A COMPARATIVE STUDY OF PENSTOCK - TRIFURCATION MODELS

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CERTIFICATE

Certified that the thesis entitled "A COMPARATIVE STUDY OF PENSTOCK-TRIFURCATION MODELS" which is being submitted by Sri S.N.P. Sharma in partial fulfilment for the award of the degree of Master of Engineering in Hydraulics and Irrigation Engineering of University of Roorkee is a record of the student's own work, carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of five months for preparing this thesis for Master of Engineering Degree at the University.

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SYNOPSIS

A power tunnel feeding three hydroelectric units may necessitate the use of a penstock trifurcation if branching is not done by the conventional Wye arrangement. The hydraulic design of a suitable penstock trifurcation has to be arrived at on the basis of a comparative study of different alternatives. The results of model studies of only a few trifurcation models are available. This thesis deals with the experimental study of the losses at trifurcations of three different types (i) trifurcation with suitable transition, (ii) two Wye junctions and (iii) trifurcation with an abrupt junction. A comparative study of different trifurcation models including model studies carried out elsewhere is presented in this thesis.

The present study of trifurcation models has been made with air as the fluid on a 1 : 15 scale model of the proposed penstock trifurcation for Ram Ganga Project in Uttar Pradesh. The energy-loss coefficients for different operating conditions have been determined. Dimensionless plots of the pressure distribution along the arc length are drawn for different Reynold's numbers. The results indicate that for Reynold's number greater than 10^5, head loss coefficient is almost independent of the Reynold's number. The energy loss coefficient for trifurcation provided with transition is appreciably less than for the trifurcation with abrupt junction or two Wye junctions for the condition of all the three pipes running. Where as the superiority of trifurcation with transition is established beyond doubt over trifurcation with abrupt entry, the Wye model is adjudged suprior to other two for single pipe running condition. A trifurcation model shaped so that the stagnation point is shifted in

the flow direction seems to be preferable to a trifurcation model in which transition begins at one transverse section. This is because the flow is better guided into the different branches in the former case.

LIST OF SYMBOLS

a	-	Semi major axis of elliptical profiles
b	-	Semi minor axis of elliptical profiles
D_T	-	Diameter of main(approach) penstock in feet
D_p	-	Diameter of branch penstock in feet
X	-	Distance along the developed surface.
X_1	-	Axial distance along the transition.
L	-	Length of transition along the axial direction of flow.
r	-	Radial distance from the axis
R_T	-	Radius of main penstock.
r_p	-	Radius of branch penstock.
H	-	Total energy head in feet (per lb. of fluid flowing)
ΔH	-	Head loss in feet.
V_T	-	Average velocity of approach flow
V_p	-	Average velocity of branch penstock.
V_{max}	-	Maximum velocity at any point along the diameter.
V_x	-	Velocity at any point in x branch of Wye, $x = 1, 2, 3$
V_y	-	Velocity at any point in y branch of Wye, $y = 1,2,3.$; y not equal to x.
P_T	-	Wall pressure of approach flow before the transition in lbs/ft.sq.
P_p	-	Wall pressure in branch pipe in lbs/ft^2
P_v	-	Vapour pressure of water.
P_x	-	Pressure at any point in x branch of Wye. $x = 1,2,3$
P_y	-	Pressure at any point in y branch of Wye, $y = 1,2,3$, and Y not equal to x.
P	-	Pressure at any point in lbs/ft^2.
ΔP	-	$P_T - P$
K_1	-	Kinetic energy correction factor of approach flow

K_2	-	Kinetic energy correction factor of flow in branch penstock.
K	-	Uniform sand grain roughness in feet.
Q	-	Discharge in cusecs.
w	-	Specific weight in pounds per cubic feet.
CL_1	-	Head loss coefficient $CL_1 = \frac{\Delta H}{V_T^2/2g}$
CL_2	-	Head loss coefficient $CL_2 = \frac{\Delta H}{V_p^2/2g}$
ν	-	Kinetic viscosity
$\mathbb{R}$	-	Reynold's number.
$\mathbb{M}$	-	Mach number.
$\mathbb{F}$	-	Froude Number
$\mathbb{W}$	-	Weber number
σ_c	-	Cavitation number.
D	-	Characteristic length
ϵ	-	Roughness height

$k \approx \epsilon$

CONTENTS

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CHAPTER - I

I N T R O D U C T I O N

A power tunnel is provided to connect the intake structure to the power house in any power Project. Usually the power tunnel is branched into several penstocks in order to feed the individual Turbines of the power house. Model studies described in this dissertation were carried out with special reference to Ram Ganga River Project. The Ram Ganga Project is a multipurpose river-valley project. The dam is an earth and rockfill dam, 420 feet high. The proposal for the water conductor system includes a submerged cage type intake which admits water into a concrete lined power tunnel 31 feet internal diameter. Just upstream of the dam axis, the tunnel is converted into a single steel lined penstock 26-feet internal diameter upto nearly the exit portal of the tunnel, where by provision of a transition, the single penstock divides itself into three penstocks of 10 feet diameter each to feed the individual turbines.

The branching may be made by providing a trifurcation with abrupt entry or conventional Wye arrangement or a trifurcation with suitable transition. What ever be the manner of branching, the object in planning should be to get the most efficient system of branching. Obviously, the branching system will be most efficient if the hydraulic efficiency of the branch is maximum without affecting economy of the Project. Detailed economic studies are beyond the scope of this thesis. However, capitalised values of head losses expected in various trifurcation arrangements have been presented at the end. In order to attain the maximum hydraulic efficiency of the branch system, the energy loss due to branching should be least with the least possibility of any local flow separation, which may lead to cavitation.

The energy loss at the junction may be due to form drag or surface drag or both. The loss due to branching could be visualised as the sum of the losses due to change in cross section and losses due to a change in the flow direction. We know that due to change in cross section there is a variation in velocity and loss generally results from change of velocity. Velocity increases cause small losses but decreases of velocity cause large losses b ecause of eddy flow. If the change in cross section is sudden, in case of contractions, the stream lines converge upto the Vena Contracta and then diverge to fill the sectional area in the downstream pipe. Obviously in the de-celerating zone useful energy is extracted in the creation of eddies and this energy is dissipated in heat as the eddies decay in the pipe down stream of the decelerating zone. Similarly in case of sudden enlargement of section, a rapid deceleration takes place accompanied by characteristic eddying turbulence, which may persist in the larger pipe for a distance of 50 diameter or more before the normal conditions are restored. The head loss produced at a well stream lined gradual contraction, has been found experimentally to be very small by so many workers[1,2] only because the chances of formation of eddies are minimised due to streamlining which results in minimising the cone of separation.

We also know that when fluid flows along a curvilinear path, eddy motion is created and energy is dissipated due to distortion of the velocity distribution from its normal turbulent form.

From the above discussions, it is apparent that for energy loss to be minimum one should have a branching system with well streamlined gradual contraction and minimum possible deflection of streamlines. Obviously a trifurcation with abrupt entry should form the worst choice from hydraulic point of view as it is expected to cause greater loss of energy. Experimental studies carried out in this investigation also verify this presumption. The conventional Wyes and trifurcations with suitable transitions have individual merits under different running conditions which have been discussed in Chapter VI.

In the proposed trifurcation of Ram Ganga Project, penstocks are placed symmetrically with respect to the axis of the main penstock. The main penstock is divided into three sectors of 120° each and the individual penstocks are so placed that their centres lie on the radii bisecting the sectors and situated at a suitable distance which ensures the most central location of the Penstocks with respect to the sectors and hence minimum possible deflection of the stream lines. Various elliptical transitions are to be provided along the radial planes to connect the 120° sectorial area of the main penstock with the circular area of the branch penstock. This ensures a gradual rate of change of section.

In this study, reference has also been made to trifurcation used in the Round Butte Hydroelectric Project (U.S.A.)[3] where the placing of the branch penstocks is such that the longitudinal axes of the main penstock and its three branches lie in the same plane. There is symmetry with respect to the central pipe only. The merits and demerits of this arrangement are discussed in the comparative study given in Chapter VI.

A study of trifurcation with abrupt entry has been made rather for academic reason than for any practical utility.

In the proposed Wye arrangement for Ram Ganga Project,[4] the 26 feet dia penstock has been provided with a bend of radius 78 feet and the dia of the penstock is reduced to 23.4 feet at the end of the curve. Two Wye pieces 23.4 x 19.1 x 13.5 feet and 19.1 x 13.5 x 13.5 feet have been used at proper locations to connect the three branch penstocks of 13.5 dia each. A comparative study of different types of trifurcations, including the

Wye has been made in Chapter - VI and it is expected that the study may be useful to hydro-power Engineers in deciding the type of trifurcation for a proposed hydropower scheme.

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CHAPTER - II

DESIGN CONSIDERATIONS.

Economic diameter of the main penstock is worked out on the basis of minimum total cost of penstock and accessory equipment and capitalised value of head loss in the penstock for various penstock diameters and governor closing times. The thickness of penstock depends upon the static head, Water-hammer head and external water pressure. Water hammer head is worked out on the basis of prescribed operating condition. For fixing the dimensions of any branch connection, results of experimental investigations carried out by Professor Thoma at the University of Munich (5) and similar conclusions drawn by U.S.B.R. in connection with hydraulic studies made for Boulder canyon Project are very useful. The final conclusions of the U.S.B.R. are listed below.

i) Branch connections at deflection angles of 45° or 60° are more efficient than those at 90°.

ii) A conical branch connection is more efficient than a straight connection or one with rounded edges.

iii) Losses in a branch connection depends on two factors :-

a) The ratio of amount of fluid diverted into the branch to the quantity in the main conduit just above the branch i.e. Q_p/Q_T .

and b) The ratio of the diameter of the branch to the main conduit, D_p/D_T .

The influence of these ratios is to reduce the losses when the ratio Q_p/Q_T decreases and the ratio D_p/D_T increases. Hence it is desirable to keep the branch diameter as large as practically possible and to use a conical connection with rounded edges at the upstream side of the branches. The most favourable flare for the conical connection has been experimentally found to be 12^o 40^b by U.S.B.R. It has also been experimentally verified(##) that smaller the deflection angles, the better is the hydraulic efficiency of the branch joint but if the deflection angle is less than 30^o, the effieicy is only marginally improved (6) because the decrease in head loss is also accompanied by increase in the head loss in the now longer branch pipe. Moreover for constructional facilities the U.S.B.R. does not recommend an angle less than 45^o (7).

A trifurcation should be (a) symmetrical, (b) have a low angle of incidence between the branch and main pipes, (x) have branch diameter as large as practically possible and (d) have accelerating flow in the transition and decrease in piezometric head should be continuous. The diameter of the branch penstock should not be fixed up only by maximum velocity considerations or economic dia criterion, but (c) and (d) should also be taken care of. Once the diameter of the main penstock and its branches are fixed, up, the

the only variable parameter to be decided upon is the transition length. The U.S.B.R. recommendation for the most favourable flare for conical connection fixes up the transition length without much difficulty. If the transition length is increased, velocity gradient will decrease, resulting in less energy loss. But the greater length of transition will mean greater friction loss together with increased cost of the structure. Hence, an optimum length of transition should be fixed to give minimum loss of energy in the transition and this is only possible by model studies. The loss of energy through the transition could still be minimised by stream lining the flow through the transition and this will be helpful in adopting a smaller length of the transition. In the case of an accelerating flow minimum energy loss is not the only criterion to select a model, but also that should confirm to the practical requirements. A smooth and continuous decrease of pressure in the transition region ensures less chances of local separation and consequently less energy loss. Potential flow studies indicate that free streamlines can be best approximated by elliptical profiles and sometimes by cubic parabolas. The graph for elliptical profile given in Fig. 4 is taken from Rouses' Engineering Hydraulics[8]. The diamter of the main penstock for Ram Ganga Project has been fixed up as 26 feet and that for branch pipe as 10 feet[4]. The diamter of the main penstock was fixed up by economic studies but the dia of branch penstock was fixed as the maximum diameter which can be accommodated in each sector of 120° of the main penstock with due allowance for the thickness of the branch penstock. The maximum flow rate in each of branch pipes is 2774 cfs. The main penstock 26 feet dia is divided into three sectors of 120° each. One branch penstock is placed in each sector being concentric with the circle inscribed in it. The distance between centres of main penstock and branch penstocks is 6.97 feet for most central location of the branch penstock with respect to the sectors.

Transitions are designed by providing elliptical transition along the radial planes in each sector. The minimum major to minor axis ratios which do not cause separation have been provided. Two types of trifurcations have been proposed ;

Maximum value of b = 6.2784 feet[9], r = 5 feet

b/r = 1.25568 ;

$\therefore$ a/r = 3.75 (From Fig. 4)

a = 18.75 feet say 19 feet. Therefore, transition length should not be less than 19 feet for no separation and no cavitation. A transition length of 24 feet has been proposed. Both the trifurcation models with transition tested are identical except that in model II the stagnation point of the approach flow is taken downstream by a distance which corresponds to 7'-6" in the prototype. This keeps all the three portions inclined in the downstream direction at 30° with the normal. The values of major and minor axes for different elliptical profiles in model II are given in table 5. A dimensionless plot of average velocity and area of cross-section along the transition is shown in Figure 5.

In Round Butte Hydroelectric Project,[3] the maximum discharge of 12,000 cfs was to be passed i.e. discharge in each branch penstock was 4000 cfs. The diamter of the main penstock was 23 feet and the three branch penstocks were designed to have approximately the same combined areas as the main penstock, thus maintaining the same average velocity through out when the flow was equally distributed. Trifurcation was symmetrical having deflection angle of 45° for two side pipes. Transition length was 39 feet 4.75 inches No streamlining surface was provided. A gradual converging cone was provided keeping the central flare angle nearly 13°. For the structural stability of the trifurcation, a tie bar was provided at the junction where long axes of three branches meet.

A trifurcation could also be replaced by providing two standard Wye junctions. The model studies carried out by U.S.B.R.[1] reveal that a streamlined Wye branch without tie rods, is the best from hydraulic considerations. Figures 7 shows the proposed Wye arrangement for Ram Ganga Project as suggested by the Design Directorate, Irrigation Department, (U.P.). The dimensions of the Wye arrangement have been designed to maintain the same average velocity in the branches as the approach velocity at the first Wye junction for the conditions of three pipes running.

Figure 8 gives a recent modification of Escherwys Wye Branching [10] over the conventional one shown dotted. Their improved design has been arrived at on the basis of a series of model tests.

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CHAPTER - III

SIMILARITY CRITERIA, SCALE RATIO AND CONSTRUCTION OF THE MODEL

In a General fluid flow problem it is possible to show that $\frac{\Delta P}{\frac{\rho V^2}{2}} = \phi\ (\mathbb{R}, \mathbb{F}, \mathbb{W}, \mathbb{M}, \epsilon/D)$ ....(i)

where ΔP represents the difference in pressure between two points, ρ is the density of fluid, V is the velocity of flow, $\mathbb{R}$ the Reynold's number, $\mathbb{F}$ - the Froude's number $\mathbb{W}$ - the Weber's number, $\mathbb{M}$ - the Mach number, ϵ [redacted] is the roughness height, D is a characteristic length and ϵ/D represents relative roughness. In case of pipe flow under pressure, gravity has no influence on motion. Therefore $\mathbb{F}$ is not an important number governing flow hence it may be dropped out. Compressibility effects are very very small. Even in the case of model experimentation with air in subsonic range, effect of $\mathbb{M}$ is negligible. Hence $\mathbb{M}$ also drops out. Similarly, surface tension plays no part in pipe resistance, hence, $\mathbb{W}$ drops out. Therefore,

$$\frac{\Delta P}{\frac{\rho V^2}{2}} = f(\mathbb{R}, \epsilon/D) \qquad \text{.....................(ii)}$$

For obtaining similarity between model and prototype geometric similitude should be observed and the same, $\mathbb{R}e$ in the model and prototypes provides dynamic similitude. Then only pressure coefficient $\frac{\Delta P}{\rho V^2/2}$ in the model will equal the corresponding pressure coefficient in the prototype. It is very difficult to represent the same relative roughness in the model as in the prototype. It is also not practicable to get as high Reynold's number in the model as in the prototype and this demands relatively smoother surface in the model than in the prototype. Although model surface is made as smooth as possible, it remains rougher than the similitude demand. However, in most model studies including transitions, the inertial effects or those resulting from changes in magnitude or direction of velocity do dominate the effects of surface resistance. Under such circumstances if the roughness in the model is smoothened adequately such that the same region of flow is maintained in the model and prototype both (either both have smooth turbulent, transition flow or rough turbulent flow), the pressure coefficient obtained by model testing may be reasonably used to predict the losses in the prototype.

It has been experimentally observed by U.S.B.R.(1) that the scale effect is appreciable in case of model studies for losses through pipe junctions . In geometrically similar models the head losses observed in bigger models (higher scale ratio) were less than the head losses observed in smaller models (lower scale ratio). This inference was further verified by observing head loss in the prototype which was less than the head loss predicted by the model studies. Hence, in selection of scale ratio, attempts should be made to produce larger models within the limits of availability of space, time, economy and accuracy desired. In smaller models the head loss observed will be more because of viscous effects being more pronounced. The scale ratio will also be limited by the lowest value of Reynold's number which must be attained in the model for attaining dynamical similarity of flow. It can be seen from Moody's diagram [8] that for value of Re > 10^5, friction factor f is almost constant for a given D/K. It has been observed experimentally by other workers [3,5,9] also that for Re > 10^5 pressure coefficient $\frac{\Delta P}{\rho V^2/2}$ is almost idependent of the value of Re. Hence in selection of scale ratio one must keep in mind this lower limit of Reynold's number. While representing a model in the laboratory one must ensure that sufficient reach both upstream and downstream of the test section is represented so that approach flow as well as the flow in the downstream portion be fully established[11], otherwise results predicted by model studies may be erroneous.

The present model studies have been carried out with special reference to branching of 26 feet diameter main penstock of Ram Ganga River Project into three branch penstocks of 10 feet diameter each. The maximum discharge through the main penstock is 8320 cusecs. The prototype velocities in the main penstock and branch penstocks for different operating conditions are given in Table - 1.

TABLE - I

Dischafge in cusecs	Velocity in main penstock ft/sec.	Velocity in branches feet/sec	Number of branches in operation
8320	15.65	35.3	All the three
5546.66	10.43	35.3	Any two
2773.33	5.22	35.3	Any one

Assuming 80° F as the water temperature, the Reynold's number in the main penstock varies from 1.46 x 10^7 to 4.39 x 10^7 whereas $\mathbb{R}$ in branch penstock remains 3.82 x 10^7 for all running conditions. The model studies were to be carried out in a wind tunnel having test section of the size 32" x 45" , 10 feet long. Eight inches internal diameter standard steel pipes, 10 feet long were available in stock. The utilisation of readily available standard steel pipes as branch penstocks in the model was considered to be an economic and time saving measure, towards the construction of the model. Thus keeping in view the availability of space, a scale ratio of 1 : 15 was selected for the model. The salient features of the model are given in Table - 2.

TABLE - 2

Item	Inches
Diameter of the Main Penstock	20.80
Diameter of the branch Penstocks	8
Length of Transition	19.2
Length of main penstock (chosen to represent u/s normal flow)	30
Length of branch penstocks (choosen to represent d/s normal flow)	120

The inner surface of main penstock and branch penstocks have been made as smooth as possible : The main transition portion was prepared in wood. The inner surface was made very smooth by continuous sand paper rubbing, polishing and varnishing it. In the model velocity observed in the main penstock was sufficient to give Reynold's number of the order of 4×10^5 for various conditions of operation.

This ensured the same region of flow (Transition flow in the present case i.e. flow between smooth turbulent flow and rough transition flow) in the model and prototype both. For the same trifurcation model the scale ratio chosen at Irrigation Research Institute , Roorkee, is 1 : 36 and water was used as the fluid in the model. They had a still lower range of R and higher relative roughness of the model. The scale ratio chosen for model studies of round Butte Penstock trifurcation with water was 1 : 23.7 .

TABLE - 2

Item	Inches
Diameter of the main penstock	20.0
Diameter of the branch penstocks	6
Length of transition	19.2
Length of main penstock (chosen to represent 6/5 normal flow)	30
Length of branch penstocks (chosen to represent 6/5 normal flow)	120

The inner surface of main penstock and branch penstocks have been made as smooth as possible ; the main transition portion was prepared in wood. The inner surface was made very smooth by continuous sand paper rubbing, polishing and varnishing etc. In the model velocity observed in the main penstock was sufficient to give Reynold's numbers of the order of 4×10^5 for various conditions of operation.

To ensure the same regime of flow (transition flow in the present case i.e. flow between smooth turbulent flow and rough transition flow) in the model and prototype both, for the same trifurcation model the scale ratio chosen at Irrigation Research Institute, Roorkee, is 1 : 24 and water was used as the fluid in the model. They had a still lower range of R and higher relative roughness of the model. The scale ratio chosen for model studies of [illegible] dam trifurcation with water was 1 : [illegible]

Construction of Models :

Model - I : The model was constructed and studied by Juyal and results are given in his M.E. Thesis [9].

Model - II :

Main Penstock - The main penstock has been constructed by rolling G.I. Sheet to a circular pipe of 20.8 inch internal diameter and 30 inches in length. Five piezometers A, B, C, D and E have been provided in the main penstock to measure the piezometric head.

Transition - Deodar wood was used for preparing the transition of the model. Three holes of 8 inches diameter were made in a 20.8 inches diameter and one inch thick circular disc of wodd, to represent the position of branch penstocks at the end of the transition. Wooden templates representing elliptical inlet profiles were made. One end of each template was fixed in the grooves cut in the 20.8 inches diameter circular disc and the other end was kept free. The gap between the templates was filled by wooden pieces . These were properly glued together to give a smooth surface. Any projections of the wooden pieces were properly filed to make them flush with the templates. Separate templates of known cross sections of the transition were prepared to check the correct-ness of the transition prepared as above. The inner surface of the transition was made as smooth as possible by continuous sand paper rubbing, polishing and varnishing. Three rows of piezometers were fitted along three typical planes of the transition as shown in the figure given on top of pressure distribution graphs.

A wooden pipe of 8 inhhes internal diameter and 9.5 inches long (well finished internally) was prepared and fitted between the transition and each one of the branch penstocks to represent the beginning of the branch penstock. This was done to facilitate velocity measurement in the downstream side. Three steel pipes of 8 inches nominal diameter and 10 feet long were used to represent branch penstocks. Three piezometers F, G and I were provided in the branch penstocks also. The transition model II is shown in Plate No. 2. For comparison transition Model I studied by Juyal is shown in Plate No. 1. For Model II, cross sections of the transition at different distances is given in Figure 6. The general view of the wind tunnel with experimental set up is shown in plate 3 and 4.

Construction of Trifurcation Model with Abrupt Entry :

Similar to the construction of model II, three holes of 8 inches diameters were made in a wooden piece 22 inches square and one inch thick. After removing the transition piece of Model II, this wooden piece was fitted to the main penstock with the same locations of its holes as in model II. Three steel pipes used in Model II were fitted against the three holes in the wooden plate. Joints were properly closed by plasticine.

Construction of Wye Model :-

The central section of the proposed Wye arrangement shown in Figure 7, was properly laid on ground after being reduced according to the scale ratio of 1 : 15. Wooden templates representing half periphery of the model at various critical sections were prepared and cement concrete moulds representing half inner volume of the model were prepared. The surface of this concrete mould was made to correspond in shape to the inner surface of the model with the help of wooden templates. Continuous templates were used to represent the two Wye pieces properly. The surface was neatly plastered and the mould was cured properly for ensuring adequate hardening of the concrete. The full mould consisted of a number of typical portions. The general view of the mould is shown in Plate 5. G.I. sheets were cut to represent the developed surface of certain portions of the mould. They were moulded to its shape properly. For each portion two such moulded sheets were prepared and they were joined to make full model for that portion. All such portions were properly joined and welded to give one piece of the Wye arrangement. Altogether 17 piezometers were connected to the Wye arrangement for giving the piezometric head at different points. The general view of the complete Wye arrangement is shown in plate 6.

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CHAPTER - IV

INSTRUMENTATION AND EXPERIMENTATION

The experimental investigations for determining losses in a trifurcation model with abrupt entry and trifurcation model II with suitable transitions, were carried out in a closed circuit wind tunnel having a test section 32" x 45" x 10 feet long. The blower is a propeller type fan run by a 50 H.P. motor. The R.P.M. of the propeller is 1175. There is an arrangement for varying the flow rate by adjusting the angle of the propeller blades. The wind tunnel cross section was plugged at the beginning of the test section with the help of a ply wood board having central hole of 20.8 inches diameter to connect the main penstock of the model. The cross section of the tunnel at the other end of the test section was plugged with another plywood board with three symmetrically placed 8 inches diameter holes to contain the three branch penstocks of the model. A similar plywood board was used in between the two ends of the test section to give adequate support to the three branch penstocks. The 20.8 inches diameter 2.5 feet long G.I. sheet circular pipe representing the main penstock was placed in the test section with its periphery coinciding with the 20.8 inches dia hole in the plywood board. In order to provide smooth entry of inflow into the main penstock the upstream end of the main penstock was given suitable curvature. The main penstock was supported and kept in position by pressing it with two crescent shaped thick wooden plates rigidly connected to the body of the wind tunnel . Five piezometer tappings A, B, C, D and E were provided in the body of the main penstock. A, 9.6 mm, diameter hollow graduated rod connecting the total head tube was placed centrally across the main penstock in the vertical plane containing piezometer B. One end of the rod was sealed by connecting it to a solid handle while the other end was connected to a plastic tube leading to the manometer.

The wooden transition as described in Chapter III and shown in plate 2 was placed in just after the main penstock. Assuming symmetrical positions of the branch pipes 3 rows of piezometers along critical planes were provided in the transition connecting only one of the branch penstocks. A wooden pipe 8 inches in diameter and 9.5 inches long was rigidly placed between the transition with piezometer tappings and the corresponding branch pipe. A hollow graduated rod connecting the total head tube just like the one in the main penstock, was placed across the wooden pipe to measure the total head in the branch penstock and a piezometer F was provided to give the corresponding pressure head. An 8 inches dia mild steel pipe was rigidly placed after the wooden pipe , represent the branch penstock. Two more 8" dia m.s. pipes connecting directly to the remaining two holes of the transition were placed to represent the remaining two branch pipes. Piezometers G_1, G, H and I were provided in the branch pipe connecting the wooden pipe to measure piezometric heads in the branch penstocks. All the three branch penstocks discharge freely into the wind tunnel. For part operation, caps were used to stop the flow in any of the pipes. All the joints were made air tight by providing plasticine packing of joints. Small pieces of plastic tubes with one end sealed were used to close the pressure tappings when not in use. The compl ete set up is shown in plates 3 and 4.

For testing the trifurcation with abrupt entry the same experimental set up as described above was modified to suit the requirements. The wooden transition and the wooden pipe were removed. A wooden disc having three symmetrical holes as described in chapter III was placed at the end of the main penstock and three eight inches dia steel pipes were directly connected to the three holes of the wooden disc. Six piezometers F_1, F_2, F, G , H and I were provided in one of the branch penstocks to measure the piezometric head in the branch penstocks. All the three branch penstocks were discharging freely into the wind tunnel. The same caps were utilised to stop the flow for part running conditions as in the case of the trifurcation with transition. All the joints were made air tight with plasticene sealing.

The Wye model as described in Chapter III was supported on a braced wooden frame to keep equilibrium and minimize vibration when the model was in running condition. Each branch penstock was connected to an exhaust fan

provided with speed control arrangement. Two fans were of exactly the same specification and the third one has higher R.P.M. However, the regulating arrangement provided with the third fan, was more precise to run it at any desired speed. At the downstream end of each branch penstock an orifice meter 6" x 10.8" was provided to regulate the discharge. The exhaust fan was placed in a circular pipe preceded by a diverging cone to connect the downstream end of the branch penstock. One total head tube facing the direction of flow was rigidly placed in the centre of the orifice in each of the branch penstock. The pressure tapping was provided at a distance 6" upstream of the orifice point in each branch pipe. Altogether seventeen piezometer tappings sere provided in the whole Wye arrangement to measure the piezometric heads at various points. In order to stop the flow in a particular branch, the exhaust fan for that branch was stopped. Ply wood boards were also placed against the opening at the end of the desired branch. The whole set up for Wye model is shown in Plate 6.

Piezometers were provided to measure the embient pressure. Stagnation tubes were used to measure the total head of the flow. Piezometers and stagnation tubes were connected to an adjustable slope inclined multitube manometer. A brief description of these instruments is given below.

Piezometers :- In order to provide piezometer tappings in the main penstock, 1 mm dia holes were drilled at the marked points in the body of the penstock. These holes were

static plus dynamic head in the branch penstock after the transition. The corresponding static head was observed by the piezometer reading at F. Stagnation tubes were fixed normal to the rod and the joint between the rod and the tube was checked to be leak proof. Care was taken to keep the stagnation tube parallel to the flow. For visual observation a glass covered small opening was provided in the main penstock. In the case of the branch penstock, a groove cut in the hollow graduated rod was made to coincide with a mark on the wooden pipe to ensure direction of stagnation tube parallel to the direction of flow. As the fluid used was air and normally pressures less than atmospheric pressure were to be recorded, a multi tube adjustable slope inclined manometer containing methylated spirit of specific gravity 0.835 was used to measure the pressure. The slope of the manometer was maintained equal to 0.30 throughout the experiment. The manometer consisted of 20 tubes fixed on a silvered glass. In order to avoid parallax, the image of the horizontal thread [illegible] , the thread itself actuated by vernier arrangement, was made to coincide with the lower meniscus of the spirit in the tube. The least count of the vernier was 0.01 cm. A U-tube manometer having a fixed slope of 0.18 was connected to piezometer A in the main penstock and piezometer H in the branch penstock. By maintaining the same pressure difference between these two points, the flow during any particular observation was supposed to remain constant. Plate III and IV show the manometer and U tube also. A thermometer was fixed in the

provided with speed control arrangement. Two fans were of exactly the same specification and the third one has higher R.P.M. However, the regulating arrangement provided with the third fan, was more precise to run it at any desired speed. At the downstream end of each branch penstock an orifice meter 6" x 10.8" was provided to regulate the discharge. The exhaust fan was placed in a circular pipe preceded by a diverging cone to connect the downstream end of the branch penstock. One total head tube facing the direction of flow was rigidly placed in the centre of the orifice in each of the branch penstock. The pressure tapping was provided at a distance 6" upstream of the orifice point in each branch pipe. Altogether seventeen piezometer tappings sere provided in the whole Wye arrangement to measure the piezometric heads at various points. In order to stop the flow in a particular branch, the exhaust fan for that branch was stopped. Ply wood boards were also placed against the opening at the end of the desired branch. The whole set up for Wye model is shown in Plate 6.

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Piezometers :- In order to provide piezometer tappings in the main penstock, 1 mm dia holes were drilled at the marked points in the body of the penstock. These holes were

covered with caps having small opening at the top. The caps were rigidly attached to the main penstock and 3/16" internal diameter brass tube pieces nearly 2 inches long were welded at the top of the caps. Piezometers in wooden transition consisted of brass tubes of 3/32" internal diameter and 1/8" external diameter. Piezometers were kept normal to the surface. Piezometers in steel pipes consisted of 3/16" internal diameter steel tubes. All the piezometers were made free from burrs and their openings were made flush with the inner surface. The distances between piezometers are given in Table 9. In wooden transition the distance was measured along the developed surface. The spacings of piezometers were decided keeping in view the variation of pressure expected. Close spacings were adopted in the region of rapid variation in pressure. The stagnation tube to measure the total head consisted of 1.8 mm dia hypodermic needle properly rounded at the leading edge. The needle was mounted on a hollow graduated brass rod put across the section. By moving the rod along its axis total head measurement was recorded along one diameter of the section. One stagnation tube was installed in the main penstock at a distance of 15.5 inches upstream from the beginning of the transition to measure the static head plus dynamic head and corresponding static head was observed by the piezometer reading at B as described earlier. One stagnation tube was installed in the wooden pipe at a distance of 5.5" from the end of transition to measure the static plus dynamic head in the branch penstock after the transition. The corresponding static head was observed by the piezometer reading at F. Stagnation tubes were fixed normal to the rod and the joint between the rod and the tube was checked to be leak proof. Care was taken to keep the stagnation tube parallel to the flow. For visual observation a glass covered small opening was provided in the main penstock. In the case of the branch penstock, a groove cut in the hollow graduated rod was made to coincide with a mark on the wooden pipe to ensure direction of stagnation tube parallel to the direction of flow. As the fluid used was air and normally pressures less than atmospheric pressure were to be recorded, a multi tube adjustable slope inclined manometer containing methylated spirit of specific gravity 0.835 was used to measure the pressure. The slope of the manometer was maintained equal to 0.30 throughout the experiment. The manometer consisted of 20 tubes fixed on a silvered glass. In order to avoid parallax, the image of the horizontal thread ~~actuated~~ , the thread itself actuated by vernier arrangement, was made to coincide with the lower meniscus of the spirit in the tube. The least count of the vernier was 0.01 cm. A U-tube manometer having a fixed slope of 0.18 was connected to piezometer A in the main penstock and piezometer H in the branch penstock. By maintaining the same pressure difference between these two points, the flow during any particular observation was supposed to remain constant. Plate III and IV show the manometer and U tube also. A thermometer was fixed in the wind tunnel to record the temperature of fluid in running condition. The same instrumentations were used for trifurcation with abrupt entry also. Piezometer tappings were provided in the Wye model exactly in the same manner as done in the trifurcation model. For discharge measurement a thin circular G.I. sheet with a central hole of 6" diameter was welded in each of 10.8 inch inner dia branch penstock. A 1.8 mm dia hypodermic needle was properly welded to an L shaped thin hollow tube. The vertical arm of the tube was rigidly placed across the branch penstock such that the needle (stagnation tube) remained exactly at the centre of the orifice facing the direction of flow. The corresponding static pressure for the mean velociity measurement by applying the principles of fluid dynamics was observed by a piezometer located 6 inches (dia of the orifice) upstream of the orifice. All the thrae total head tubes and seventeen piezometers were connected to the 20 tubes of the multi tube inclined manometer. Temperatures were recorded by placing a thermometer in the Wye model while the model was in running condition. Observations were taken for the following conditions of operation in all the three models :-

i) All the three branch penstocks running

ii) Any two branches running

and iii) Any one branch running.

Observations for each run included pressure measurements, velocity measurements and record of temperatures. Before, the start of any run, initial readings of all the 20 tubes of the manometer were recorded by coinciding the thread to the lower meniscus of alcohol in each tube and the initial temperature was also recorded. When the fan was started nearly fifteen minutes were allowed for stabilization of the flow conditions and then only recording of final readings was started. While testing the trifurcation model II with transition the first ten tubes of the manometer were connected to the piezometer provided in the main penstock and the branch penstock. The next 10 tubes were connected to piezometers provided in the transition in succession, taking one row of piezometers at a time because the number of manometer tubes was less than the number of piezometer tappings. But this difficulty was not experienced while testing the trifurcation with abrupt entry or the Wye model [redacted] as the number of piezometers was not exceeding twenty. In some cases minor fluctuations were observed in manometer readings. Under such conditions, the mean of maximum and minimum readings recorded was taken as the average pressure. The difference between pressures recorded by tappings A and H was recorded in the U tube manometer and this difference was maintained during a particular run by adjusting the pitch of the blades of the fanpropeller. For velocity, distribution in the main penstock or the branch, the hollow graduated rods containing the stagnation tubes were moved along the diameter in steps and the total head readings were recorded for different positions of the tube. Corresponding static tube readings at B and F respectively were also recorded.

Ten runs were taken for trifurcation model II with

CHAPTER - V

ANALYSIS OF DATA

The loss of head in a trifurcation or a y arrangement can be estimated by applying energy principle between two normal sections before and after the junction provided pressure and velocity measurements are available on those sections. Before entering a section stream lines get disturbed and after the junction also it requires a substantial distance for attaining normal flow condition in the downstream direction. Hence proper care must be taken to ensure normal flow conditions at the sections where energy theorem is being applied. In both the trifurcation model II with transition and the trifurcation with abrupt entry the area ratio between the branch and the main penstock is the same for given operating conditions. Hence the same expression for loss coefficient will apply for both the cases. However, the area ratio for the y model is different hence different expressions for loss coefficient for the y model have been separately given.

Considering a trifurcation model, if Q is the discharge in the branch pipe for three pipes running condition, discharge in the main penstock will be 3 Q. Applying energy theorem between a normal section before the trifurcation and symmetrical established sections in the branches we get,

$$3Q\omega \left[\frac{P_T}{\omega} + K_1 \frac{V^2}{2g} \right] = 3Q\omega \left[\frac{P_p}{\omega} + K_2 \frac{V_p^2}{2g} \right] + 3Q\omega \Delta H$$

$$\text{or } \Delta H = \frac{P_T - P_p}{\omega} + K_1 \frac{V_T^2}{2g} - K_2 \frac{V_p^2}{2g}$$

$$\text{Loss coefficient } CL = \frac{\Delta H}{V_T^2/2g} = \frac{P_T - P_p}{\rho \frac{V_T^2}{2}} + K_1 - K_2 (V_p/V_T)^2$$

Generally values of K_1 and K_2 are greater than unity, hence for a conservative estimate of C_L, $K_1 = K_2 = 1$ may be assumed.

Hence, $C_L = \frac{\Delta P}{\rho V_T^2/2} + 1 - (V_p/V_T)^2$ 5.1

Expr

Expression 5.1 holds good for the Trifurcation with transition or the trifurcation with abrupt entry for other conditions of operation also. The ratio V_p/V_T will be 2.25 , 3.38 and 6.76 for three pipes running, two pipes running and one pipe running canditions respectively. Substituting these values the expression for loss coefficient will be given by the following expressions :

Three pipes running $C_L = \frac{\Delta P}{\rho V_T^2/2} - 4.06$ 5.1a

Two pipes running $C_L = \frac{\Delta P}{\rho V_T^2/2} - 10.4$ 5.1.b

Single pipe running $C_L = \frac{\Delta P}{\rho V_T^2/2} - 44.8$ 5.1c

Similar expressions for the loss coefficient for the Wye arrangement can also be deduced by applying energy principle between a normal section before the first Wye branch and a normal section in each of the running branches.

<u>Three branches running :</u>

$$3Q\omega\left[\frac{P_T}{w}+\frac{V_T^2}{2g}\right]=Q\omega\left[\frac{P_1}{w}+\frac{V_1^2}{2g}\right]+Q\omega\left[\frac{P_2}{w}+\frac{V_2^2}{2g}\right]$$

$$+\ Q\omega\left[\frac{P_3}{w}+\frac{V_3^2}{2g}\right]+\left(3Q\,\omega\Delta H\right)\ \ldots\ldots 5.2$$

Assuming energy coefficients to be unity in every case. The dimensions of the Wye arrangement have been designed in such a way that for the three pipes running conditions

$V_T = V_1 = V_2 = V_3$

Hence 5.2 reduces to

$$3\,\Delta H = \frac{(P_T - P_1) + (P_T - P_2) + (P_T - P_3)}{w}$$

or Loss coefficient

$$CL = \frac{\Delta H}{V_T^2/2g} = \frac{1/3[\,\Delta P_1 + \Delta P_2 + \Delta P_3\,]}{\rho V_T^2/2}\ \ldots\ldots 5.2a$$

Two Branches Running :

$$2Q\omega\left[\frac{P_T}{w}+\frac{V_T^2}{2g}\right]=Q\omega\left[\frac{P_x}{w}+\frac{V_x^2}{2g}\right]+Q\omega\left[\frac{P_y}{w}+\frac{V_y^2}{2g}\right]$$

$$+\ 2\,Q\,\omega\,\Delta H\ \ldots\ldots\ldots 5.3$$

Here $V_x = V_y = 1.5\ V_T$

Hence $V_x^2 = V_y^2 = 2.25\ V_T^2$

Hence 5.3 reduces to

$$2\,\Delta H = \frac{(P_T - P_x) + (P_T - P_y)}{w} - 2.5\ V_T^2/2g$$

$$\text{or}\quad CL = \frac{\Delta H}{V_T^2/2g} = \frac{1/2\,[\,\Delta P_x + \Delta P_y\,]}{\rho V_T^2/2} - 1.25\ \ldots\ldots 5.3b$$

One branch running :

$$Q\,w\left[\frac{P_T}{w} + \frac{V_T^2}{2g}\right] = Q\,w\left[\frac{P_x}{w} + \frac{V_T^2}{2g}\right] + Q\,w\,\Delta H \qquad \ldots\ldots.5.4$$

$$\text{or}\quad \Delta H = \frac{P_T - P_x}{w} + \frac{V_T^2}{2g} - \frac{V_x^2}{2g}$$

In this case $V_x = 3\,V_T$,

$$CL = \frac{\Delta H}{V_T^2/2g} = \frac{\Delta P_x}{\rho V_T^2/2} - 8 \qquad \ldots\ldots\ldots5.4a$$

The values of $\Delta P/\rho V_T^2/2$ are plotted against dimensionless distance along the developed surface , x/D_T for trifurcation model II with transition along the three rows of piezometers separately as shown in Figures 11 to 19. The first and the last points correspond to B and I piezometers respectively. Because the entrance loss effect extends to some distance downstream also, the curve depicts appreciable curvature in the beginning . It is only after the point G, that the curve approximately terminates in a straight line. The slope of the straight portion which is approximately tangential at G represents to some scale the straight pipe friction per foot for a particular discharge and temperature This straight portion was produced upward till the end of the transition to get the value of $\frac{\Delta P}{\rho V_T^2/2}$ at G less the friction loss between the end of the transition and point G had there been normal flow. These corrected values of $\frac{\Delta P}{\rho V_T^2/2}$ when substituted in equations 5.1a to 5.1 c give values of loss coefficient for different conditions of operation for the trifurcation model II with transition. In the case of the trifurcation with abrupt entry it took a still greater distance for the flow to be stabilised after the trifurcation. At the point I normal flow conditions were considered to prevail and the value of $\frac{\Delta P}{\rho V_T^2/2}$ at I, duly corrected for friction between the trifurcation and point I was taken for estimating the loss coefficient . The established flow region in the branches of the Wye arrangement was found still further downstream of the junctions. The form loss was thought to be much more pronounced in this case due to comparatively greater deceleration and change in flow direction. No correction for friction loss was therefore made. Thus, the loss coefficient for the Wye though it includes friction losses also may be considered mainly due to form loss. The values of $\frac{\Delta P}{\rho V_T^2/2}$ in the branches at the last piezometers were taken for calculating the loss coefficient. The values of loss coefficients as computed for different models have been given in Table 7. From plotes of $\frac{\Delta P}{\rho V_T^2/2}$ versus dimensionless distance, it is obvious that for Re $> 10^5$, the loss coefficient is almost independent of Reynold's number.

The coefficients under different running conditions for the trifurcation model I studied by Juyal[9] , have also been re-calculated by plotting $\frac{\Delta P}{\rho V_T^2/2}$ values even after point F upto I because the flow conditions in the braches are not established as will be obvious from the curvature of the $\frac{\Delta P}{\rho V_T^2/2}$ curve in the vicinity of F.

The loss coefficients and the related data are tabulated in Table 8.

The minimum value of cavitation number

$$\sigma_{cr} = \frac{P_T - P_v}{\rho V_T^2 / 2} \qquad \text{for prototype comes to 90} \qquad (9)$$

corresponding to the three pipes running condition

This has been calculated on the assumption of the reservoir full condition i.e. total hydrastatic head in the reservoir being taken as 330 feet nearly.

-:o:-

CHAPTER - VI

DISCUSSION OF RESULTS

Table -4 shows the values of the loss coefficient and corresponding head losses for the different trifurcation models under different conditions of operation. Quite naturally the value of the loss coefficient are the maximum for the trifurcation with abrupt entry because of flow expansion following its separation and contraction. For this case, however, the lower values of loss coefficient in part running condition need explanation. It has been emphasized earlier also that the branch penstock in the model should be sufficiently long to cause normal flow conditions in the branch pipe after the trifurcation so that the section considered for applying energy principle for determination of loss coefficient does not fall in the disturbed zone. The slope of the straight portion of the pressure diagram along the penstock in the case of part running conditions for the trifurcation with abrupt entry is definitely greater than the normal friction slope obtained in the trifurcation with transition, indicating that for the abrupt transition, the observed loss coefficient may be lower than actual loss coefficients for part running conditions.

The loss coefficients or head loss for the Wye model continuously decrease as the flow changes from three pipes running condition to two pipes running condition and one pipe running condition. This result is understandable because in the case of three pipes running condition, the flow is bifurcated at two Wye junctions having maximum deflection as the flow enters the three individual penstock pipes, while in the case of two pipes running condition, the flow is bifurcated at onlyone Wye junction and experiences less deflection in entering two penstock pipes and in the case of single pipe running condition the flow is undivided and experiences deflection at only one point. Moreover, the velocities being progressively smaller as conditions change from three pipe running to two and one pipe running, deflection of stream lines is more easily accomplished. The loss coefficients in the case of trifurcation model II with transition is the least for three pipes running conditions and is maximum for two pipes running condition. We know that head loss is predominantly due to form resistance and in the case of three pipes running the form resistance is least because the fluid in each sector is gradually converged to the corresponding branch section with least deflection of stream lines. In the case of two pipes running conditions, flow from the third sector corresponding to the closed pipe is abruptly diverted towards the other two running branches and the flow has to split up into two branches besides having abrupt change in direction. Hence in two pipes running condition the loss coefficient is maximum. In the case of one pipe running condition, the whole flow converges to only one running pipe. The deflection of stream lines does occur but the flow does not split up as in the case of two pipes running. Due to the lower velocity of approach the stream lines can bend with less of energy loss as compared to the case of two pipes running condition. The value of the loss coefficient for trifurcation model I is least for three pipes running condition and maximum for one pipe running condition. As has been stated already, model I was tested by Juyal and loss coefficients have been calculated with the data obtained from his observations. Juyal has explained his results in his thesis [9].

Figure 10 gives velocity distributions for the three conditions of operation. The velocity distribution in the approach flow remains uniform for all conditions of operation but the velocity distribution in the branch pipe is definitely not uniform in the case of one pipe running condition. This is not unusual because due to deflection of stream lines velocity in the outerside of the bend is bound to be less than velocity in the inner side This effect is pronounced along the diameter perpendicular to AB because of the greater curvature of stream lines along the plane normal to AB. In the case of two pipes running, the non uniformity recorded is negligible.

Figures 11 to 19 give dimensionless pressure distributions along the transition surface and along the branch penstock for different conditions of operation of trifurcation model II. Figures 11 to 13 give dimensionless pressure variation along three critical planes for the condition of three pipes flowing. From these curves it is apparent that pressures o/ decrease gradually along the transition along all the three planes. At piezometer 17, however, a condition in the nature of a stagnation zone is indicated denoting a rise in local pressure.Such a condition at the corresponding point was also observed in the model I[9]. At this point the transition surface is such that the stream lines are convex towards the surface. After this point pressure decreases continuously along the transition.

Another remarkable feature of the pressure distribution curve is the slight increase in pressure resulting in a decelerating flow just after the transition. This indicates local separation at the end of the transition mf and the entry into the penstock. Still further downstream the pressure decreases continuously till the pressure line represents the straight pipe friction portion to some scale corresponding to normal established flow.

Figurres 14 to 16 give dimensionless pressure variation along the transition for two pipes running condition (model II). Figure 14 shows pressure variation along piezometers 1 to 7. Due to sudden convergence of stream lines at the entrance, the pressure drops suddenly and it increases gradually as the stream lines diverge and touch the surface. The pressure then decreases continuously with slight incfease after the transition for reasons already explained for the occurrence of similar phenomenon in the case of three pipes running condition and finally it decreases gradually to the straight pipe friction condition. The pressure decreases continuoesly along piezometers 8 to 16.

At piezometer 17 there is a slight increase in pressure similar to that observed under three pipes condition but it gradually decreases thereafter. Figure 16 shows that pressure variation in two pipes running condition is slightly different when the combination of running pipes is changed. This is mainly due to unsymmetrical location of piezometers for different combinations of running pipes. Assuming symmetrical flow, piezometers were located in the transition connecting only one branch pipe. Had the flow maintained radial symmetry in individual pipes also, this discrepancy would not have occured but the flow is not symmetrical in the transition for part running ; hence such apparent variation is not unusual.

Figure 17 to 19 depict dimensionless pressure variation along the transition for one pipe running condition (model II) . The pressure distribution is similar to that observed for two pipes running condition except that there is no indication of local separation at the piezometer 17; it is probably due to convergence of flow into a single filament.

Figure 20 shows the dimensionless pressure variation between F and I for model I. Figure 21 and 23 give dimensionless pressure distribution along the direction of flow for different conditions of operation for trifurcation model III with abrupt entry. These curves are self explanatory. Due to abrupt convergence of flow at the entry the pressure decreases suddenly, then it increases till the jet touches the surface of the branch penstock and finally it starts decreasing to attain the straight pipe friction condition. It can be seen that the slope of the tangent at the extremity of the pressure variation curves, particularly for part running conditions, is comparatively steeper as discussed previously.

Figure 24 gives the dimensionless pressure variation along different branches for the Wye model for the condition of all the three pipes running. Due to convergence and deflections of flow in the branches, the pressure distribution in branches I and II is similar to that in trifurcation with abrupt entry. The pressure in branch III is gradually decreasing because there is no sharp change in direction of flow in this branch. Even for part running conditions, the pressure distribution in various branches is similar to the pressure distribution for three pipes running condition except that the values of $\frac{\Delta P}{\rho V_T^2/2}$ decrease progressively for two pipes running and one pipe running conditions. The maximum value of $\frac{\Delta P}{\rho V_T^2/2}$ in case of model III with abrupt entry is 69.2 as compared to 66.4 and 61.5 for model I and model II respectively. These values are less than 90 hence the possibility of cavitation is ruled out in the prototype.

Table 4 gives head losses for various models under different conditions of opefation. The comparative values of head losses may be considered as a measure of the hydraulic efficiency of the models. Hydraulic efficiency of model II is best under the conditions of three pipes running and if the data of model I for loss coefficient computations under conditions of two pipes running be taken as correct, model I is hydraulically best for two pipes running condition. Obviously the Wye model has maximum hydraulic efficiency for single pipe running condition. Model II is hydraulically more efficient than model I at single pipe running condition also. Similarly model II is hydraulically more efficient than Wye model under two pipes running condition as well. Hence considering the possibility of Ram Ganga Project being used as a peaking station, the weighted average head loss for Model II corresponding to the actual operation of the turbines to meet the fluctuating load demand may be the least. Hence Model II may be considered as representing hydraulically most efficient arrangement. Model I is also superior to the Wye model for the conditions of three pipes running. Hence weighted average of head loss for model I may work out to be smaller than the weighted average of head loss for the Wye model; thus model I may be considered to be hydraulically second best. Model III with abrupt trifurcation is hydraulically the worst; thus

Wye arrangement is superior to abrupt trifurxcation from considerations of head loss at the junctions. But due considerations will have to be given to losses due to friction, bends, valves etc., between the junction and feeding point of branch penstocks before judging the superiority of model I or II over the Wye proposal. In general, friction losses in the Wye proposal are expected to be less, hence the relative merit of the Wye arrangement as judged by head loss due to branching alone can not be taken as conclusive.

The suitability of a particular arrangement should be decided by economic considerations also. Economic considerations may include cost of penstock, cost of branching system, cast of valves and capitalised cost of power loss. Head loss is converted to power loss, Capitalised value of which is calculated for an assumed life of the penstock. The following computations may give some approximate idea of capitalised value of head losses due to different branching arrangement.

Unit loss for one cusec equivalent discharge and one foot head loss at 85 percent plant efficiency is

$$0.85 \times \frac{62.4 \times 0.746}{550} \times 365 \times 24 = 630 \text{ KWh/year}$$

The generation cost per KWh at the bus bar is Rs. 0.0341

Thus, unit loss comes to Rs. 21.50 per year.

Assuming the life of the penstock to be 40 years, the rate of interest 5.5 percent.

Capitalised value of an annual loss of Re. 1/- for 40 years at the rate of 5.5 percent is

$$\text{Rs.} \quad \frac{1.055^{40} - 1}{0.055 \times 1.055^{40}} = \text{Rs. } 16.06$$

Therefore capitalised value of annual head loss is

$$\text{Rs. } 21.50 \times 16.06 \times Qhf = \text{Rs. } 18.0hf \text{ lacs}$$

where Q is the equivalent discharge of 5320 cusecs and hf is head loss in feet . The values of bus bar power rate, life of penstock, rate of interest, equivalent discharge etc., have been taken from Design memorandum 9 and 9B of Ram Ganga River Project.

The head loss computed in Table 4 for different trifurcation arrangements has been computed for maximum discharge and corresponding proportions thereof for part running condition of 8320 cusecs. These values will get reduced in the proportion $(5320/8320)^2 = .41$ when computed for equivalent discharge of 5320 cusecs. Reduced values of head losses together with corresponding capitalised costs are given in Table 3 for comparison

TABLE - 3

Models	OPERATING CONDITIONS AND CAPITALISED VALUES OF LOSSES					
	3 pipes running loss of head in ft.	Capitalised values in lacs of Rs.	2 pipes running loss of head in ft.	Capitalised values in lacs of Rs.	1 pipe running loss of head in ft.	Capitalised value in lacs of Rs.
Model I with transition	1.78	32.04	1.875	33.7	2.38	42.80
Model II with transition	1.496	27.0	1.94	34.9	1.60	28.80
Model Wye	2.59	46.65	2.07	37.3	0.894	16.10
Model III with abrupt entry	3.14	56.32	3.14	56.52	2.99	53.8

As discussed earlier, the total head losses to be considered for comparing different branching arrangement should include friction, bend, valve , losses, etc., similarly capitalised values of total head losses with a particular branching arrangement should have been considered for comparison. Neverthless, a glance at the capitalised values of head losses due to particular branching arrangement reveals a saving of the order of Rs. 25 to 30 lacs in adopting trifurcation with suitab-le transition as compared to an abrupt entry junction and a saving of the order of Rs. 10 to 15 lacs in adopting trifurcation with suitable transition as compared to the Wye arrangement.

Generally the cost of the penstock with Wyes may be slightly less than the cost of penstock, cost of plugging etc in the trifurcation arrangement with transition . Hence while making economic studies to decide any particular arrangement of branching, cost of penstock, and other appurtenances should also be considered.

The values of the loss coefficient or head loss in case of penstock trifurcation model tested for Round Butte Dam(3) are less than the values of loss coefficient for trifurcation model I or II tested here. But from the locations of the piezometers in Round Butte Trifurcation model, it is obvious that no piezometers were located downstream of branch penstock to record the pressure, at a section of normal flow. The loss of energy due to flow through trifurcation is not only associated to the region of trifurcation, rather its effect is carried in the branch downstream till the normal flow condition is reached. The following values of loss coefficients as computed by applying energy principle between a normal approach flow section and a normal branch flow section instead of considering a section just after the transition in the branch pipe, in case of models I and II suggest the importance of selecting a normal flow section after the trifurcation.

Models	CL_1 (Three pipes running) considering normal flow section in the branch	CL_1 (Three pipes running) considering section just after transition
Model I	1.14	0.44
Model II	0.96	0.20

Hence the results of Round Butte Trifucation models can not be taken for comparison.

The various trifurcation arrangements, tested for hydraulic losses in the present study had certain limitations. The diameter of the main penstock was fixed as 26 feet which limited the diameter of branch penstocks to 10 feet each. An alternative arrangement of trifurcating into penstocks of 11.5 feet diameter from a main penstock of 28 feet diameter has been mentioned in design memorandum 9B of Ram Ganga Project and comparative cost given in the design memorandum has proved the economic superiority of this alternative arrangement. From, hydraulic considerations also this alternative arrangement will prove better because the decrease in velocity of approach flow at the trifurcation will reduce the head loss in proportion to the square of the velocity. Besides, the area ratio of convergence decreases from 2.25 to 1.98, hence the head loss will further decrease. In the prototype the 10 feet diameter branch is enlarged to the penstock diameter of 13.5 feet which continues to the wall of the power house. It is felt that instead of trifurcating 26-feet diameter main penstock to 10 feet dia branch penstocks and then expanding the 10 feet dia to 13.5 feet, if 26-feet dia conduit could be expanded to 31 feet first and then trifurcated to 13.5 feet dia branches, hydraulic losses might get further reduced and this proposal may prove economical as well.

The Wye branches provided in the present studies could also be further modified to give decreased hydraulic losses. Figure 8 gives a recent modification of y branching over the conventional arrangement and figure 9 gives the improvement in the loss coefficient values due to such modifications. The marked improvement in the loss coefficient indicates the advantages of adopting such improved Wye branching.

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CHAPTER - VII

CONCLUSIONS AND RECOMMENDATIONS

From the present investigation, the following conclusions are drawn :

1. By streamlining the trifurcation of a penstock as described for models I and II, it is possible to reduce the length of transition in comparison to other conventional practices such as two Wyes and trifurcation with tie rod. A transition length of 24 feet has been adopted for models I and II to trifurcate a 26 feet diameter main penstock into three 10 feet diameter branch penstocks. For Round Butte Dam a transition length of 39'-4.75" has been adopted to connect main penstock diameter of 23 feet to branch diameter of 13 feet 7 inches. By stream lining the trifurcation with elliptical curves it became possible to reduce the transition length to nearly two thirds of the transition length adopted for Round Butte Dam. The trifurcation models I and II, described in this thesis give symmetrical branching of the flow with respect to the approach flow, and the flow is not virtually deflected. These models donot require any special arrangement like tie rod which may lead to increased loss and the vibrations of the structure.
2. The pressure diagrams indicate that the longitudinal streamlining adopted for models I and II is adequate to affect a rapid establishment of flow downstream

from the transition. The uniform velocity distribution of the approach flow in the model is similar to the velocity distribution of smooth turbulent flow in pipes at high Reynold's number.

3. The loss coefficient for three pipes running condition is less than the loss coefficients for part running conditions because abrupt deflection of stream lines occurs in part running conditions. The loss coefficient for three pipes running condition is 0.19 for model II against 0.40 for abrupt entry. Thus it can be seen that due to stream lining the flow with elliptical transitions the loss coefficient is reduced to nearly fifty percent.

4. Models I, II and III were tested for the range of Reynold's number of nearly 1×10^5 to 4×10^5 in the approach tunnel. The values of $\frac{\Delta P}{\rho V_T^2/2}$ are found to be almost independent of Reynold's number. Hence for Reynold's number above 10^5 of the approach flow, the head loss coefficient in the trifurcation is almost independent of Reynold's number.

5. The loss of head in trifurcation model I or II is less than the loss of head in the Wye arrangement for the condition of three pipes running. However, the loss of head in the case of single pipe running is least for the Wye arrangement. But friction and losses due to bends, valve etc., are more in the cases of three pipes

stress resistant steel plates which have to be imported. But the construction of the trifurcation represented in model I and II is not that much expensive because it is laid in reinforced cement with ordinary steel lining. Hence the choice of the trifurcation with suitable transition (Model I or II) is considered the best from economical point of view as well as from its hydraulic performance.

RECOMMENDATIONS :

1. Hydraulic losses for a 31 feet dia penstock trifurcating to 13.5 feet diameter branches, may be determined by model studies so that a proposal of expanding the 26-feet diameter penstock to 31 feet diameter and then trifurcating to 13.5 feet diameter branches could be compared with the present trifurcation arrangement.
2. Although the length of transition appears to be ideal for the present case, the study regarding the effect of variation in transition length on loss coefficient in such trifurcation with elliptical transition curves may prove very useful.
3. The effect of change in area ratio of main penstock and its branches will also give very useful information.
4. The loss coefficients for Wye branches modified on the lines of ISHERWYSS Wye branches for various

deflection angles and area ratios may also be investigated by model studies.

5. While representing a model in the Laboratory care should be taken to ensure that sufficient reach both upstream and downstream of the test section is represented so that the approach flow as well as the flow in downstream portion are fully established. For accurate determination of pressure at any section in the disturbed zone , mean of at least four numbers of piezometer readings, recorded along the circumference should be taken as the average pressure at that section.

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TABLE - 4

S. No.	Model	Three pipes running			Two pipes running			One pipe running		
		$CL_1 = \frac{\Delta H}{V_T^2/2g}$	$CL_2 = \frac{\Delta H}{V_T^2/2g}$	Prototype head loss in feet	CL_1	CL_2	Head loss in feet	CL_1	CL_2	Head loss in feet
1.	Trifurcation with transition, Model I	1.14	0.225	4.34	2.7	0.237	4.57	13.7	0.299	5.81
2.	Trifurcation with transition, Model II	0.96	0.189	3.65	2.8	0.246	4.74	9.2	0.201	3.91
3.	Trifurcation with abrupt entry, Model III	2.01	0.396	7.65	4.52	0.396	7.65	17.2	0.376	7.30
4.	Trifurcation by two Wye junctions	1.66	0.328	6.32	2.96	0.26	5.01	5.15	0.112	2.18

TABLE - 5

Angle which the profile makes with the bisector	Model		Prototype	
	Major axis inches	Minor axis inches	Major axis ft	Minor axis ft
0^{o}	13.2	1.573	16.5	1.967
10^{o}	13.8	1.136	17.25	1.421
20^{o}	14.3	1.901	17.875	1.126
30^{o}	14.8	0.827	18.5	1.033
40^{o}	15.3	0.901	19.125	1.126
50^{o}	15.8	1.136	19.75	1.421
60^{o}	16.45	1.573	20.56	1.967
70^{o}	17.2	2.301	21.50	2.876
80^{o}	18.2	3.509	22.75	4.386
87.66^{o}	19.2	5.023	24	6.278
90^{o}	19.2	4.781	24	5.976
100^{o}	19.2	3.866	24	4.832
110^{o}	19.2	3.079	24	3.849
120^{o}	19.2	2.452	24	3.032
130^{o}	19.2	1.901	24	2.376
140^{o}	19.2	1.494	24	1.868
150^{o}	19.2	1.193	24	1.491
160^{o}	19.2	0.987	24	1.233
170^{o}	19.2	0.866	24	1.083
180^{o}	19.2	0.827	24	1.033

TABLE-6

X_1/L	Model area of cross section ft^2	Prototype area of cross section sq.ft.	A/A_T	$V/V_T = A_T/A$
0	0.785	176.587	1.0	1.0
0.0104	0.738	165.992	0.94	1.07
0.0208	0.718	161.577	0.915	1.09
0.0312	0.695	156.279	0.885	1.12
0.052	0.675	151.865	0.86	1.16
0.104	0.612	137.738	0.78	1.28
0.156	0.571	128.555	0.728	1.37
0.208	0.537	120.786	0.684	1.46
0.26	0.501	112.663	0.638	1.56
0.312	0.475	106.836	0.605	1.65
0.417	0.435	97.829	0.554	1.80
0.52	0.402	90.413	0.512	1.95
0.625	0.381	85.654	0.485	2.06
0.734	0.364	81.760	0.463	2.15
0.833	0.351	78.934	0.447	2.23
1.0	0.348	78.249	0.443	2.26

TABLE - 7

A. LOSS COEFFICIENT FOR MODEL II WITH TRANSITION.

Run No.	V_T Average velocity in main penstock ft/sec	Reynold's No. of flow in main penstock	V_p/V_T	$\frac{\Delta P}{\rho V_T^2/2}$	$CL_1 = \frac{\Delta H}{V_T^2/2g}$	$CL_2 = \frac{\Delta H}{V_p^2/2g}$	Remarks
1	38.5	4.07×10^5					
2	37.6	4.0×10^5	2.25	5.02	0.96	0.189	Three pipes running
3	26.0	2.7×10^5					
4	17.1	1.77×10^5					
5	16.9	1.906×10^5					Two pipes running side pipe closed
6	24.9	2.65×10^5	3.38	13.2	2.8	0.246	
7	17.55	1.87×10^5					Lower pipe closed
8	24.10	2.43×10^5					Lower pipe closed
9	8.85	0.936×10^5	6.76	54.0	9.2	0.201	Single pipe running
10	11.29	1.23×10^5					

TABLE 9 (Continued)

B. LOSS COEFFICIENTS FOR MODEL III WITH ABRUPT ENTRY

Run No.	V_T Average velocity in main penstock ft/sec	Reynold's No. of flow in main penstock	V_p/V_T	$\frac{\Delta P}{\rho V_T^2/2}$	$CL_1 = \frac{\Delta H}{V_T^2/2g}$	$CL_2 = \frac{\Delta H}{V_p^2/2g}$	remarks
1	31.95	3.35×10^5					
			2.25	6.07	2.01	0.396	Three pipes running
2	37.0	3.93×10^5					
3	25.1	2.53×10^5					Two pipes running
			3.38	14.44	4.04		Side closed
4	21.5	2.18×10^5					
5	23.6	2.44×10^5		15.40	5.0		Lower pipe closed
					Av = 4.52	0.396	
6	10.0	1.027×10^5					
			6.76	62	17.2	0.376	Single pipe running
7	11.85	1.21×10^5					

TABLE - 7 (Continued)

C. LOSS COEFFICIENTS FOR THE WYE MODEL

Run No.	V_T ft/sec in 23.4 ft dia tunnel	Reynold's No. of flow (Approach flow)	$\Delta P_1 / \rho V_T^2/2$	$\Delta P_2 / \rho V_T^2/2$	$\Delta P_3 / \rho V_T^2/2$	CL $\Delta H / \frac{V_T^2}{2g}$	CL_1, Converted in terms of velocity=26 ft dia. tunnel	Equivalent CL_2 for comparison.	Remarks
1	9.45	0.885×10^5	0.95	1.0	1.30	1.08	1.66	0.328	Three pipes running
2	6.13	0.586×10^5	3.17	3.17	-	1.92	2.96*	0.26	Two pipes running Br. I and II
3	6.44	0.615×10^5	2.11	-	2.54	1.075	1.65	0.145	Br. I and III
4	7.0	0.667×10^5	-	2.53	2.08	1.075	1.65	0.145	Br. II and III
5	3.72	0.348×10^5	11.35	-	-	3.35	5.15*	0.112	One pipe running. Branch I.
6	3.72	0.348×10^5	-	11.35	-	3.35	5.15	0.112	Branch II
7	4.67	0.437×10^5	-	-	10.85	2.85	4.37	0.0954	Branch III

* In part running the maximum value of loss coefficient was adopted for comparison with other models.

TABLE - 8

LOSS COEFFICIENTS FOR MODEL I WITH TRANSITION (9)

Run No.	V_T Average velocity in main penstock ft/sec	Reynold's No. of flow in main penstock	V_p/V_T	$\frac{\Delta P}{\rho V_T^2/2g}$ from pressure diagram	CL_1 $\frac{\Delta H}{V_T^2/2g}$	CL_2 $\frac{\Delta H}{V_p^2/2g}$	Remarks
3	29.4	2.8×10^5					
4	33.2	3.2×10^5	2.25	5.2	1.14	0.225	Three pipes running
5	39.0	3.7×10^5					
6	17.6	1.7×10^5					
7	27.0	2.5×10^5	3.38	13.1	2.7	0.237	Two pipes running
8	8.28	0.8×10^5					
9	12.83	1.2×10^5	6.76	58.5	13.7	0.299	One pipe running

TABLE - 9

A. LOCATION OF PIEZOMETERS IN MODEL II WITH TRANSITION

Piezometer	Distance x/D_T	Piezometer	Distance x/D_T	Piezometer	Distance x/D_T
B	0.0	B	0.0	B	0.0
C	0.578	C	0.578	C	0.578
D	0.67	D	0.67	D	0.67
E	0.72	E	0.72	E	0.72
Transition starts	0.78	Transition starts	0.78	Transition starts	0.78
1	0.923	8	0.802	17	0.826
2	0.972	9	0.851	18	0.874
3	1.02	10	0.90	19	0.923
4	1.065	11	0.95	20	0.973
5	1.21	12	1.09	21	1.115
6	1.35	13	1.24	22	1.265
7	1.50	14	1.305	23	1.425
Transition ends	1.55	15	1.53	24	1.56
F	1.67	16	1.675	25	1.70
G_1	2.13	Transition ends	1.71	Transition ends	1.785
G	2.70	F	1.83	F	1.902
H	3.85	G_1	2.29	G_1	2.36
I	5.02	G	2.86	G	2.93
		H	4.02	H	4.09
		I	5.17	I	5.25

Table - 9 (Continued)

B. LOCATION OF PIEZOMETER IN MODEL III WITH ABRUPT ENTRY

Piezomter	B	D	Abrupt junction	F_1	F_2	F	G	H	I
Distance x/D_T	0	0.67	0.78	0.935	1.505	1.925	2.66	3.82	5.25

C. LOCATION OF PIEZOMETER IN THE WYE ARRANGEMENT.

Piezometer	3	4(Branch I starts)	4a	4b	4c	4d
Distance x/D_T	0	1.07	2.33	3.05	4.21	4.50
Piezometer	5	6 (Branch II starts)	6a	6b	6c	
Distance x/D_T	2.76	3.78	4.50	5.95	6.53	
Piezometer	7	8	9	10		
Distance x/D_T	4.92	6.97	7.52	8.1		

(D_T = 20.8 inches
(x is measured from
(piezometer 3 located
(at a distance of 21.5
(inches upstream of
(branch I.

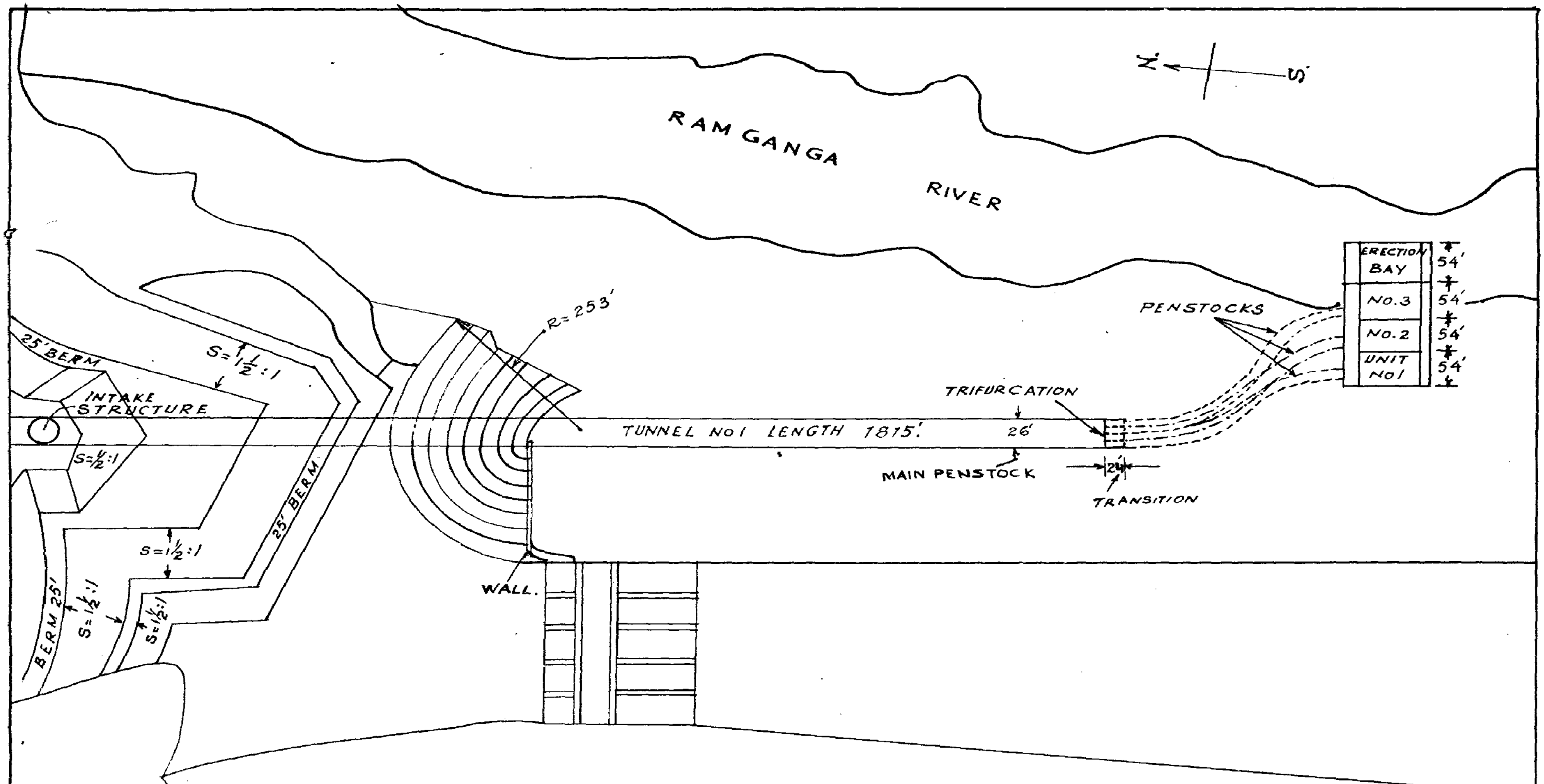


FIG. 1 LAYOUT OF TUNNEL & PENSTOCK

NOT TO SCALE

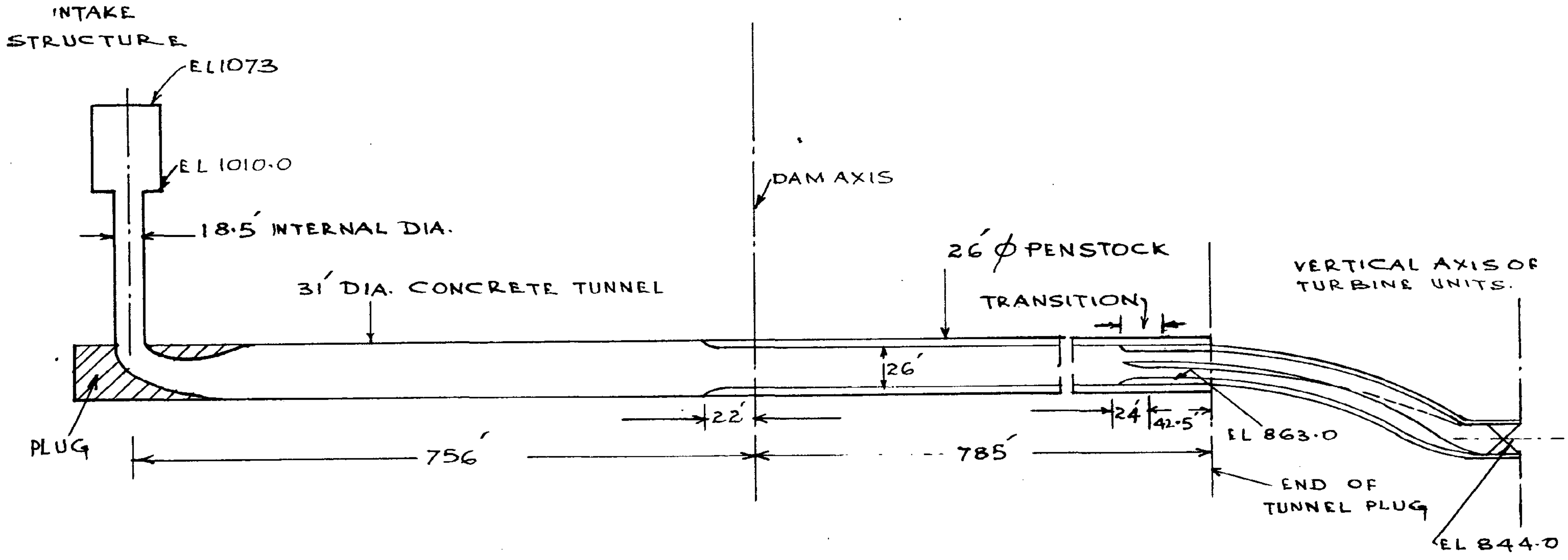


FIG. 2. ALONGITUDINAL SECTION OF TUNNEL & PEN STOCK
[NOT TO SCALE]

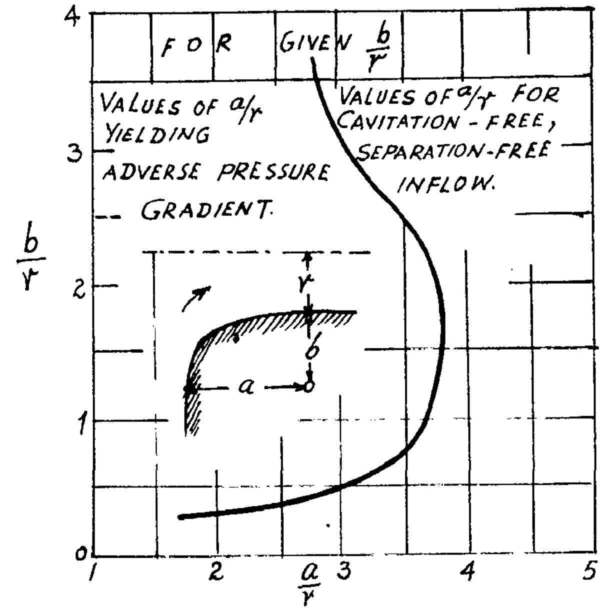
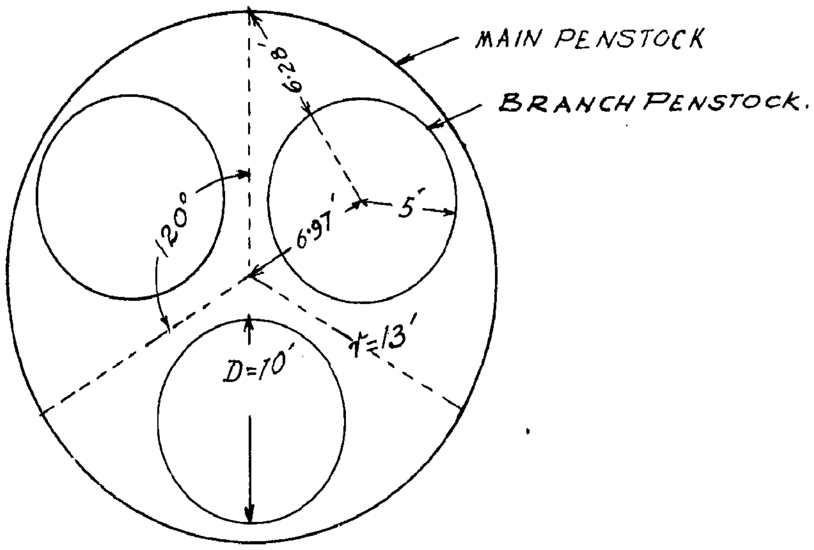


FIG. 4 CHARACTERISTIC OF ENTRANCES HAVING ELLIPTICAL PROFILES.

(TAKEN FROM THE BOOK "ENGINEERING HYDRAULICS" EDITED BY ROUSE).



FIC.3 [illegible]

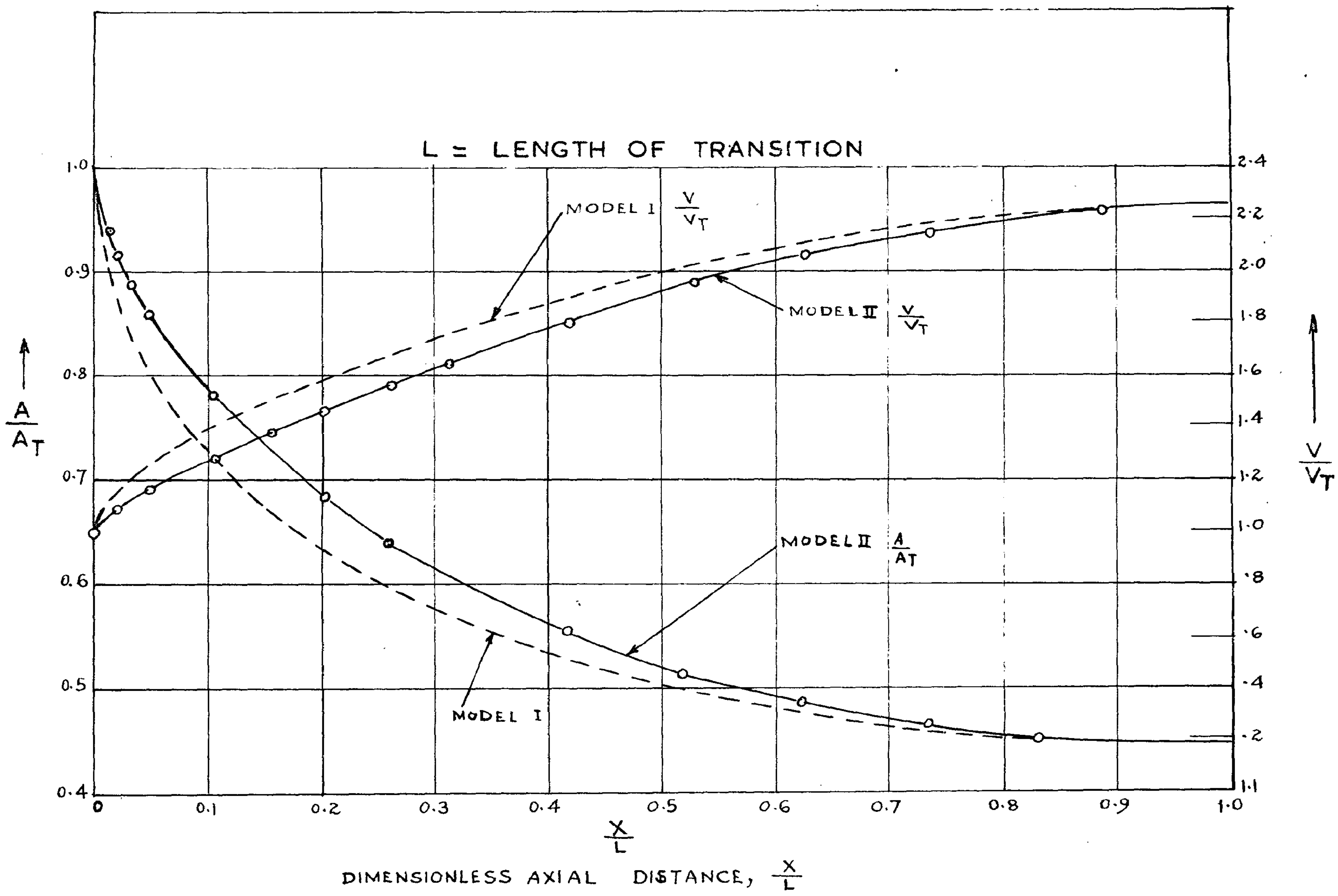


FIG. NO. 5 CROSS SECTIONAL AREAS AND MEAN VELOCITIES ALONG THE TRANSITION LENGTH.

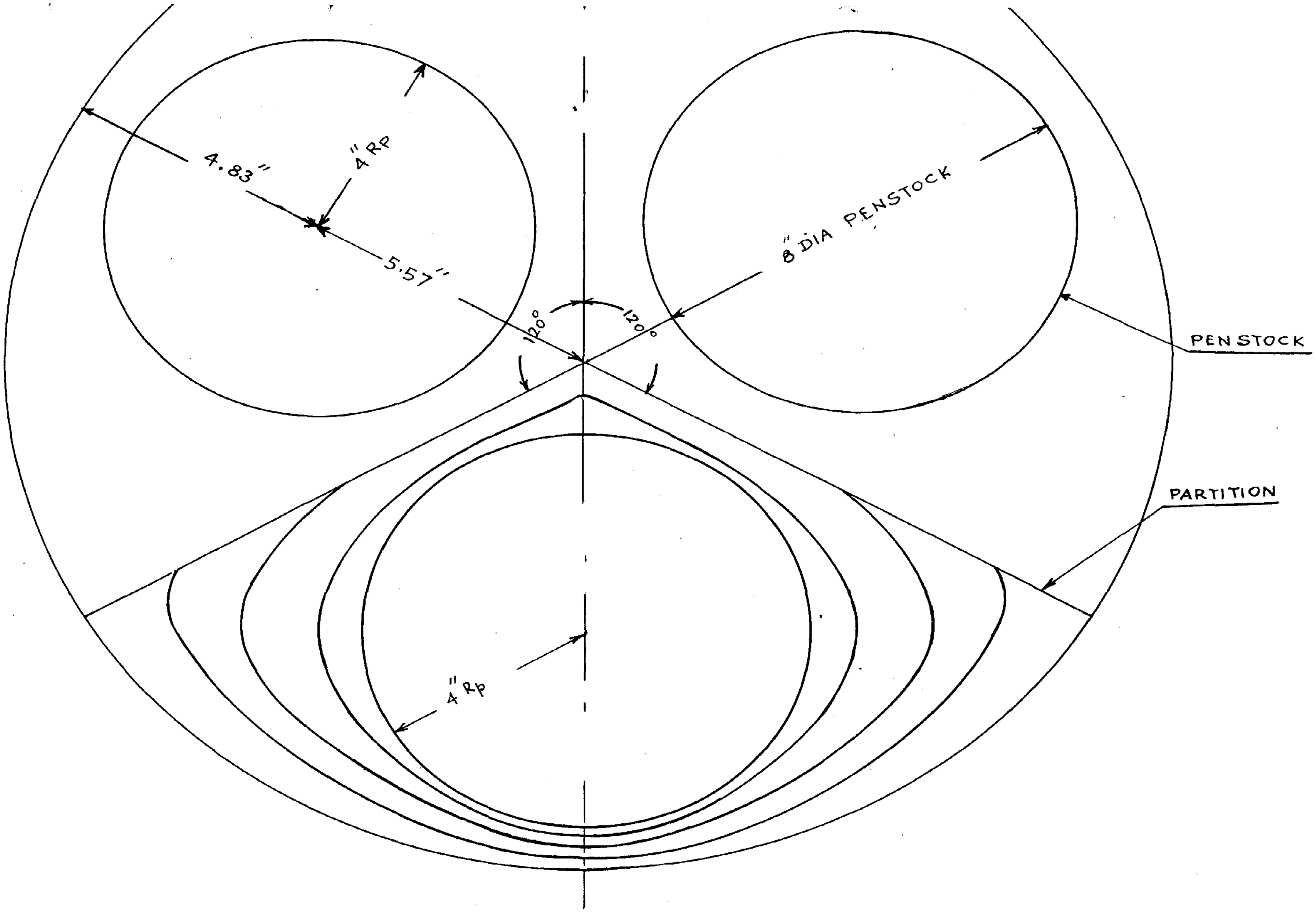


FIG. NO. 6 - APPROACH PENSTOCK AND THE THREE BRANCHPIPES.

(CROSS SECTIONS)

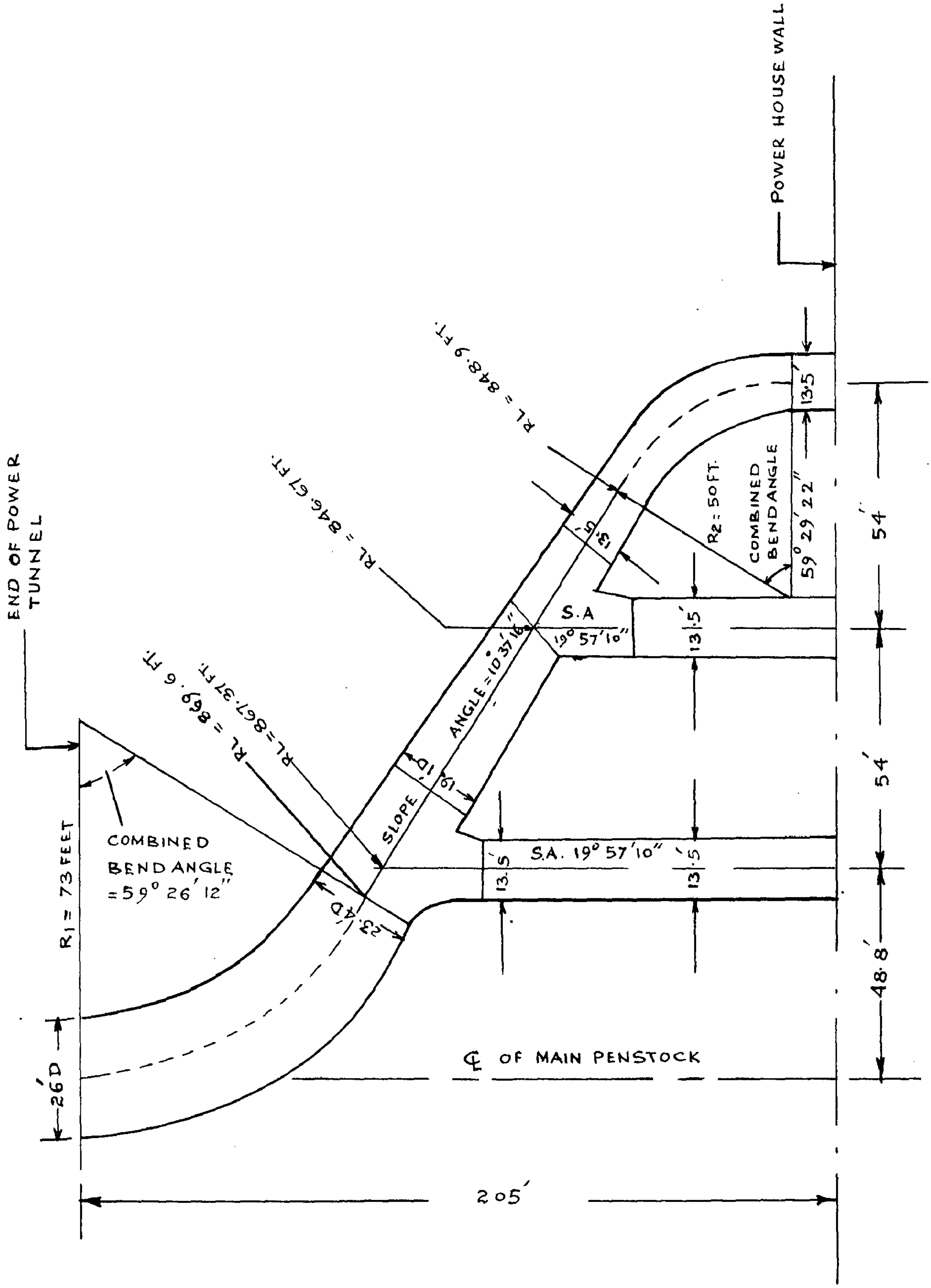


FIG.NO.7 PLAN OF PROPOSED WYE ARR...

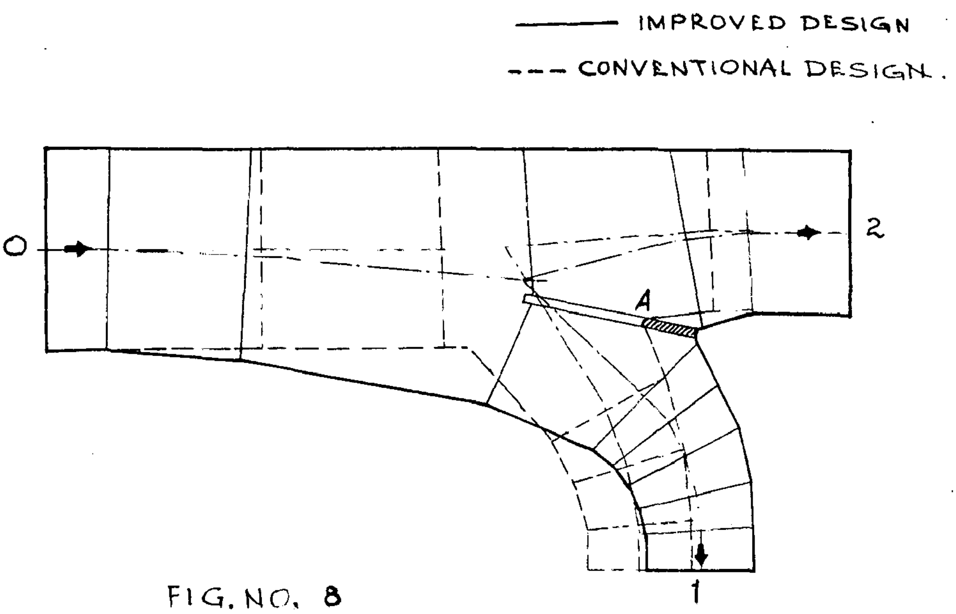
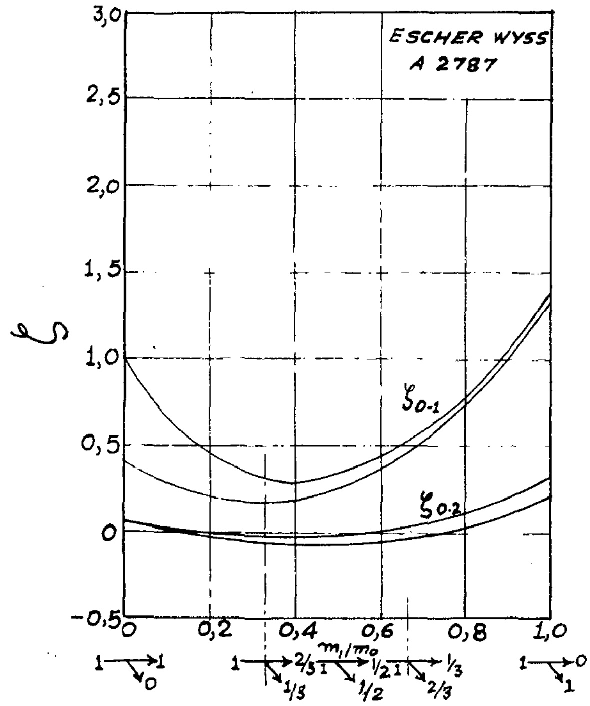


FIG. NO. 8



$$\zeta_{0-1} = \frac{\Delta H_{0-1}}{\frac{V_0^2}{2g}}$$

$$\zeta_{0-2} = \frac{\Delta H_{0-2}}{\frac{V_0^2}{2g}}$$

FIG. NO. 9

[TAKEN FROM ESCHER WYS NEWS VOLUME 39, 1966 No.2]

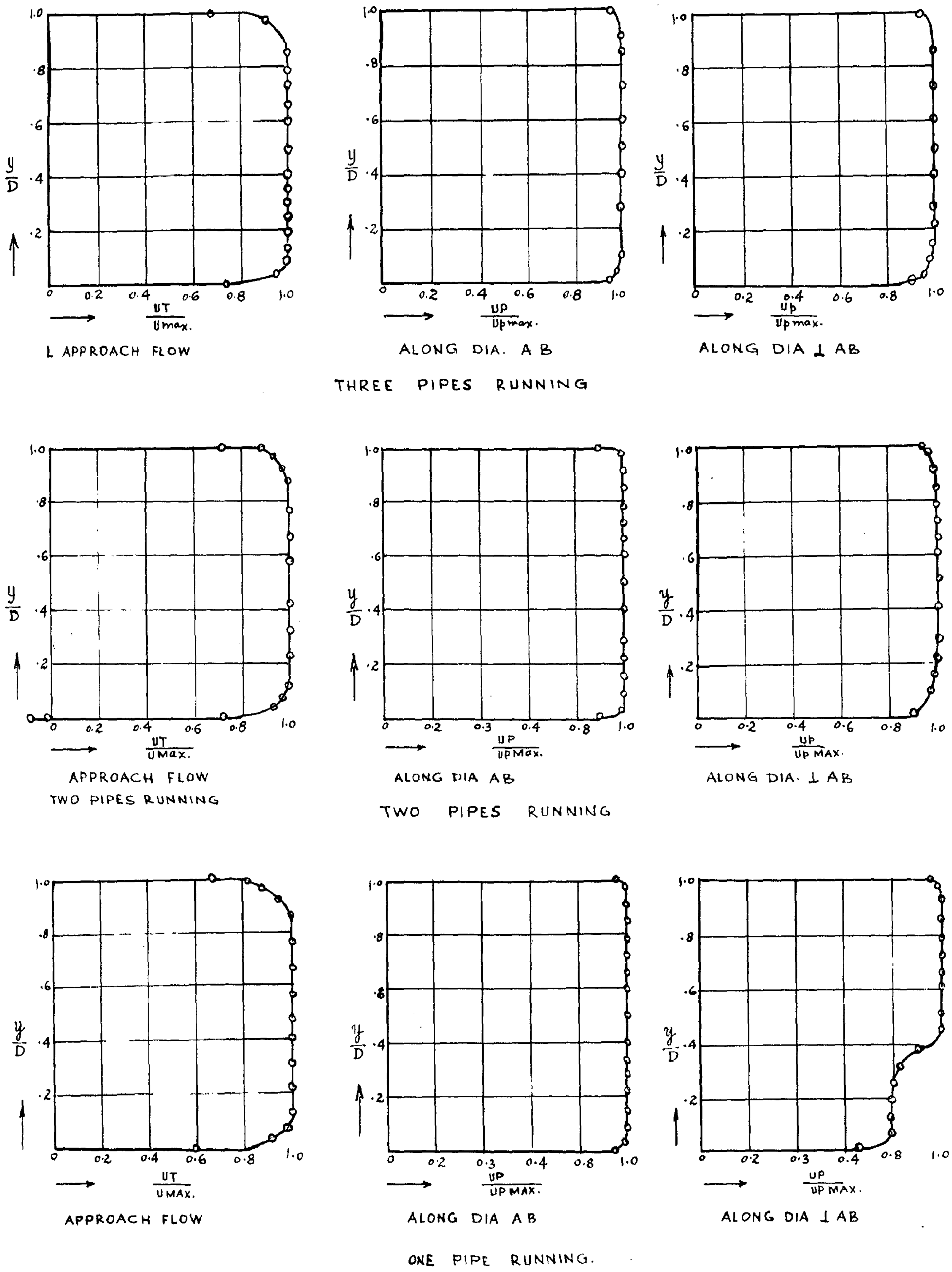


FIG. NO. 10 DIMENSIONLESS VELOCITY PROFILES

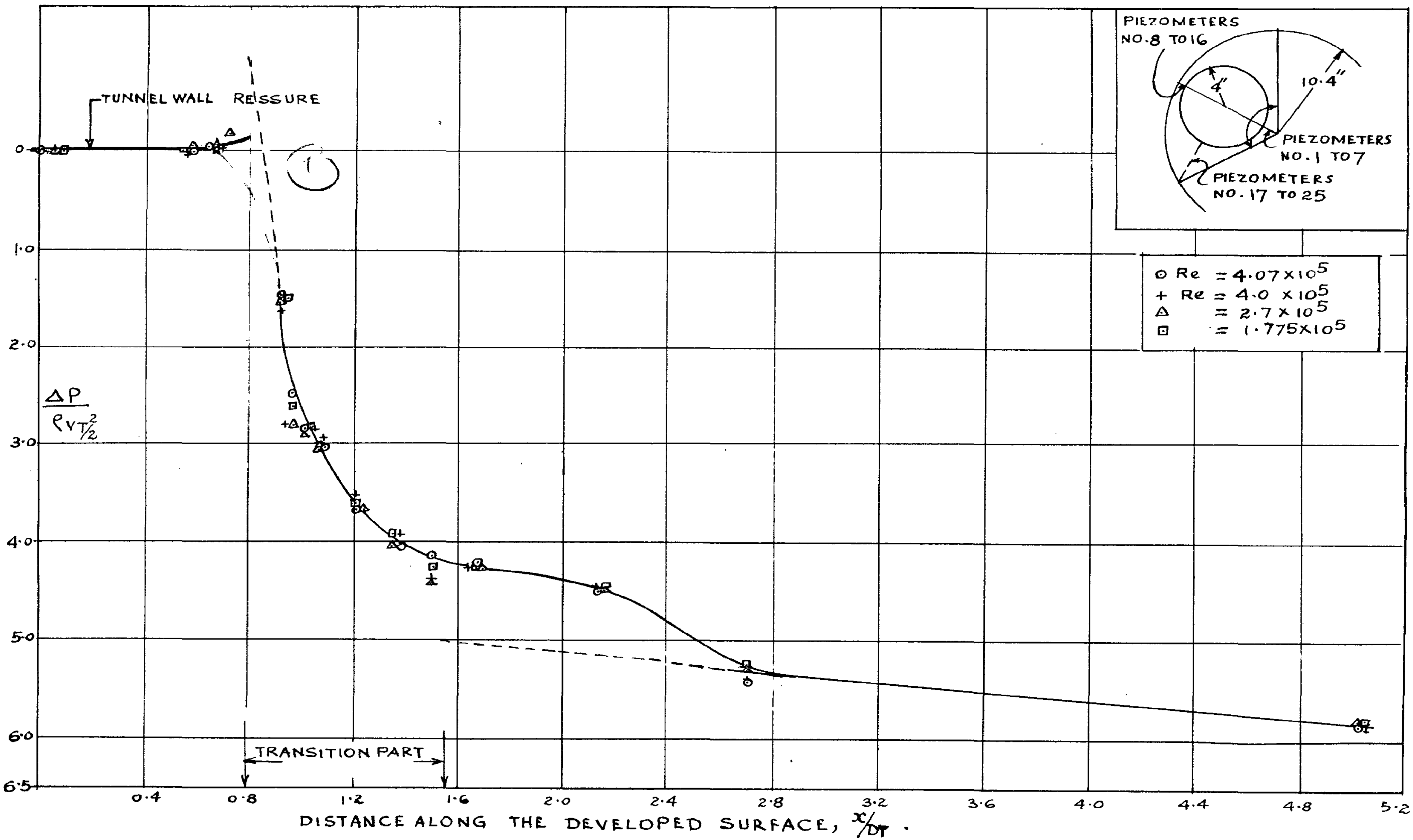


FIG. NO. 11 DIMENSION LESS PRESSURE DISTRIBUTION ALONG PIEZO NO. 1 TO 7.

(THREE PIPES RUNNING)

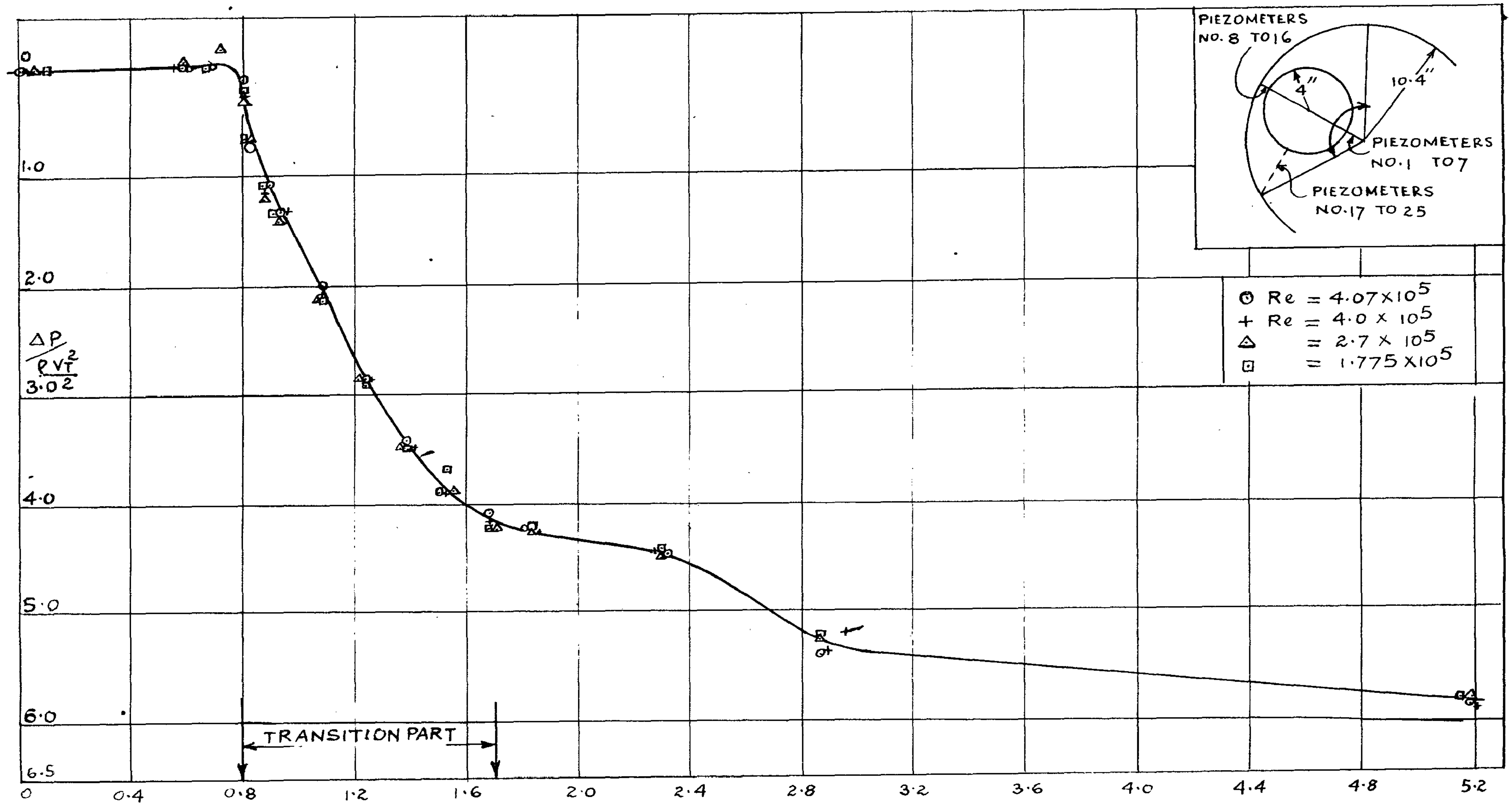


FIG. NO. 12 DIMENSION LESS PRESSURE DISTRIBUTION ALONG PIEZO NO. 8 TO 16

(THREE PIPES RUNNING)

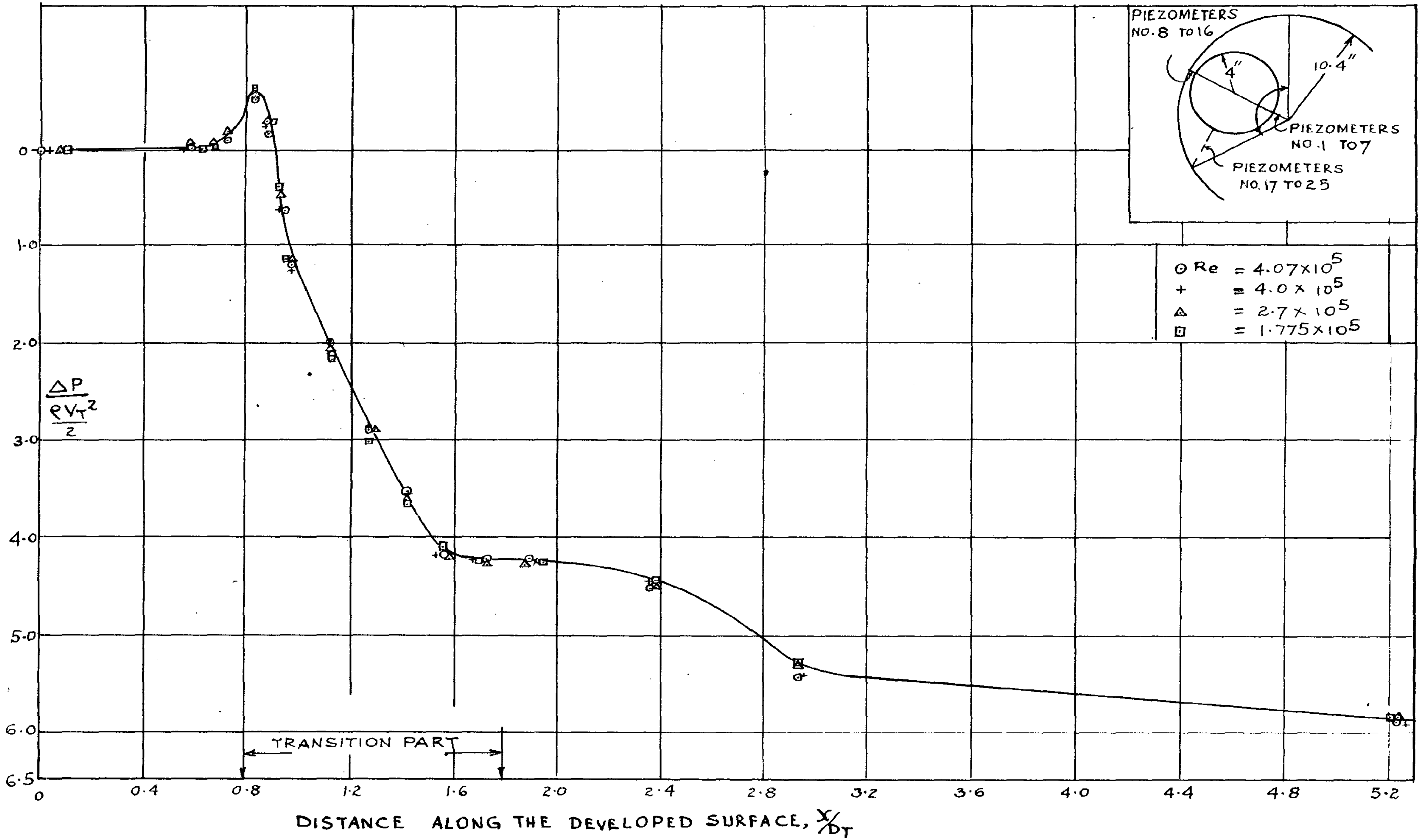


FIG. NO. 13 DIMENSION LESS PRESSURE DISTRIBUTION ALONG PIEZ. NO. 17 TO 25

(THREE PIPES RUNNING)

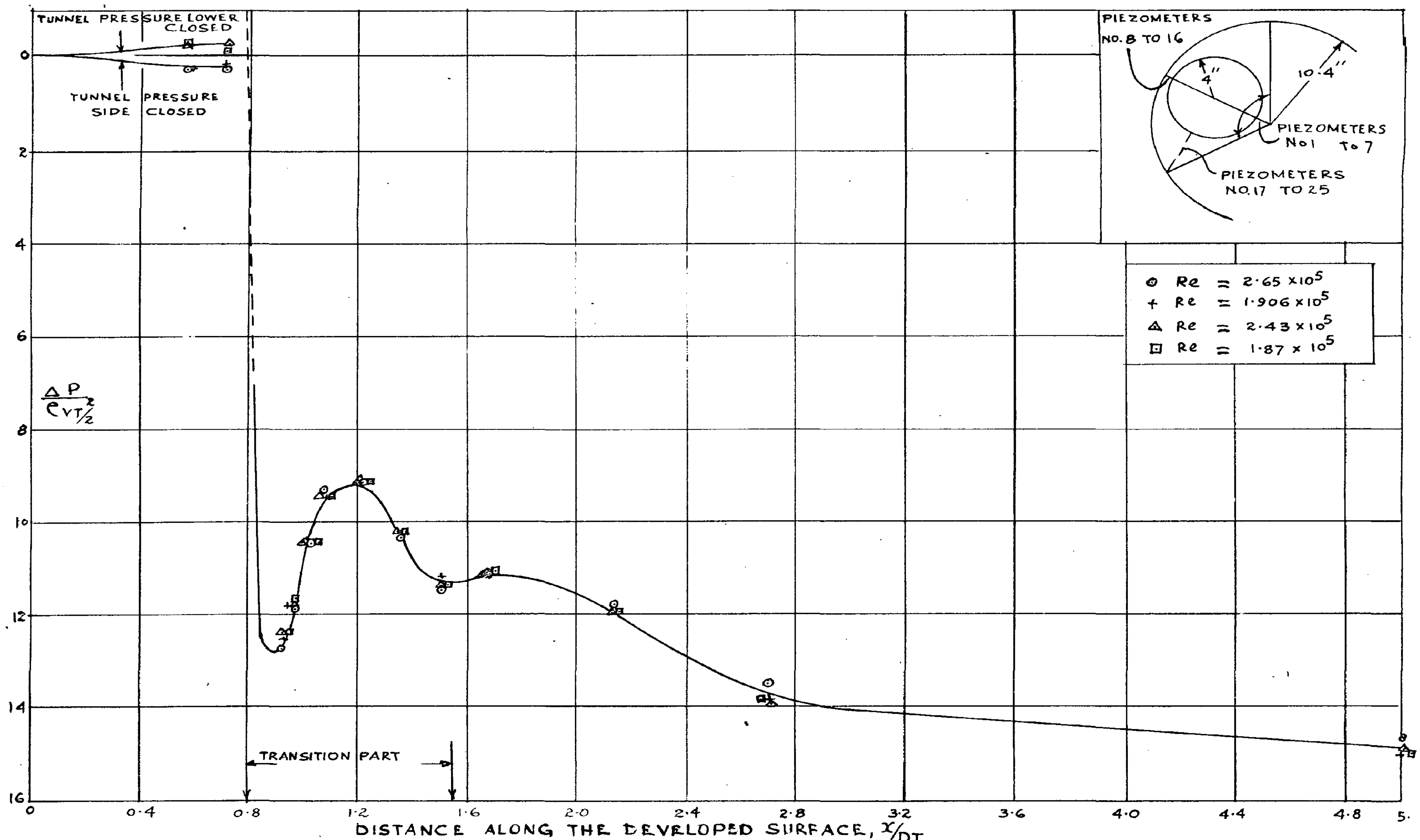


FIG. NO. 14 DIMENSIONLESS PRESSURE DISTRIBUTION ALONG PIEZO NO. 1 TO 7.
(TWO PIPES RUNNING)

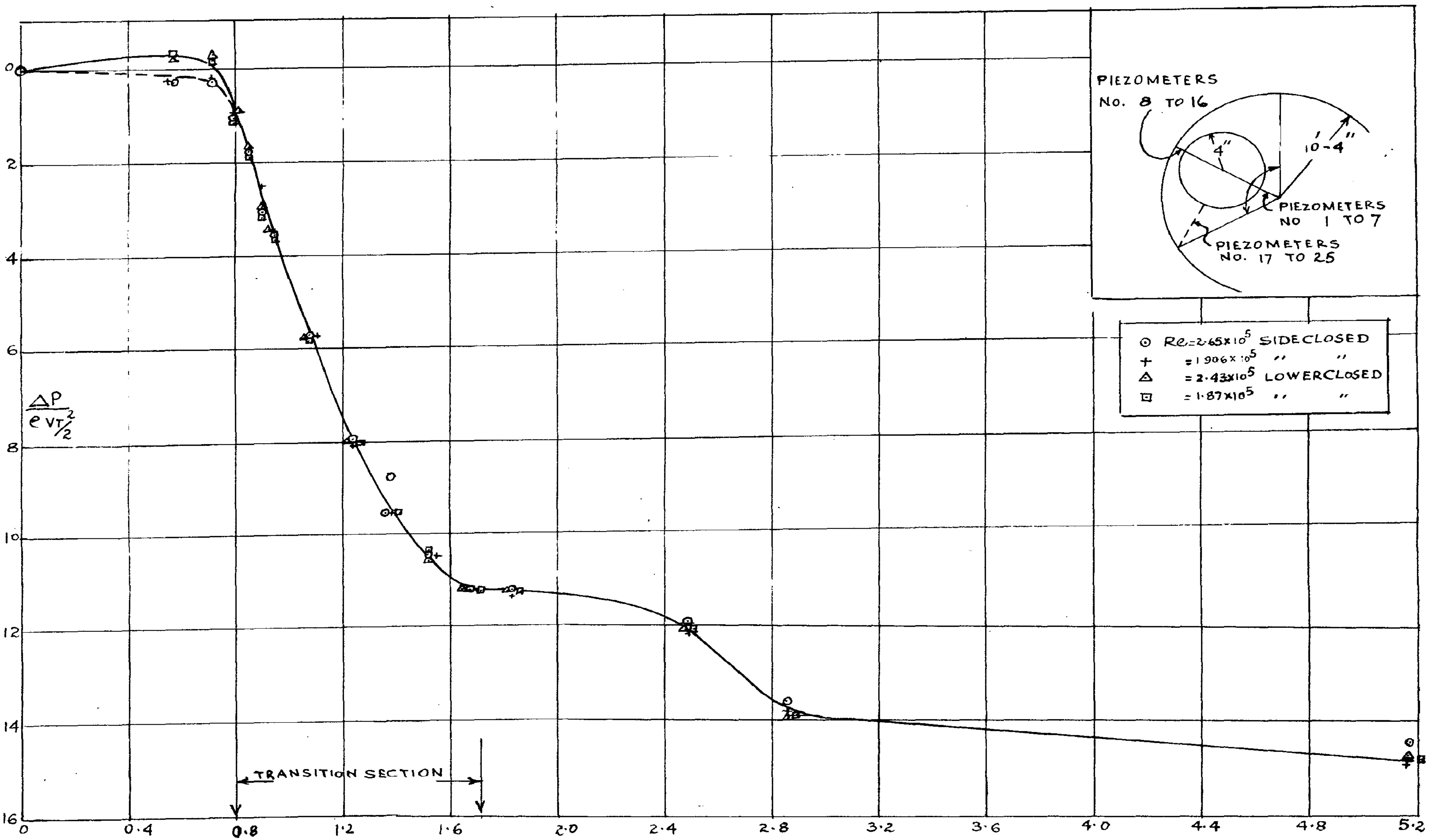


FIG. NO. 15 DIMENSION LESS PRESSURE DISTRIBUTION ALONG PIEZO. NO. 8 TO 16

(TWO PIPES RUNNING).

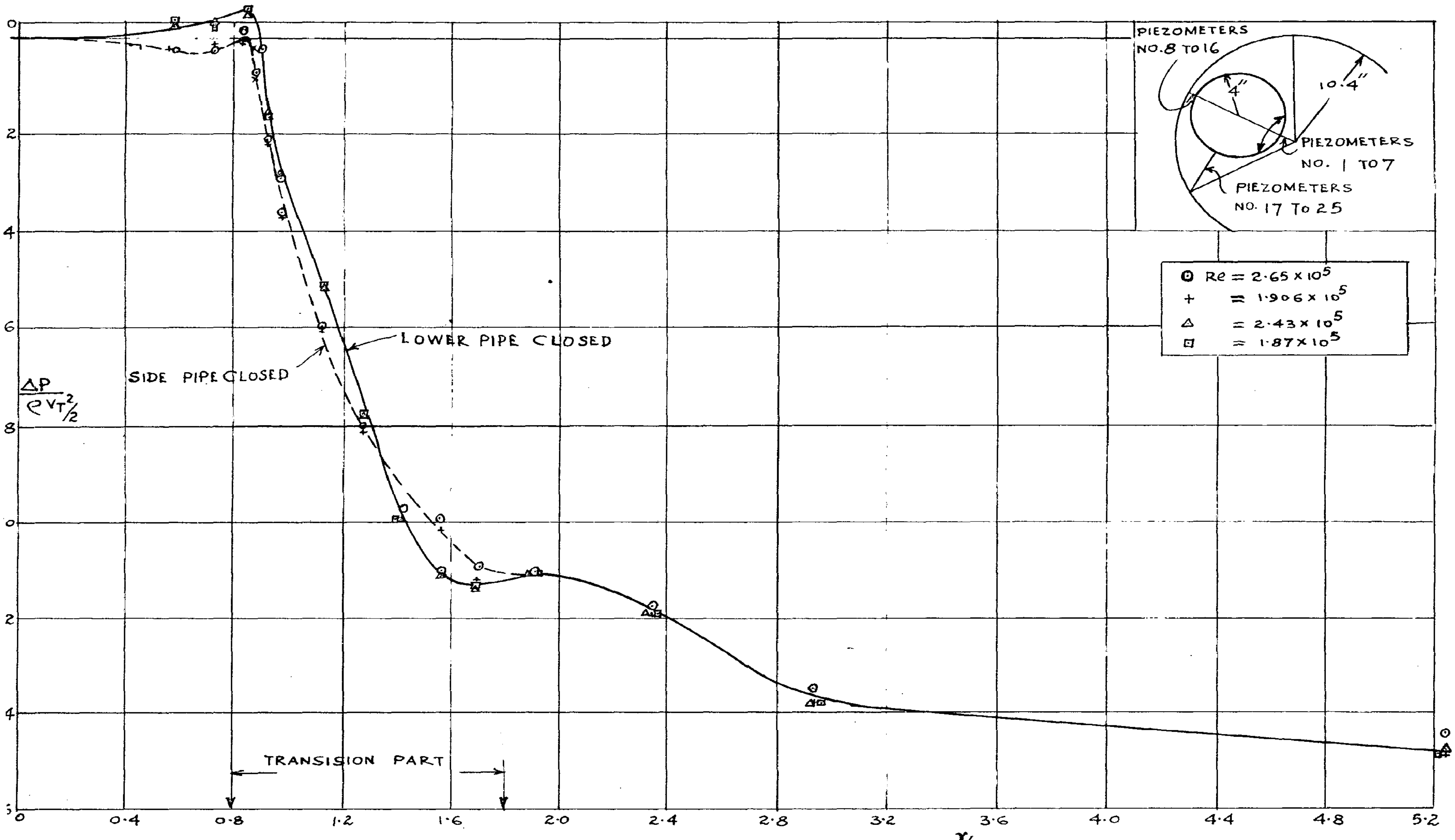


FIG. NO. 16 DIMENSION LESS PRESSURE DISTRIBUTION ALONG PIEZO NO. 17 TO 25
(TWO PIPES RUNNING)

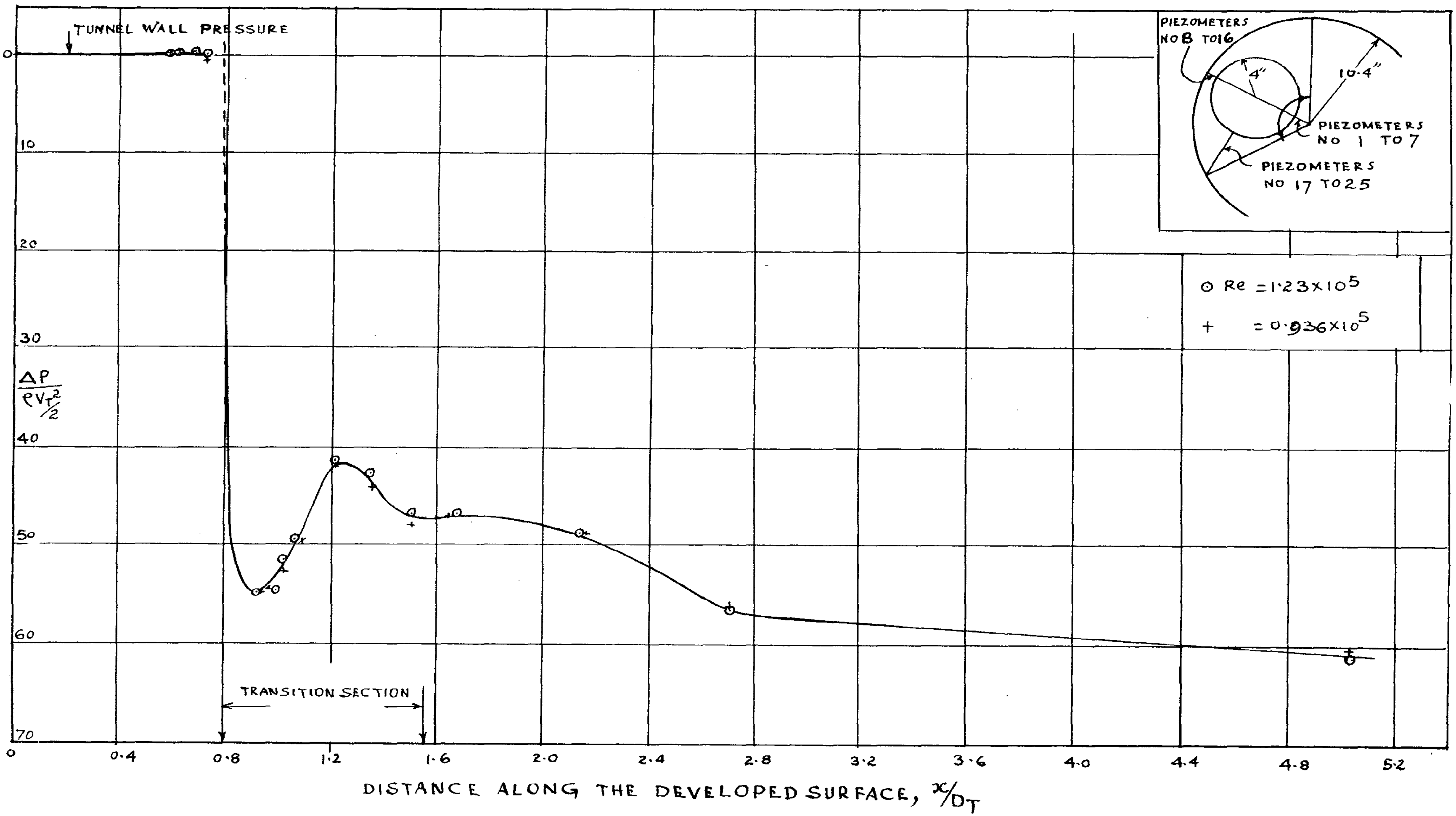


FIG. NO. 17 DIMENSIONLESS PRESSURE DISTRIBUTION ALONG PIEZO NO. 1 TO 7.

(ONE PIPE RUNNING)

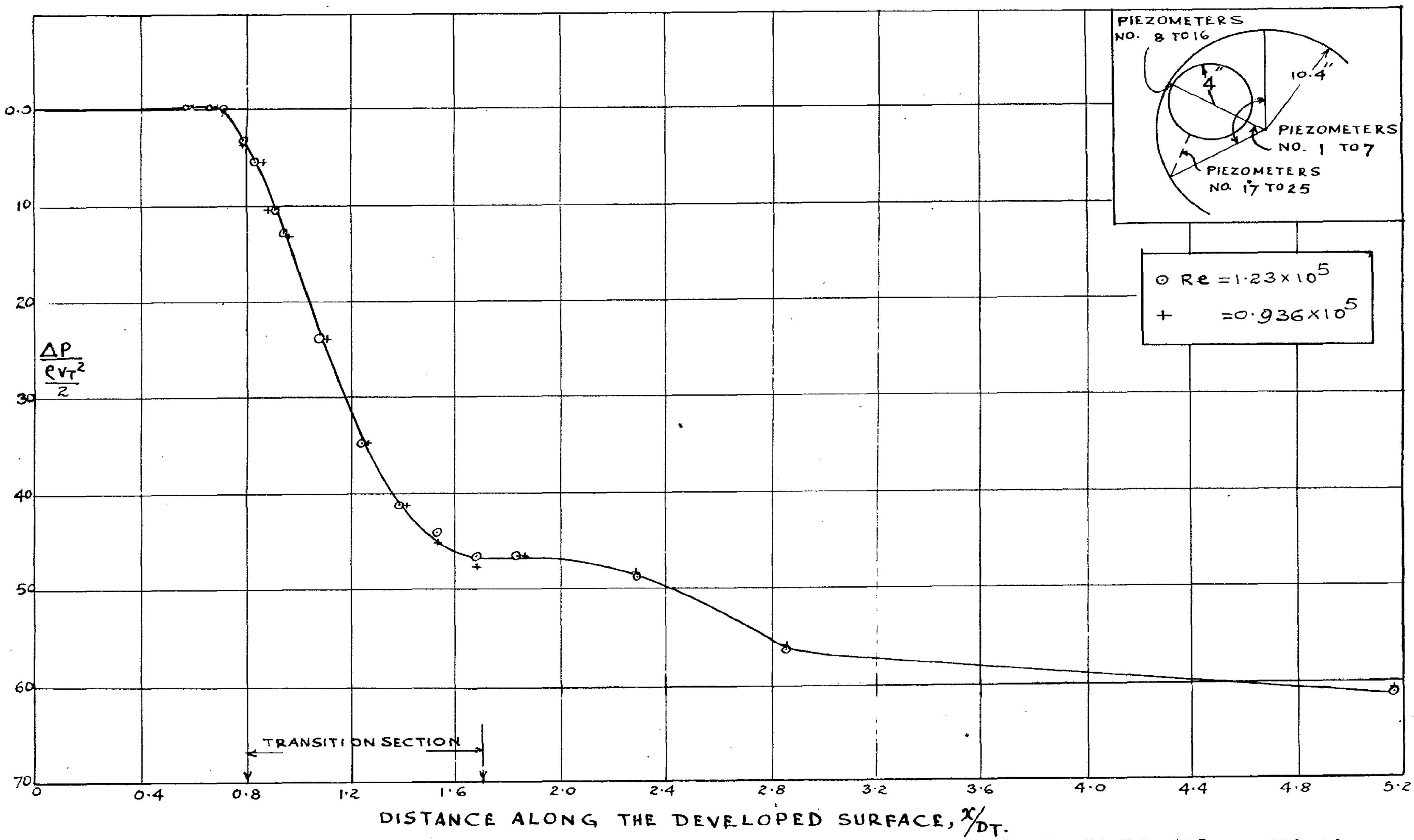


FIG. NO. 18 DIMENSIONLESS PRESSURE DISTRIBUTION ALONG PIEZO NO. 8 TO 16

(ONE PIPE RUNNING.)

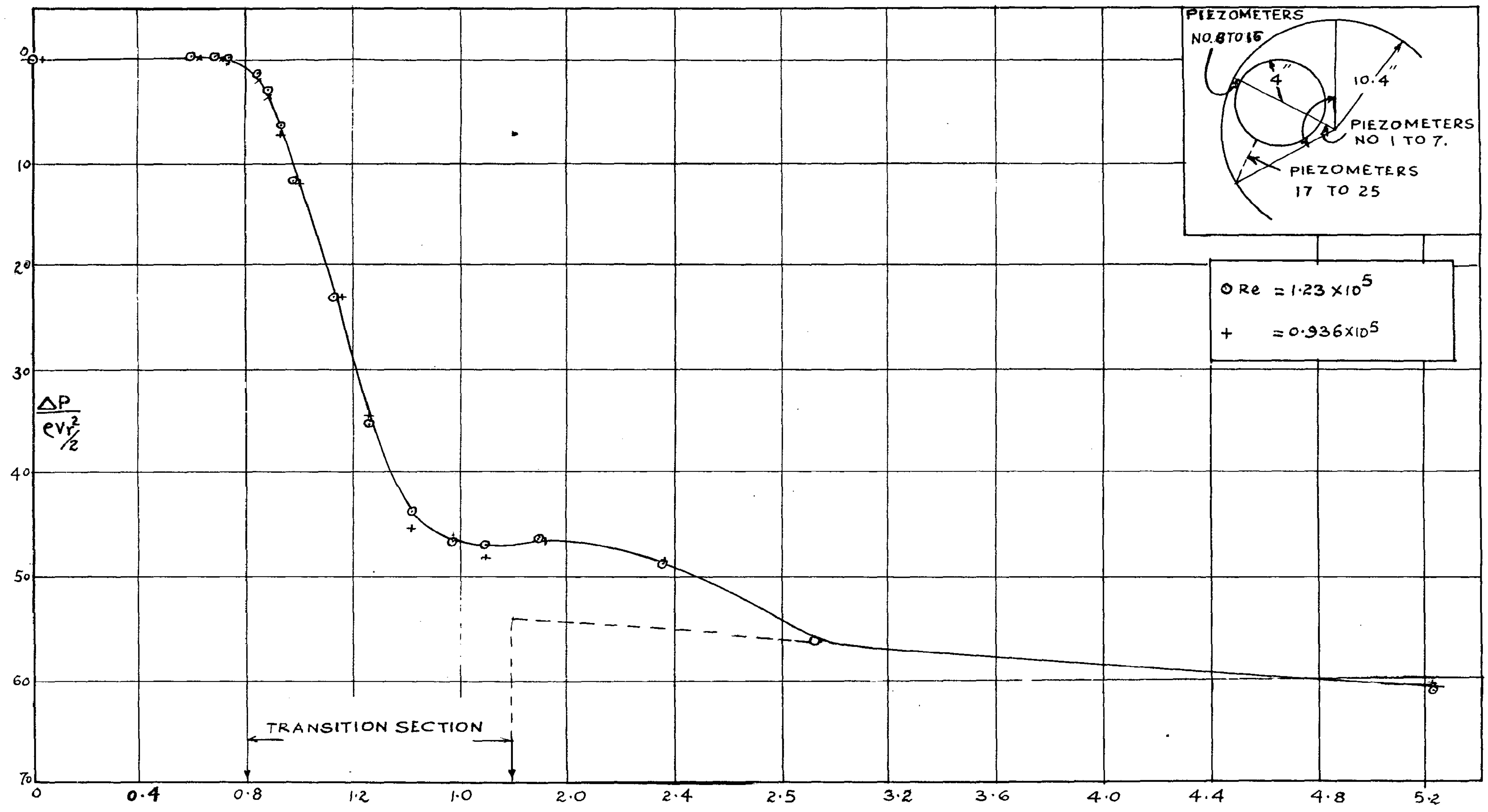


FIG. NO. 19 DIMENSION LESS PRESSURE DISTRIBUTION ALONG PIEZO NO. 17 TO 25

(ONE PIPE RUNNING)

TRIFURCATION MODEL I

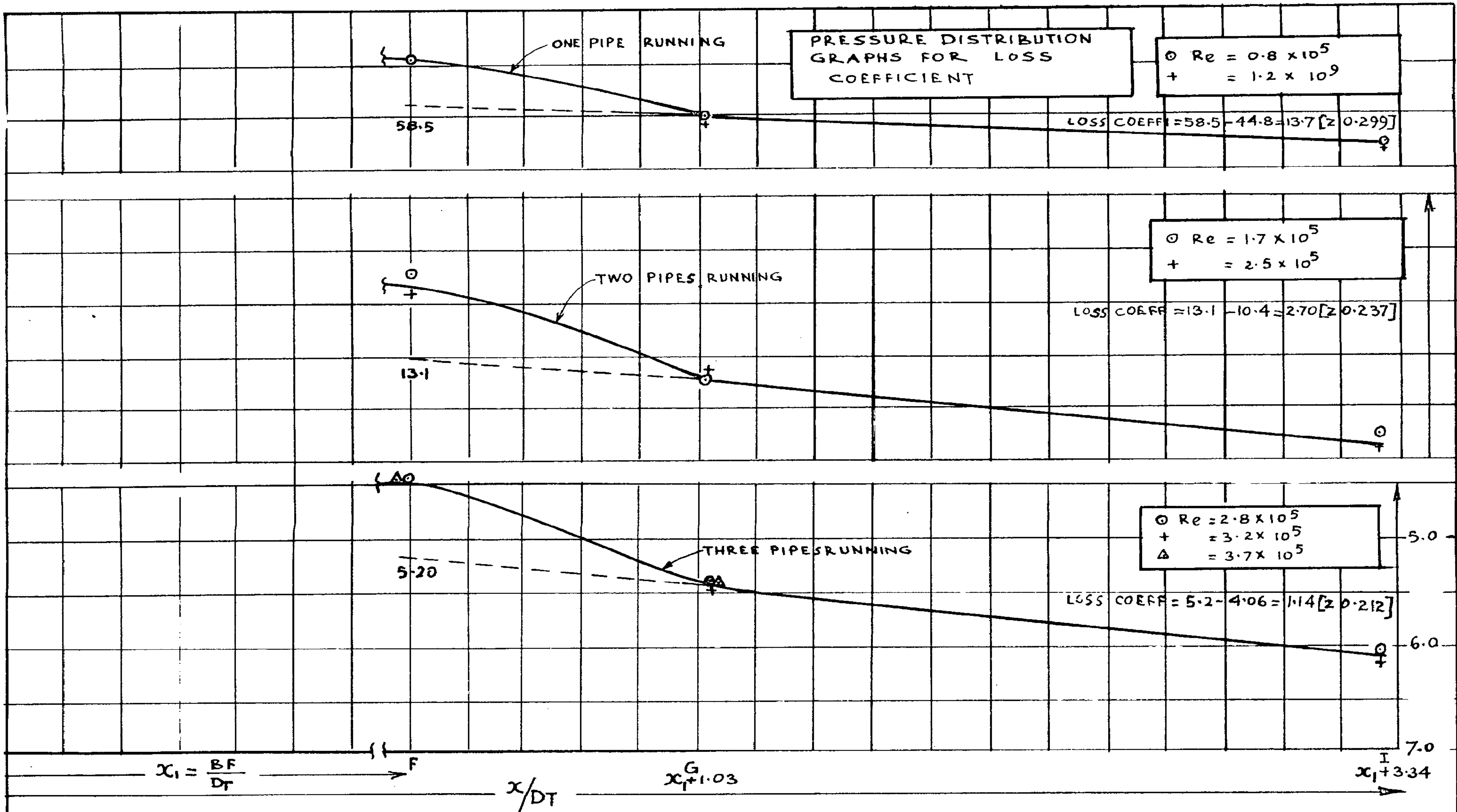


FIG. NO. 20– DIMENSION LESS PRESSURE DISTRIBUTION ALONG DIRECTION OF FLOW.

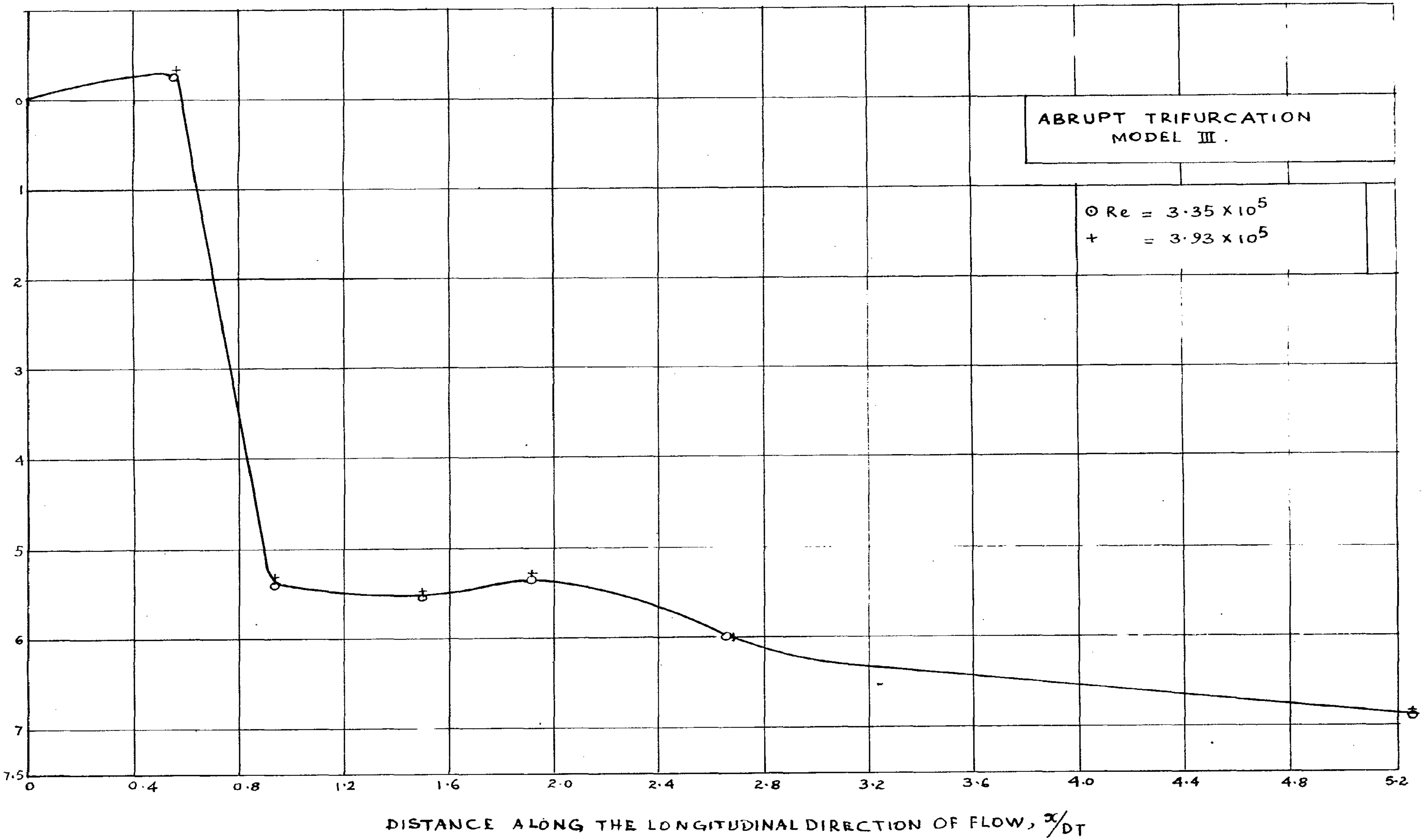


FIG. NO. 21 DIMENSIONLESS PRESSURE DISTRIBUTION ALONG DIRECTION OF FLOW. (ALL 3 PIPES RUNNING)

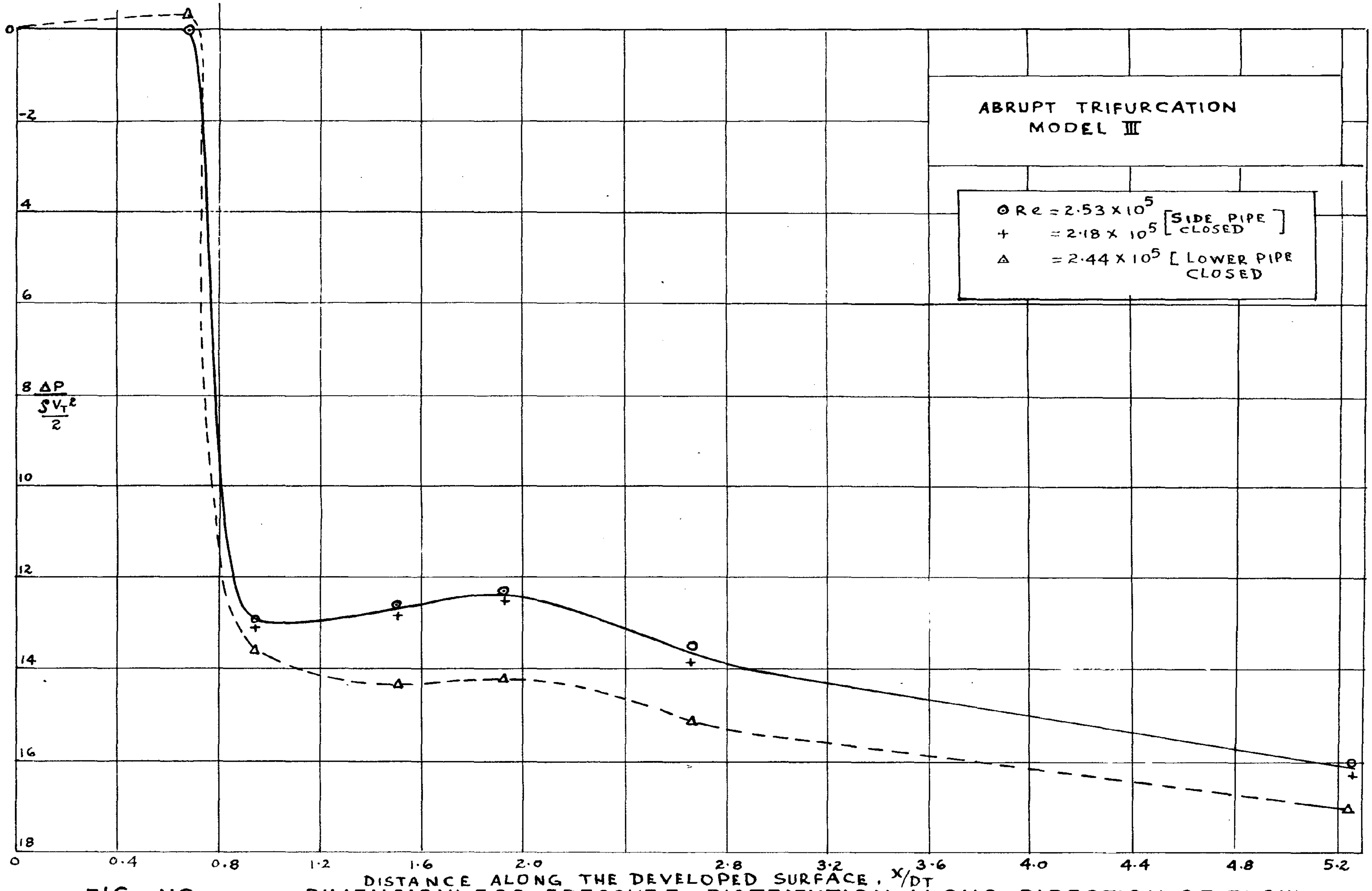


FIG. NO. 22 DIMENSIONLESS PRESSURE DISTRIBUTION ALONG DIRECTION OF FLOW.
(TWO PIPES RUNNING)

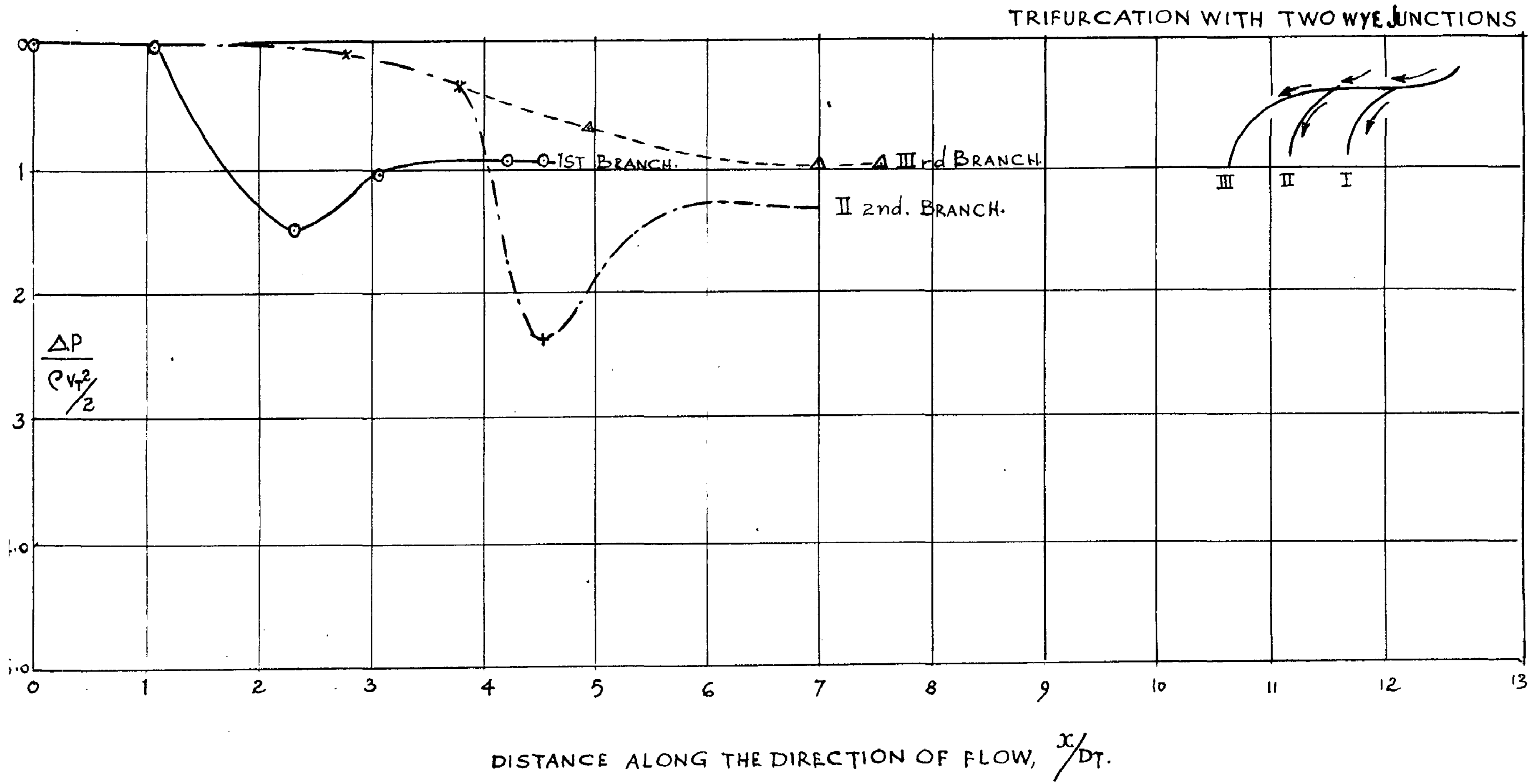


FIG. NO. 24. **DIMENSIONLESS PRESSURE DISTRIBUTION ALONG BRANCHES.**

[THREE PIPES RUNNING]

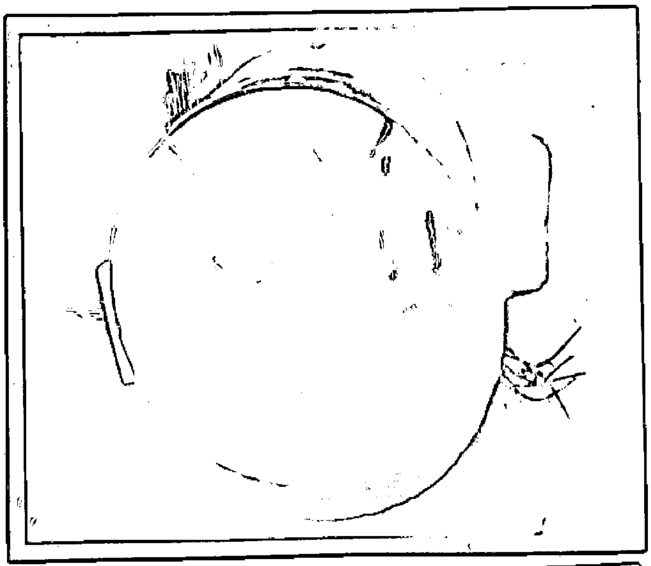


Plate 1. Trifurcation Model with Transition

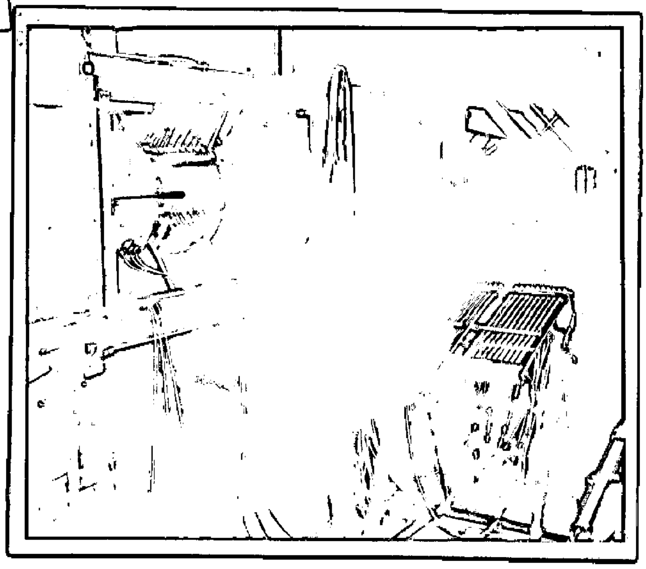


Plate 3. Complete set up showing test section and manometers for Model II and III.

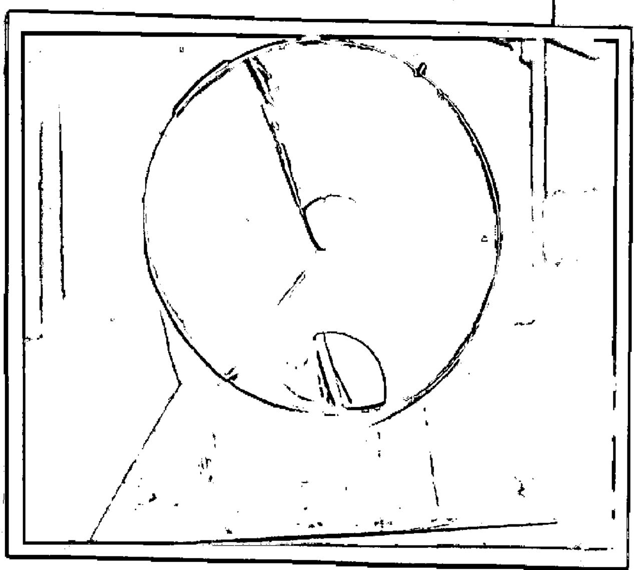


Plate 2. Trifurcation Model II with Transition

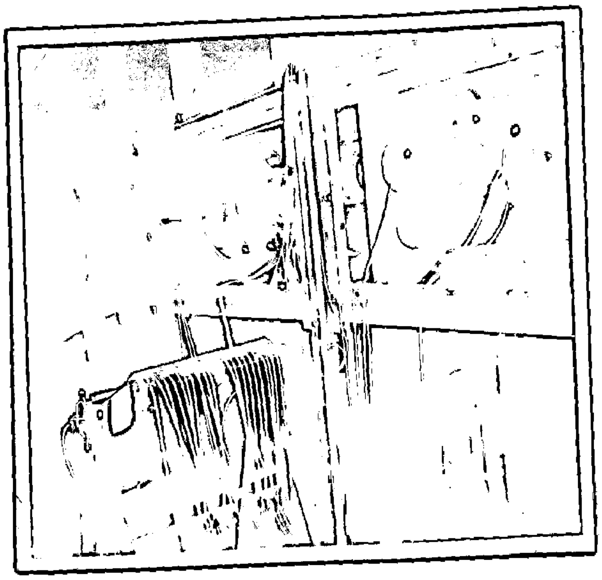


Plate 4. Complete set up showing test section and manométers for Model II and III.

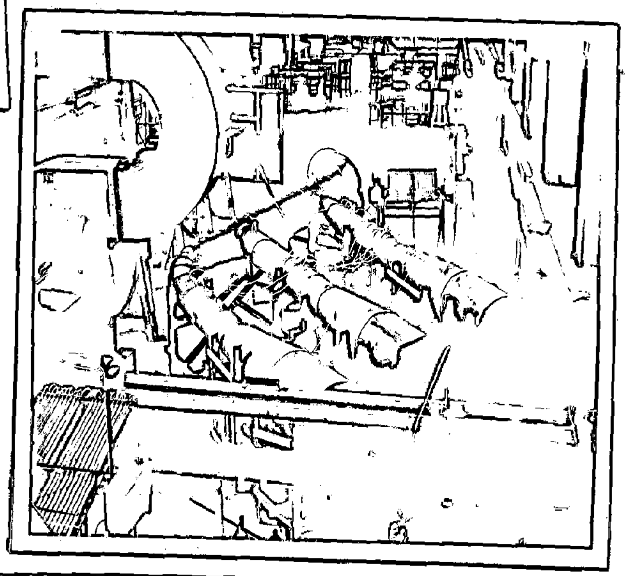


Plate 6. Complete set up showing Wye Arrangement

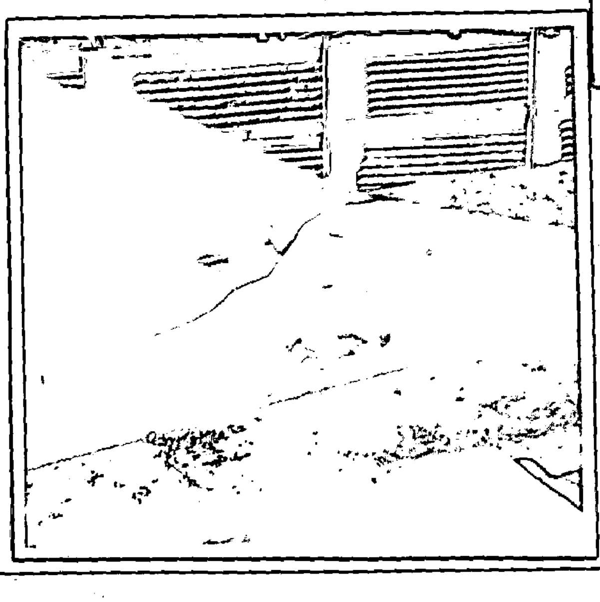


Plate 5. Mould for Wye Arrangement