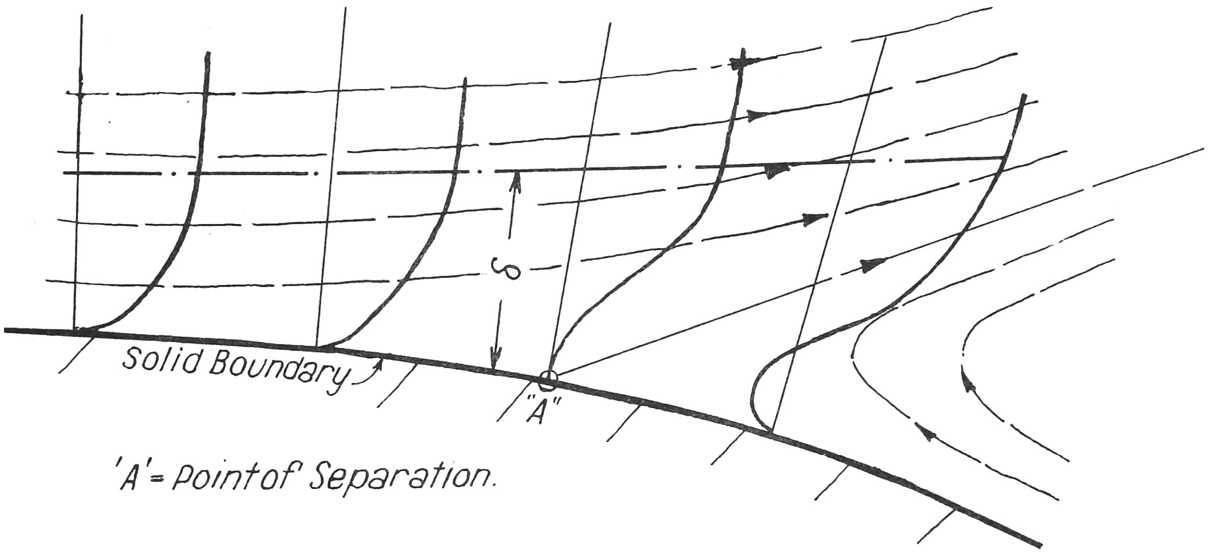

Fig. B.

It should be the aim of a designer of a pump intake to eliminate the occurrence of separation, if this is possible within the limits of space in the channel or pit. For pits or channels in confined spaces elimination may not be practicable and alternative counter measures may be taken.

Accurate calculation of the extent of boundary layer beyond the point of separation is not practicable on present knowledge. In addition, channels with free surfaces are subject to secondary flows where changes of direction occur. Also, the effect of boundary friction at the invert renders the pattern of flow assymmetrical and unsuitable for boundary layer calculations except where the channels are relatively deep in which case theoretical treatment may be applied to establish the approximate position of the point of separation.

The extent of separated flow can, however, be readily observed in an hydraulic model and it is pertinent to consider the conditions under which similarity is sufficiently established between model and prototype to enable satisfactory predictions of prototype behaviour to be made from a model.

For wave formation, the establishment of cross flows, shape of air entraining vortices etc. the principal forces affecting liquid motion or surface shape are inertial and gravitational. Where viscous effects become appreciable, e.g. flow near boundaries or for bubble size and movement, possible distortion of prototype behaviour as represented by a model should be considered.

Operating a model at a corresponding Froude Number is convenient because lower velocities are used in the model than those ruling in the prototype. For flow in a model to be similar to flow in a prototype where gravitational and viscous effects are both influential in the flow pattern, it is not possible to satisfy two criteria for similarity. If $\mathbb{F}_m = \mathbb{F}_p$ it is not possible for values of scale ratio $\mathcal{L} \neq 1$ to obtain the ratio of viscous force to inertial force constant.

A step towards similarity will be achieved however if the model size and flows are adjusted so that the mode of flow is turbulent in the model as in the prototype.

In addition, building a model with hydraulically smooth surfaces contributes towards a reduction of the distortion in the velocity distribution if flow occurs in the prototype under wholly rough conditions.

The model and prototype flows approach similarity if the ratio of the velocities in the model and prototype are in a near constant ratio for all corresponding points on a given normal to the channel boundary.

From the velocity distributions, the point of separation may be calculated by the method of Ross Ref. (c).

For a straight channel of sufficient length for the velocity distribution to become uniform and for entrance effects to be eliminated the velocity distribution along a normal to the boundary will become logarithmic close to the wall.

For channels in which the depth exceeds the width, surface flows will become similar in distribution to flows between parallel walls.

Observations show that vortices which form near pump pit entrances in channels originate in the separated flow where the channel walls turn into the pump pit and a comparison of prototype and model flows in the boundary layer is valuable as an aid to determine the position of the point of separation in both model and prototype.

Flow in boundary layers has been reviewed by Hama Ref. (b) in which he cites three equations which may be used to plot the velocity distribution.

The Law of the Wall (Clauser)

$$\frac{u}{v_*} = 5{\cdot}6 \log \frac{y v_*}{\nu} + 4{\cdot}9 \qquad \text{......(1)}$$

for values of y between δ' and 0.15 δ

The Law of the Outer Profile

$$\frac{U-u}{v_*} = 9{\cdot}6\left(1 - \frac{y}{\delta}\right)^2 \qquad \text{......(2)}$$

for values of y between 0.15δ and δ

The velocity "Defect" Law

$$\frac{U-u}{v_*} = -\left(5{\cdot}6 \log \frac{y v_*}{\delta_* U} + 0{\cdot}6\right) \qquad \text{......(3)}$$

The following notation is used in the above equations and subsequently in this text:-

$\mathbb{R}$ = Reynolds number = $\frac{Vd}{\nu}$

$\mathbb{F}$ = Froude number = $\frac{V}{\sqrt{lg}}$

U = free stream velocity i.e. velocity at δ

v_* = friction velocity = $\sqrt{\frac{\tau_o}{\rho}}$ = $\sqrt{\frac{f}{8}}\, V$

τ_o = fluid shear stress at solid boundary

ρ = density of fluid

f = Darcy Friction Factor

V = mean velocity of fluid flow = $\frac{Q}{A}$

Q = flow in channel in c.f.s.

A = water way area of channel in square feet

y = distance along a normal to the solid boundary

δ = boundary layer thickness, i.e. $y \to \delta$ as $u \to U$

ζ = scale ratio of model and prototype =

δ_* = displacement thickness = $\int_0^{y=\infty} (1 - \frac{u}{U}) dy$

=

Subscripts "p" and "m" refer to prototype and model respectively and likewise subscripts "s" and "r" refer to smooth and rough boundaries.

The velocity "Defect Law" which applies over the range of equations (1) is not so convenient for calculation as equations (1). In the treatment which follows equations (1) and (2) are adopted.

To compare model and prototype velocity distributions assuming that the model has been so designed that with $F_m = F_p$ turbulent flow exists in the model, the ratio between the values of u_m and u_p will in general be established by the use of equation (1) and will be continued by equation (2). Since equation (2) expresses $\frac{U-u}{V_*}$ as $\phi(\frac{y}{\delta})$ rather than 'y' itself, the compared profiles plotted in nondimensional form will tend to preserve the difference of $\frac{u}{V_*}$ generated by equation (1) as 'y' is taken from δ' (= Laminar sublayer thickness) to $0.15\,\delta$

From equation (1) $$\frac{u_m}{u_p} = \frac{V_{*m}\left\{5.6 \log \frac{y_m V_{*m}}{\nu} + 4.9\right\}}{V_{*p}\left\{5.6 \log \frac{y_p V_{*p}}{\nu} + 4.9\right\}} \quad \ldots\ldots(4)$$

Substitute for $V_* = \sqrt{\frac{f}{8}}\, V$

$$\frac{u_m}{u_p} = \frac{f_m^{\frac{1}{2}} V_m \left\{5.6 \log \frac{y_m \sqrt{\frac{f_m}{8}} V_m}{\nu} + 4.9\right\}}{f_p^{\frac{1}{2}} V_p \left\{5.6 \log \frac{y_p \sqrt{\frac{f_p}{8}} V_p}{\nu} + 4.9\right\}}$$

for water at 75° $\nu \approx 10^{-5} ft^2/sec$ and $\log \frac{1}{\nu} = 5$

and substituting $y_p = \zeta y_m$ and $V_p = \zeta^{\frac{1}{2}} V_m$

$$\frac{u_m}{u_p} = \left(\frac{f_m}{f_p}\right)^{\frac{1}{2}} \frac{1}{\zeta^{\frac{1}{2}}} \frac{\left\{5.6 \log y_m V_m \sqrt{f_m} + 30.4\right\}}{\left\{5.6 \log y_m V_m \sqrt{f_p}\, \zeta^{\frac{3}{2}} + 30.4\right\}}$$

For similarity $$\frac{u_m}{u_p} = Constant \times \frac{1}{\zeta^{\frac{1}{2}}} \qquad \left(\begin{array}{l} For\ F_m = F_p \\ Constant = 1 \end{array}\right)$$

i.e. $$\left(\frac{f_m}{f_p}\right)^{\frac{1}{2}} \frac{5.6 \log y_m V_m \sqrt{f_m} + 30.4}{5.6 \log y_m V_m \sqrt{f_p} + 8.4 \log \zeta + 30.4} = Const. \ldots\ldots(5)$$

It will be seen that, to satisfy this equation f_m, f_p and ζ are required to simultaneously have unique values. A fact which is perhaps more readily shown by the evident impossibility of satisfying $F_m = F_p$ and $R_m = R_p$ simultaneously for one fluid. Equation (5) does however indicate possible adjustments which may be made in establishing the scale of a model.

For channels of reinforced concrete and prototype $\mathbb{R}_{de}$ of the order of 10^6 flow occurs under wholly rough conditions and the value of f_p is determined by the roughness of the channel boundaries.

(For channels at Lake Macquarie Power Station Site, tests have shown that a value of Manning's "n" appropriate to prototype flow conditions is 0·018

The equivalent Darcy Friction Factor for this and a flow of 50 c.f.s. or higher is 0.02.)

From a study of a friction factor chart, it will be clear that a scale model of smaller than prototype size with smooth surfaces can by working at a suitable point on the f v. $\mathbb{R}_d$ curve for smooth surfaces operate at a value of f_m close to f_p.

Furthermore, Clauser and Hama have shown, Ref. (b) and (c) that the velocity distribution curve for rough walls may be written in the form

$$\frac{u}{v_*} = 5{\cdot}6 \log \frac{y\, v_*}{\nu} + 4{\cdot}9 - \frac{\Delta U}{v_*} \qquad \ldots\ldots(6)$$

where ΔU is the shift or change in the velocity distribution profile against a rough wall as compared to a smooth wall and v_* is taken as for smooth walls.

The value of $\frac{\Delta U}{v_*}$ may be found from

$$\sqrt{\frac{8}{f_s}} - \sqrt{\frac{8}{f_r}} = \frac{\Delta U}{v_*} \qquad \ldots\ldots(7)$$

Substituting equation (5) in equation (1) and rewriting equation (5), we get for a smooth model and a rough prototype

$$\left(\frac{f_m}{f_{ps}}\right)^{\frac{1}{2}} \frac{5{\cdot}6 \log y_m V_m \sqrt{f_m} + 30{\cdot}4}{5{\cdot}6 \log y_m V_m \sqrt{f_{ps}} + 8{\cdot}4 \log \zeta - \frac{\Delta U}{v_{*ps}} + 30{\cdot}4} = Const \qquad \ldots\ldots(8)$$

It will be noted that $\frac{\Delta U}{v_*}$ contributes to the reduction of the scale factor term 8.4 Log. ζ in equation (5).

In practice it is not feasible to select a model scale to satisfy equations (5) or (8) but it is practicable to select a scale within a known range of experimentally suitable scales and by plotting the model velocity distribution against the prototype on a non-dimensional basis e.g. $\frac{y}{\delta}$ v. $\frac{u}{v_*}$ obtain a comparison of the model and prototype curves.

The increase in model velocity may be estimated to obtain improved correspondence by calculating the velocity $\frac{\Delta u}{v_*}$ shift in the model curve necessary to superimpose the model curve on that of the prototype.

This has been done for the case of the rectangular channel at Lake Macquarie Power Station for a depth of 6 feet and a flow of 49.3 c.f.s. based on Manning's "n" in prototype = 0.018 and a model scale of 1:8.73 and for a depth of 10 feet.

The velocity profiles are compared in Figure (C)

<u>EXAMPLE</u> - <u>ADJUSTMENT OF MODEL FLOW, MODEL SCALE 1: 8.73</u>

From Fig. (C)

$$\left(\frac{u}{v_*}\right)_p - \left(\frac{u}{v_*}\right)_m = \left(\frac{u}{v_*}\right)_{ma} - \left(\frac{u}{v_*}\right)_m = 0\cdot 8$$

where subscript "a" is for adjusted flow in the model.

i.e. $$5.6 \text{ Log } \frac{y_m v_{*ma}}{\nu} - 5.6 \text{ Log } \frac{y_m v_{*m}}{\nu} = 0.8$$

Rearranging and eliminating y and ν

$$\text{Log } \frac{v_{*ma}}{v_{*m}} = \frac{0.8}{5.6} = 0.142$$

or $$\frac{v_{*ma}}{v_{*m}} = 1.39$$

assuming "f" is taken constant over the adjustment

$$\therefore \quad V_{ma} = 1\cdot 4\ V_m$$

$\therefore$ the model flow may be increased 40 per cent over the corresponding Froude flow to improve correspondence between model and prototype provided surface effects are not seriously distorted. Distortion of surface pattern can be readily observed in a model.

Flow approaching a pump casing in an open channel will exhibit a flow pattern similar to Figures B. and C.

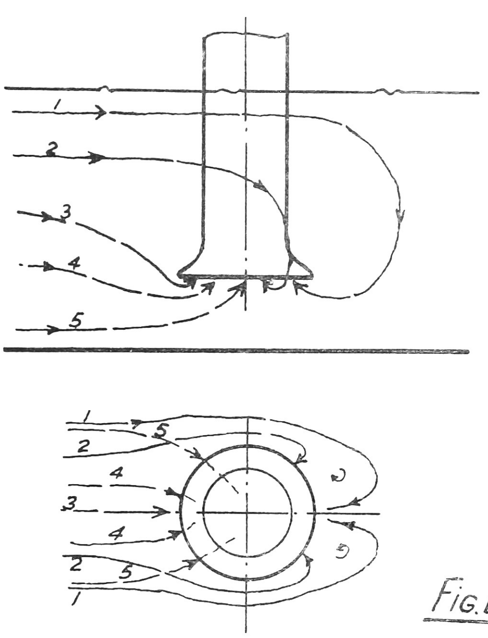

Fig.B.

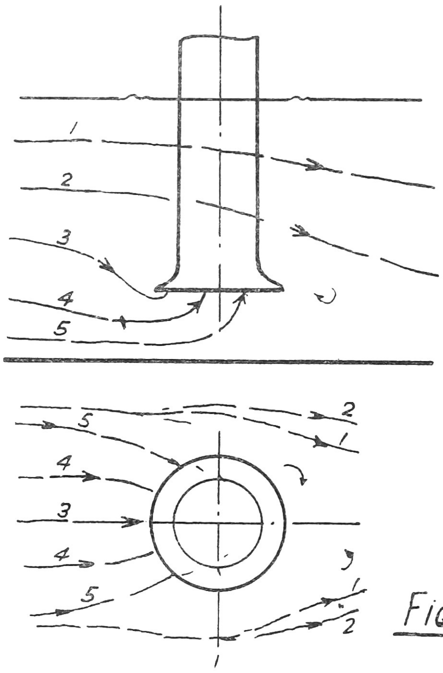

Fig.C.

The flow pattern of Figure B. is for a pump at the end of a channel. The flow pattern for Figure C. is for a pump in a channel with continuing flow downstream.

In the case of the pump, Figure B, air entrainment is likely if the Reynolds Number of the surface flows is $>$ 20 but $<$ 20,000 when the surface flow is turned downwards and is drawn towards the bell entrance. The effect of superimposing vertical velocity components on vortex flow with convergence towards the pump bell is to amplify the angular velocity of the rotating filaments in the vortex and when the centrifugal force on a filament reaches equilibrium with the gravitational force an air core is formed.

Air entrainment can be minimised if:-

(a) the surface approach flow is maintained at a high enough value to prevent vortices forming in the wake.

(b) boundary layer separation is controlled by restricting the passage at the rear of the pump to the optimum consistent with uniform distribution of flow over the lip of the bellmouth.

(c) by inserting a horizontal subsurface baffle to increase the length of path of the flow from the surface to the bellmouth such that vorticity in the wake decays before downward motion commences.

At the present state of knowledge both (b) and (c) are best achieved by observing a model.

In the case represented in Figure C and as a guide in designing the intake channels to avoid air entrainment, it may be assumed that the mean velocity in the channel downstream of the pump is to be maintained at a value greater than V_v as calculated for the approach flow by Equation(3)

Alternatively, if the surface approach velocity is maintained high enough for the Reynolds Number of the flow past the pump to exceed 20,000 then the wake will be turbulent and free of individual vortices.

The theoretical treatment in the foregoing is based on the assumption of a wide channel and effect of reducing the spacing between the walls of the channel will distort the flow about the pump casing and in the wake. An approach velocity of 0.5 feet per second satisfies the Reynolds Number for a turbulent wake and observations of model behaviour appear to support its adoption as a design figure until further experiments are conducted to ascertain more accurately the velocity fields about pump casings placed in a channel.

CHARACTERISTICS OF THE "KARMAN WAKE" AND THEIR APPLICATION TO PUMP PIT DESIGN.

The generation of the "Karman Wake" is a special case of separation of the boundary layer at the surface of a fixed body in a flowing fluid. The wake is a region of disturbed fluid extending downstream of the body and gradually merging with the main stream.

If the body is a vertical cylinder and the fluid has a free surface, the wake will show visible identifiable vortices or more or less uniform turbulence according to the magnitude of the Reynolds Number ($\mathbb{R}$) of the flow where

$$\mathbb{R} = \frac{v D}{\nu}$$

and v = mean velocity of the undisturbed stream

D = diameter of the cylinder

ν = Kinematic viscosity of the fluid

The geometry of the wake at low Reynold Numbers is as shown in Fig. "A".

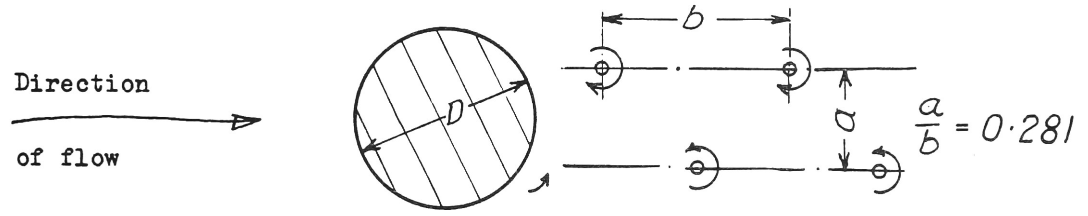

Fig. "A"

The velocity of the vortices relative to the body will be v_v which is always lower than v_o = the uniform velocity of approach to the cylinder.

The value of v_v is related to the frequency (f) of formation of the vortices in the following equation:-

$$f = \frac{v_o - v_v}{b} \quad \text{............. (1)}$$

The frequency has also been found to be a function of the Reynold Number of the cylinder and stream which is given by Taylor

$$f = 0{\cdot}198 \frac{v_o}{D}\left(1 - \frac{19{\cdot}7}{\mathbb{R}}\right) \quad \text{............. (2)}$$

for Reynolds Numbers $>$ 120 the vortices in the wake begin to lose identity and at Reynolds Numbers $>$ 20,000 the wake is fully turbulent and individual vortices cannot be determined.

Now from Equation (1)

$$v_v = v_o - bf$$

and from Equation (2)

$$v_v = v_o - 0{\cdot}198 \frac{v_o}{D}\left(1 - \frac{19{\cdot}7}{\mathbb{R}}\right) b$$

substitute

$$b = \frac{a}{0{\cdot}281} \approx 3{\cdot}5\, D$$

$$v_v = v_o - 0{\cdot}7\, v_o \left(1 - \frac{19{\cdot}7}{\mathbb{R}}\right) = v_o\left(0{\cdot}3 + \frac{13{\cdot}8}{\mathbb{R}}\right) \quad \text{............ (3)}$$

For $\mathbb{R}$ = 20 $\quad v_v \approx v_o$

For $\mathbb{R}$ = 20,000 $\quad v_v \approx 0{\cdot}3\, v_o$

Appendix X is not in the original print copy.

APPENDIX XI.

PARTICULARS OF CIRCULATING WATER PUMPS IN SOME N.S.W. POWER STATIONS.

Station	Bunnerong "B"		Pyrmont "B"	White Bay	Tallawarra		Lake Macquarie	
Units	8 - 9	10 - 11	18 - 21	1 and 2	1 - 4	* 5 and 6	1 - 3	4 - 6
Capacity G.P.M.	21,500	25,875	22,500	17,500	13,500	31,250	18,500	24,250
Head	29	20	23.5	-	39	22	20.5	22
Speed R.P.M.	585	535	585	735	585	580	730	585
Stages	2	1	2	1	2	1	1	1
Impeller Dia-Inches	28"	33"	27"	24½"	24"	32-1/4"	24"	33"
Boss Dia-Inches	10-3/4"	16½"	14"	11"	9-5/8"	18.89	12"	16.5"
Waterway Area sq. ft.	3.65	4.46	2.90	2.61	2.64	4.14	2.36	4.45
Mean Axial Velocity f.p.s.	15.72	15.49	20.66	17.80	13.66	20.14	20.92	14.51
Bellmouth Approx. submergence	36"	48"	57"	53"	64"		48"	90"

* Design not yet confirmed