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Central Electricity Generating Board

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1975
PRICE £1.50 NET

C.P. No.1335*
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MEASUREMENTS OF SECONDARY LOSS IN A MODEL TURBINE WITH VARIABLE INLET BOUNDARY LAYER

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SUMMARY

Detailed measurements have been made of the casing boundary layer flow before and after the nozzle blades of a single stage model air turbine. The measurements were made with the natural casing inlet boundary layer and two artificially thickened boundary layers. The results differ considerably from those usually obtained in two dimensional cascades. There was no sign of the usual secondary loss core and for the thick boundary layers the circumferentially averaged total pressure increased along stream surfaces near to the casing, this implies a negative secondary loss. The explanation appears to be that low energy fluid from the upstream casing boundary layer is transported radially inwards along the blade surface or wake and is discharged into the mainstream over the whole of the blade span.

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*Replaces A.R.C.35 921

1. INTRODUCTION

The effect of inlet boundary layer thickness on the secondary loss in two dimensional cascades has been studied in detail by Came (1). He found that the secondary loss arising within the blade row increased with increasing inlet boundary layer thickness up to values of δ^*/C of at least 0.05. However, in steam turbines the casing geometry is often such that the boundary layer at inlet to the nozzles must be either separated or reattaching after a large separation with consequent values of δ^*/C much greater than those tested in cascades.

It is also well known (2) that secondary flows and loss in an annular blade row can be considerably influenced by radial movement of low total pressure fluid towards the hub either along a separated region on the blade surface or along the wake. However, previous measurements by the authors (3) in an annular cascade of similar turning and aspect ratio to the model turbine nozzles had not revealed any appreciable radial transport of casing boundary layer fluid. Even with a very thick casing boundary layer ($\delta^*/C = 0.0736$) conventional secondary loss cores were formed, the only unusual feature being that almost all the secondary loss could be accounted for by loss present in the upstream boundary layer.

To study the effects of very thick casing boundary layers on turbine performance it was decided to artificially thicken the boundary layer at entry to a low speed model turbine by placing 'trip wires' around the casing at about one annulus height upstream of the nozzles. Traverses after the nozzles and rotor were used to investigate the effects of these boundary layers on nozzle loss and turbine efficiency.

The model turbine used in these investigations is shown in Figure 1 and has been described in (4). It is a high aspect ratio machine with untwisted nozzles and a highly twisted rotor designed for zero exit swirl. The flow enters the machine through a honeycomb and screens which reduce the turbulence level to about 1% and introduce a slight loss of total pressure relative to atmosphere. Radial traverses can be made at 10 axial stations and combined radial and circumferential traverses can be made at stations immediately before the nozzles, between nozzles and rotor and immediately after the rotor. Previous flow measurements in the machine had been made with a ⅛" diameter 5 hole probe but to study the details of secondary loss a very small 'cobra' probe with head thickness 0.4 mm was used and radial components of velocity were neglected. Because of the difficulty of traversing this probe very close to the hub it was initially decided to investigate only the casing boundary layer and loss.

2. RESULTS

Measurements were first made with the natural casing boundary layer entering the nozzles. This was very thin (Figure 2) having an overall thickness of about 3 mm, $\delta^* \simeq .275$ mm and $\delta^*/C = .007$. Circumferential traverses behind the nozzles (Figure 3) revealed no sign of a conventional secondary loss core and very close to the wall there was an unusual pattern of 'inverted' wakes. These were regions of high total pressure adjacent to the blade pressure surface superimposed on the lower total pressure fluid in the boundary layer. At distances greater than 3 mm from the wall they gave way to conventional blade wakes. Figure 4 shows comparisons of the total pressure before the blade row with the mass averaged values after the blade row. There is considerable loss occurring on the wall within the blade row and signs of an increase of loss in the blade wakes between 5 and 10 mm from the hub.

The casing boundary layer was next increased in thickness by placing a ring of 9 mm diameter plastic tubing around the throat of the intake. The resulting boundary layer profile immediately before the nozzles is shown in Figure 2. The overall thickness of this layer is about 25 mm, $\delta^* \approx 3.1$ mm and $\delta^*/C = 0.078$. The nozzle wakes (Figure 5) again show no sign of a secondary loss core and the same 'inverted wake' effect close to the wall. The total pressures before and after the nozzles (Figure 6) now show a region at about 5 mm from the wall where there appears to be no loss within the blade row. However, it must be remembered that no allowance has been made for the radial shift of the streamlines. There is also a region at 10 - 25 mm from the wall where the loss in the wake is appreciably higher than at mid span. The loss in the casing boundary layer after the nozzles (i.e. within 3 mm of the wall) is very similar to that with the thin boundary layer.

To obtain a casing boundary layer with relative thickness similar to that thought likely to occur in steam turbines a ring of 24 mm diameter plastic tubing was placed around the throat of the intake. This produced an inlet velocity profile shown in Figure 2 with $\delta \approx 50$ mm, $\delta^* \approx 10.5$ mm and $\delta^*/C = 0.26$. This boundary layer was therefore relatively much thicker than any reported in previous investigations. The flow pattern after the nozzles was, however, very similar to that found in the previous two cases. The nozzle wakes (Figure 7) still show no sign of a secondary loss core and show the 'inverted wake' effect near the wall. Comparison of the total pressures before and after the nozzles (Figure 8) now reveals an extensive region, up to 30 mm from the wall, where the total pressure appears to have decreased on passage through the nozzles. This region is much too large to be explainable by streamline shift so to try to discover what had happened to the low energy fluid the traverses were continued to the hub.

The results are shown in Figure 9 where the total pressures are plotted as functions of mass flow so that changes along a streamline can be found directly. Even this does not reveal immediately where the low energy fluid has gone. There is an obvious increase in loss in the region of the hub but it does not seem large enough to account for the deficiency near the casing. The circumferential traverses (Figure 7) show indications of a secondary loss core near the hub and qualitative tests indicated that the size of this core was affected by applying boundary layer suction at the casing. Some of the fluid from the casing boundary layer must, therefore, have moved radially inwards as far as the hub. It is also clear from comparison of the nozzle loss coefficients (Figure 9) with previous values obtained with the natural casing boundary layer, that the nozzle profile loss has increased by about 50% over most of the span, particularly near to the hub.

Figure 8 also shows that with the very thick boundary layer the loss in the casing boundary layer after the nozzles, i.e. within 3 mm of the wall, is greatly reduced compared to the previous two cases.

The nozzle outlet angles obtained by mass flow weighting the circumferential traverses are shown in Figure 10 for all three boundary layers. In all cases these show the usual overturning very close to the wall but only the thin boundary layer shows any sign of the expected underturning at greater distances from the wall.

3. DISCUSSION

The traverses have revealed an absence of many of the usual secondary flow and loss phenomena. In all cases there was evidence of transfer of high total pressure mainstream fluid onto the casing at its junction with the blade pressure surface thus producing the 'inverted wake' effect. There is also evidence of fluid being removed from the vicinity of the casing and shed into the blade wakes at a lower radius. Both of these results are consistent with the usual secondary flow phenomena whereby the wall boundary layer is swept onto the blade suction surface and is replaced by higher total pressure fluid. However, it is usual for the low energy fluid to leave the suction surface as a loss core and there are no signs of such cores in the present results. Instead the low energy fluid appears to be shed gradually into the wake over an appreciable spanwise distance.

For the thickest boundary layer there is evidence that some of the low energy fluid has reached the hub whilst some is shed into the wake over the inner 2/3 of the span, appearing as increased profile loss. However, inspection of Figure 9 shows that it is difficult to account for all of the casing boundary layer loss in this way. Also such a large radial transfer of fluid would require large areas of separated flow either on the blade surface or in the wake. The calculated blade surface velocity distributions are such that no separated regions are expected and this is confirmed by the low profile loss obtained with the thin boundary layer. The trailing edge of the blade is also thin so it is hard to see how large amounts of fluid can move radially in the wake. In fact previous traverses with the 5 hole probe showed only very low radial velocities in the blade wakes. It does not, therefore, seem possible to account for the results obtained with the thickest boundary layer by the usual mechanism of radial flow in separated regions.

An alternative or complementary explanation is possible in terms of the very high turbulence levels (20 - 30%) in the inlet boundary layer. These will produce a variety of effects which may contribute to the apparent increase in total pressure near the casing. Firstly, the probe will register a time average total pressure which, in a highly turbulent flow, will be lower than a mass average. In comparing total pressures before and after the nozzles it is the mass average which should be used. Since the RMS turbulence in the streamwise direction will be much less after the nozzles than before them the probe might be expected to register an apparent increase in total pressure on these grounds alone. Secondly, the radial components of the turbulent velocity fluctuations will remain virtually unchanged on passage through the nozzles and will produce mixing between the boundary layer and mainstream fluid. This will result in an increase in total pressure along a mean streamline in the boundary layer and a corresponding decrease in the mainstream. Thirdly, the centrifugal pressure field within and behind the nozzles may cause a separation of the high and low energy components of the turbulent motion. A high velocity (and hence high total pressure) 'particle' will be centrifuged outwards whilst a low velocity 'particle' will move radially inwards. Thus there will be a tendency for the total pressure to increase near the casing and decrease at the inner boundary of the turbulent layer.

The same high turbulence may account for the uniformity of the outlet angles, the mixing being so intense as to average out angle variations. No attempt has been made to estimate the outlet angle variations predicted by secondary flow theory applied to the measured inlet shear flows but it seems inevitable that it would predict considerable underturning around the outer edge of the boundary layer. No such underturning is observed in practice for the two thicker boundary layers.

In conclusion it can be said that although it is very difficult to interpret and explain the results obtained, the indications are that the secondary loss internal to the blade row is not greatly increased, and may even by decreased, by very thick casing boundary layers. Work is still proceeding to try to find a more satisfactory explanation of the phenomena observed.

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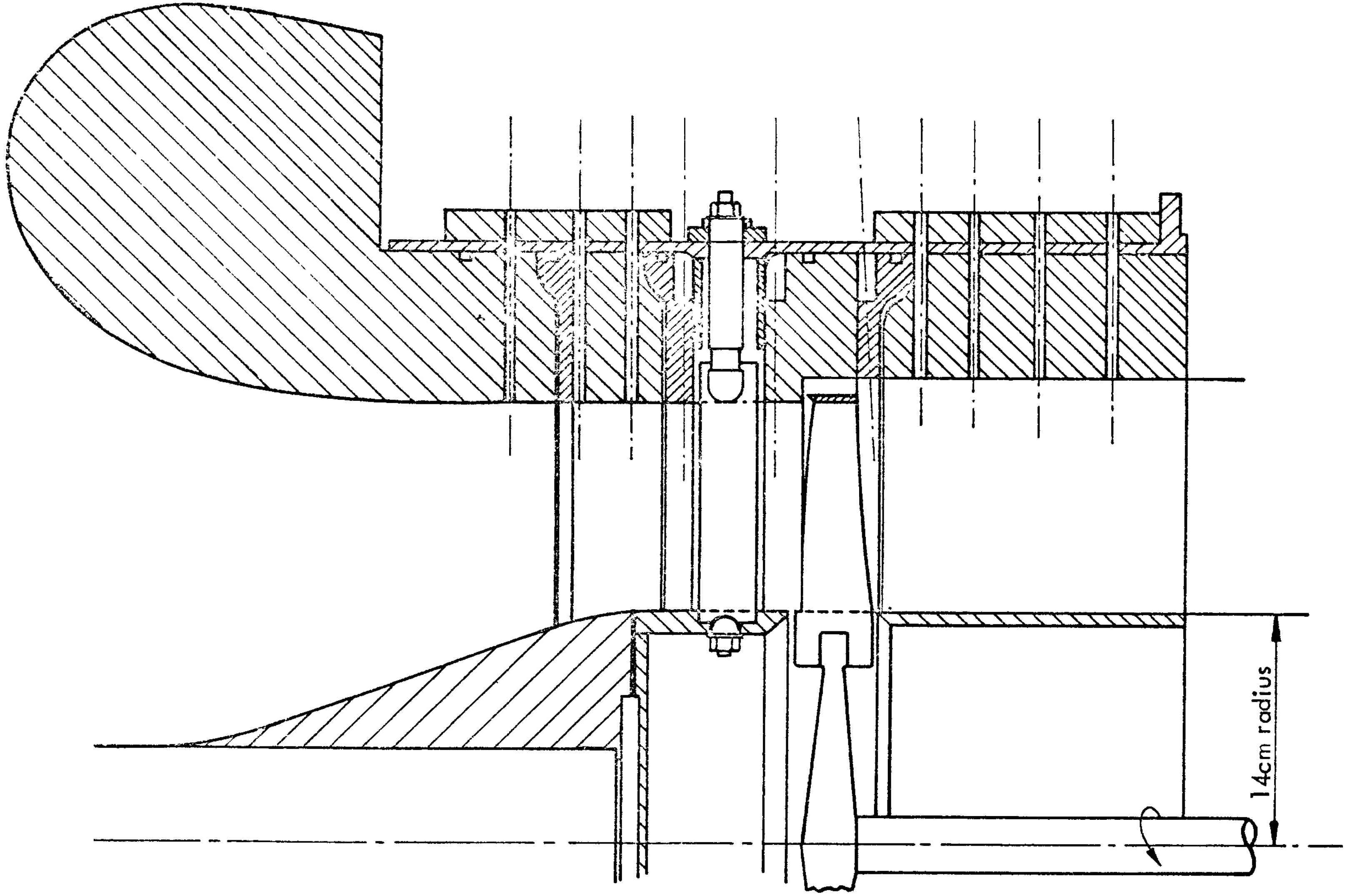

FIGURE 1. PARALLEL ANNULUS BUILD OF MODEL TURBINE

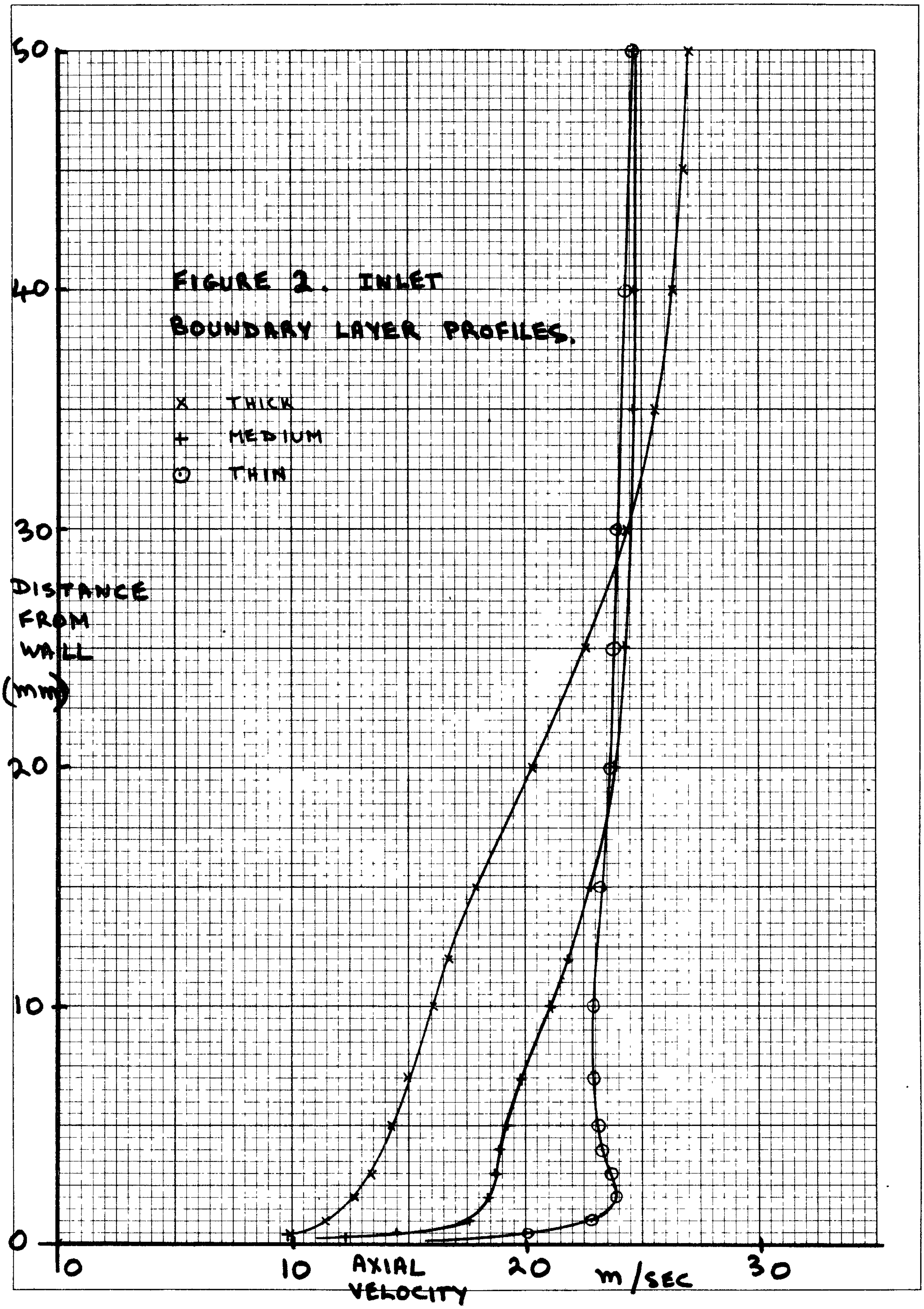

FIGURE 2. INLET BOUNDARY LAYER PROFILES.

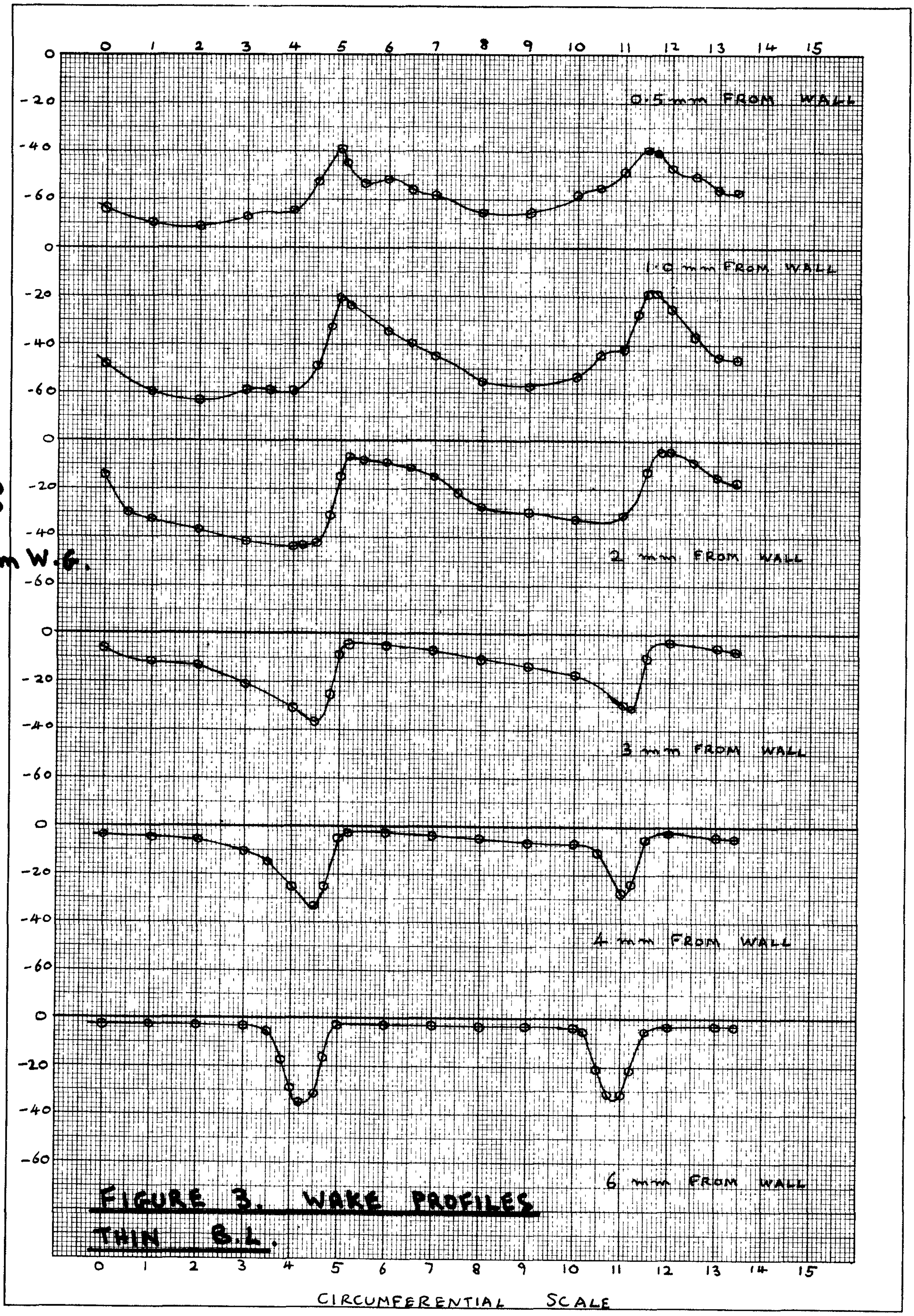

FIGURE 3. WAKE PROFILES

THIN B.L.

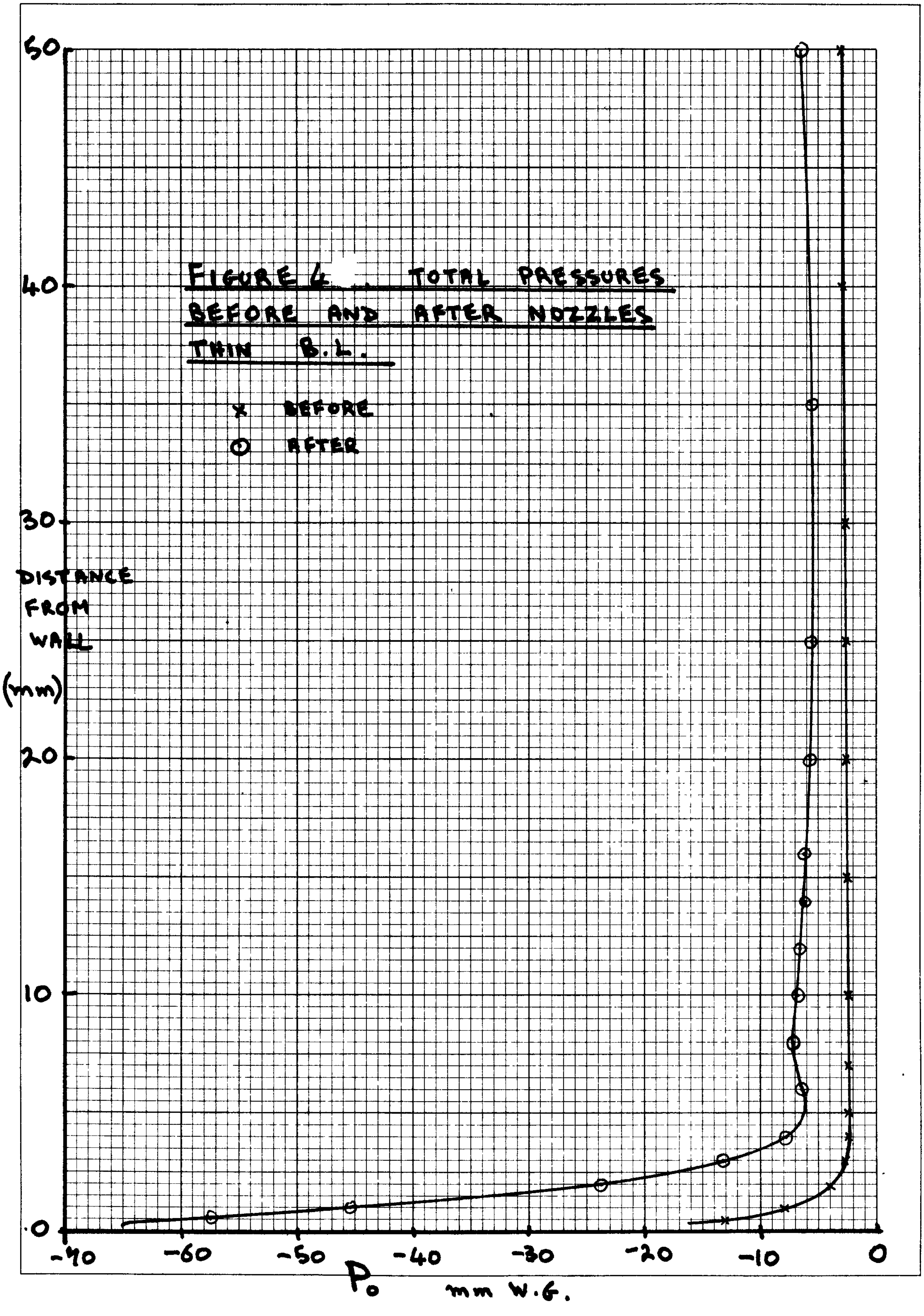

FIGURE 6 . TOTAL PRESSURES BEFORE AND AFTER NOZZLES
THIN B.L.

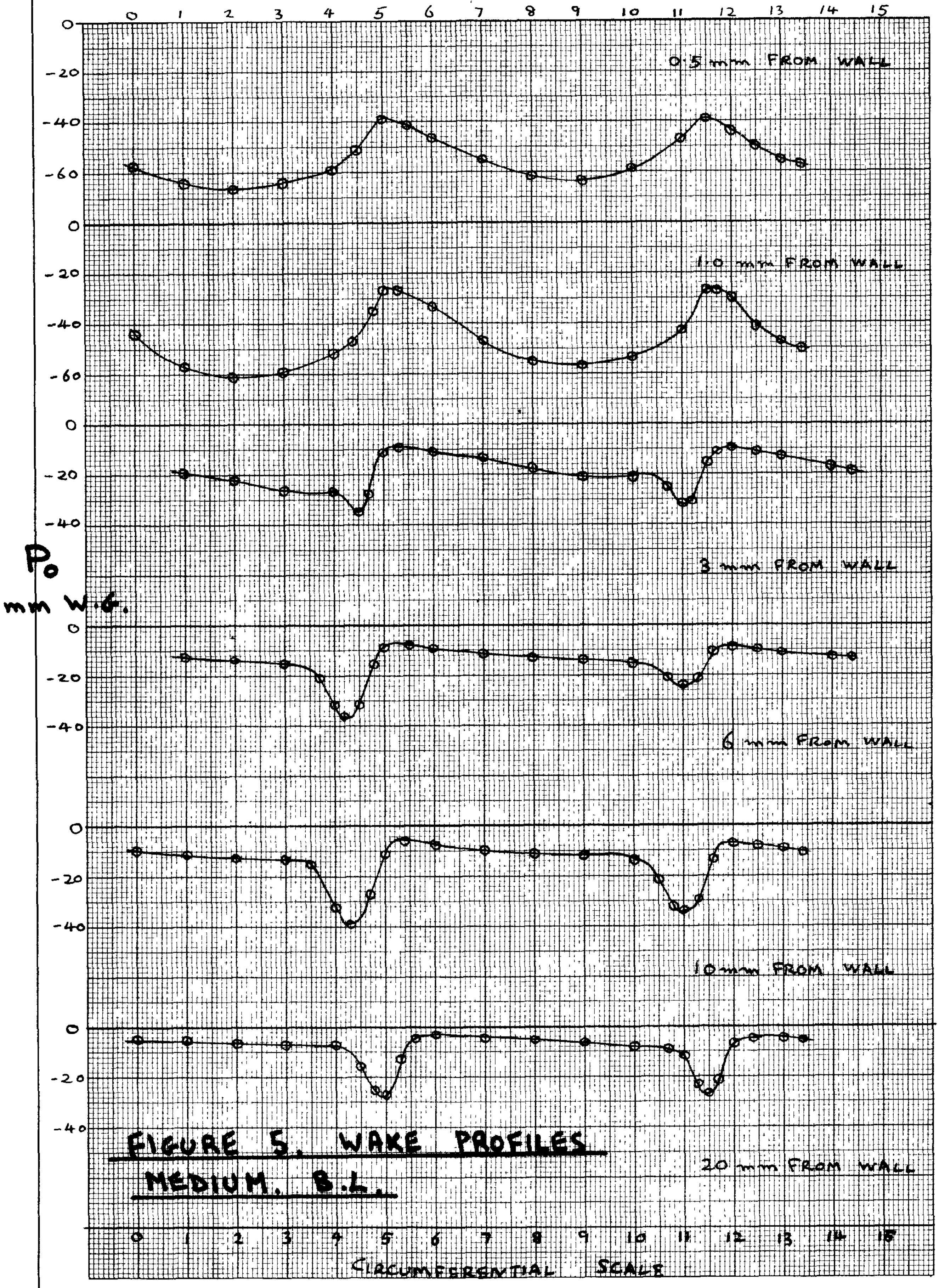

FIGURE 5. WAKE PROFILES
MEDIUM. B.L.

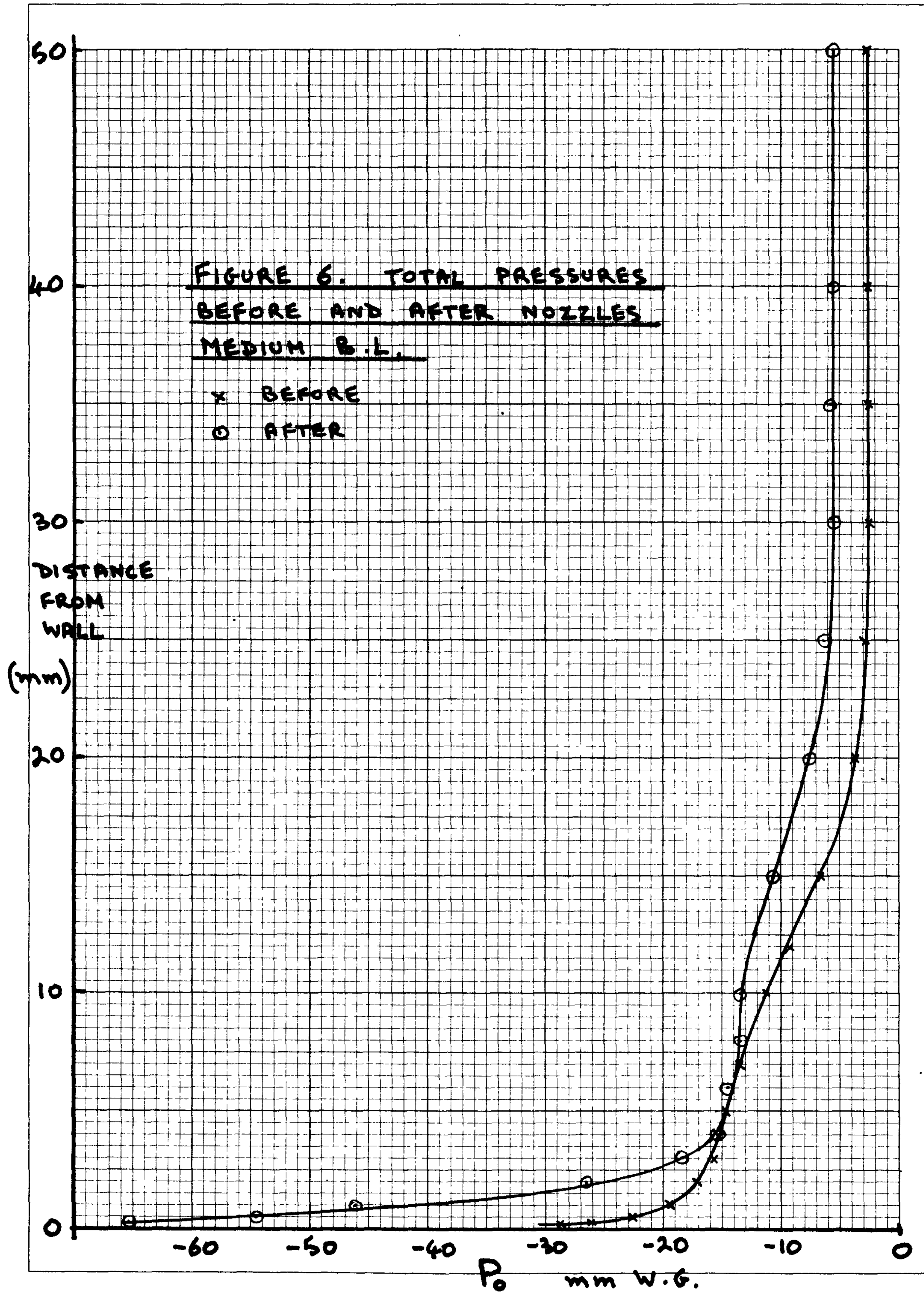

FIGURE 6. TOTAL PRESSURES BEFORE AND AFTER NOZZLES MEDIUM B.L.

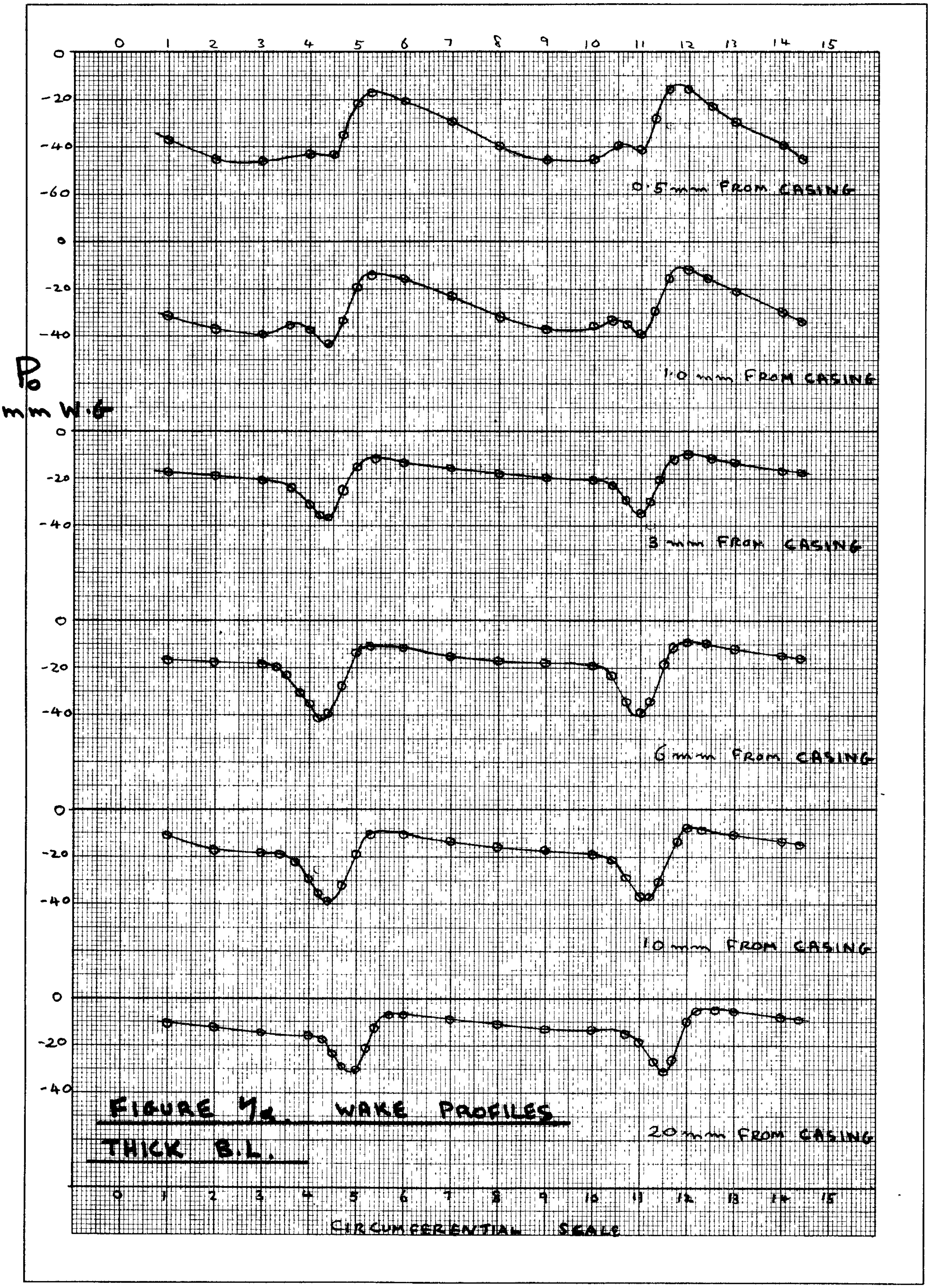

FIGURE 4a. WAKE PROFILES

THICK B.L.

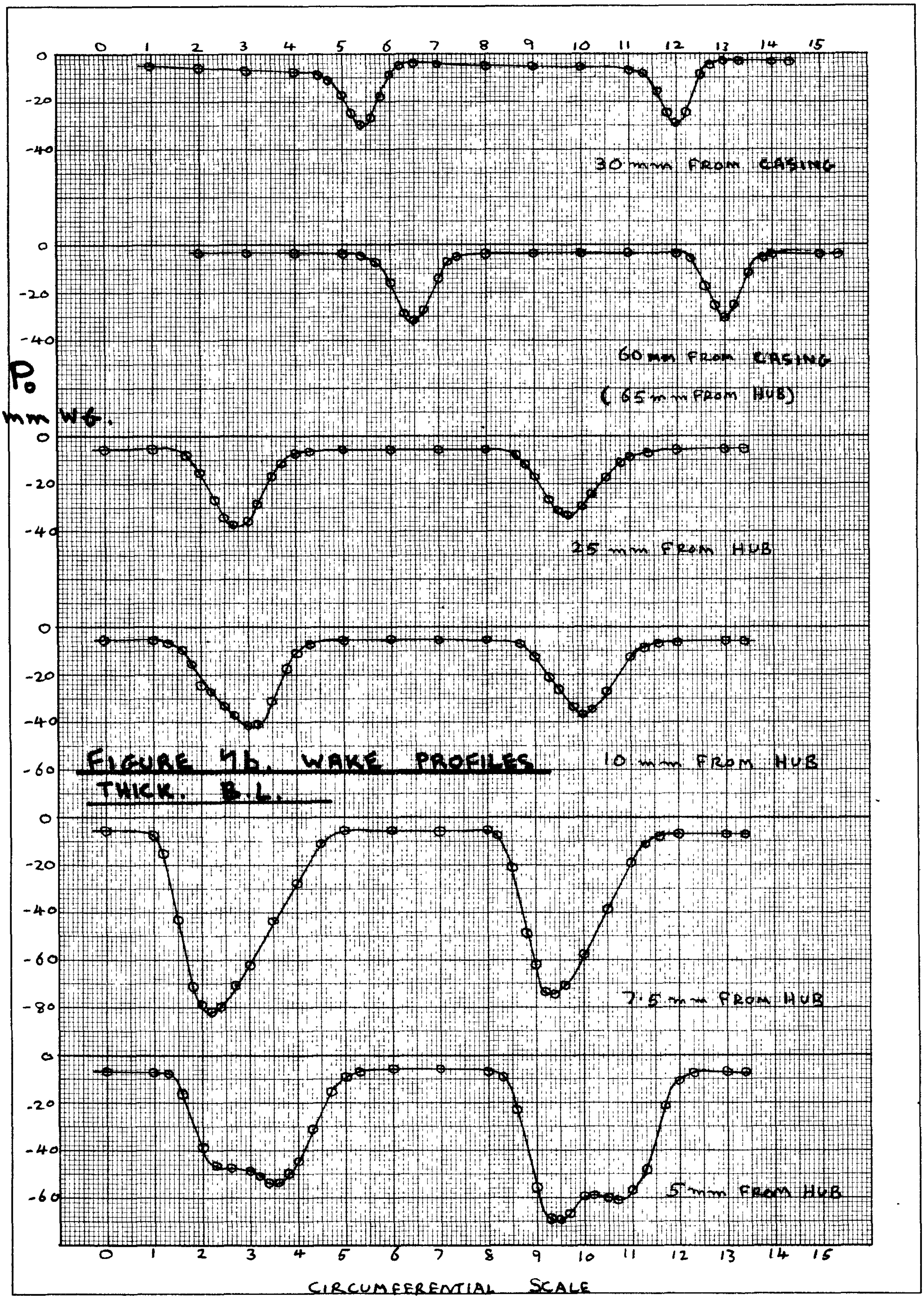

FIGURE 4b. WAKE PROFILES
THICK. B.L.

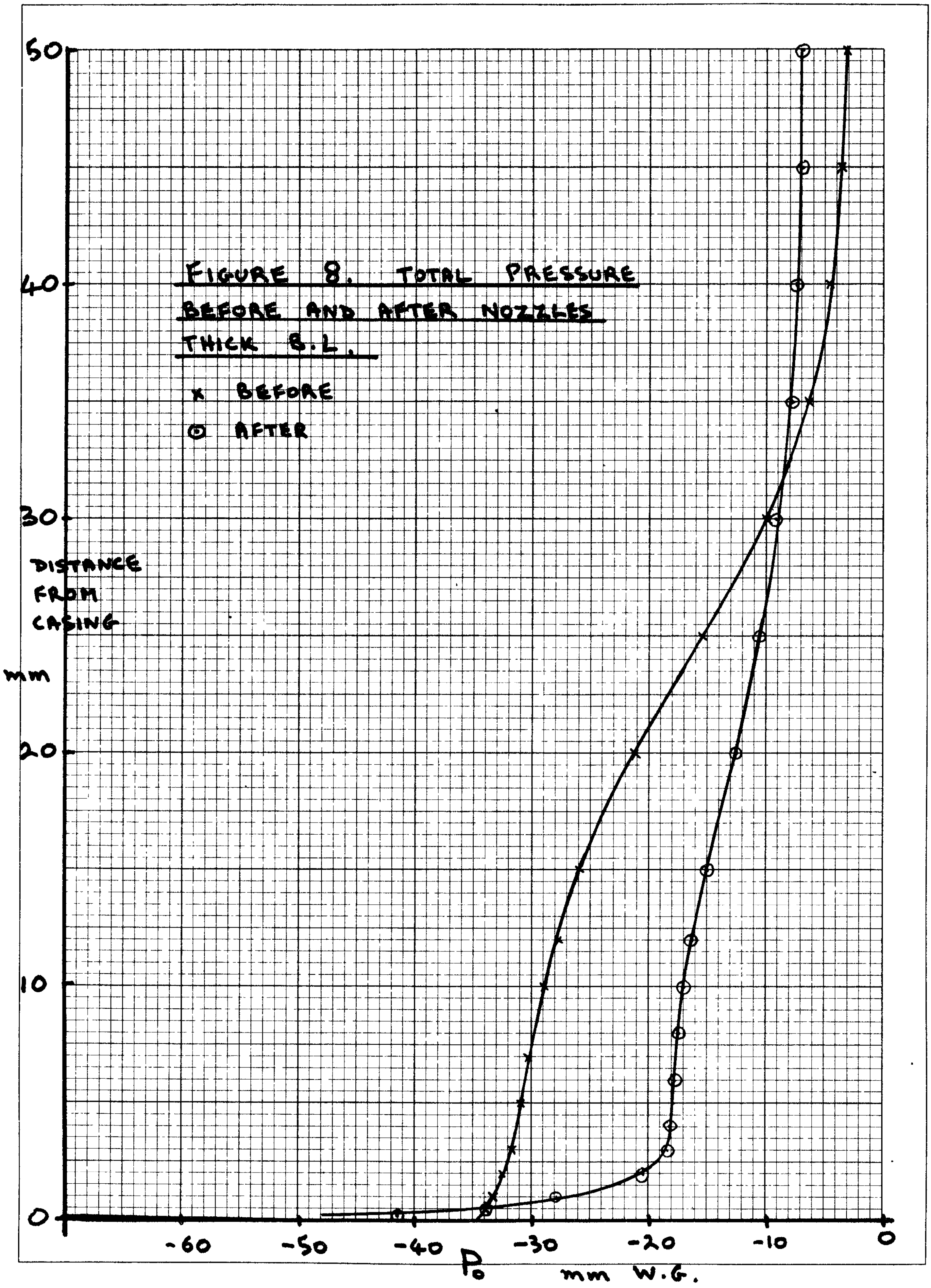

FIGURE 8. TOTAL PRESSURE BEFORE AND AFTER NOZZLES THICK B.L.

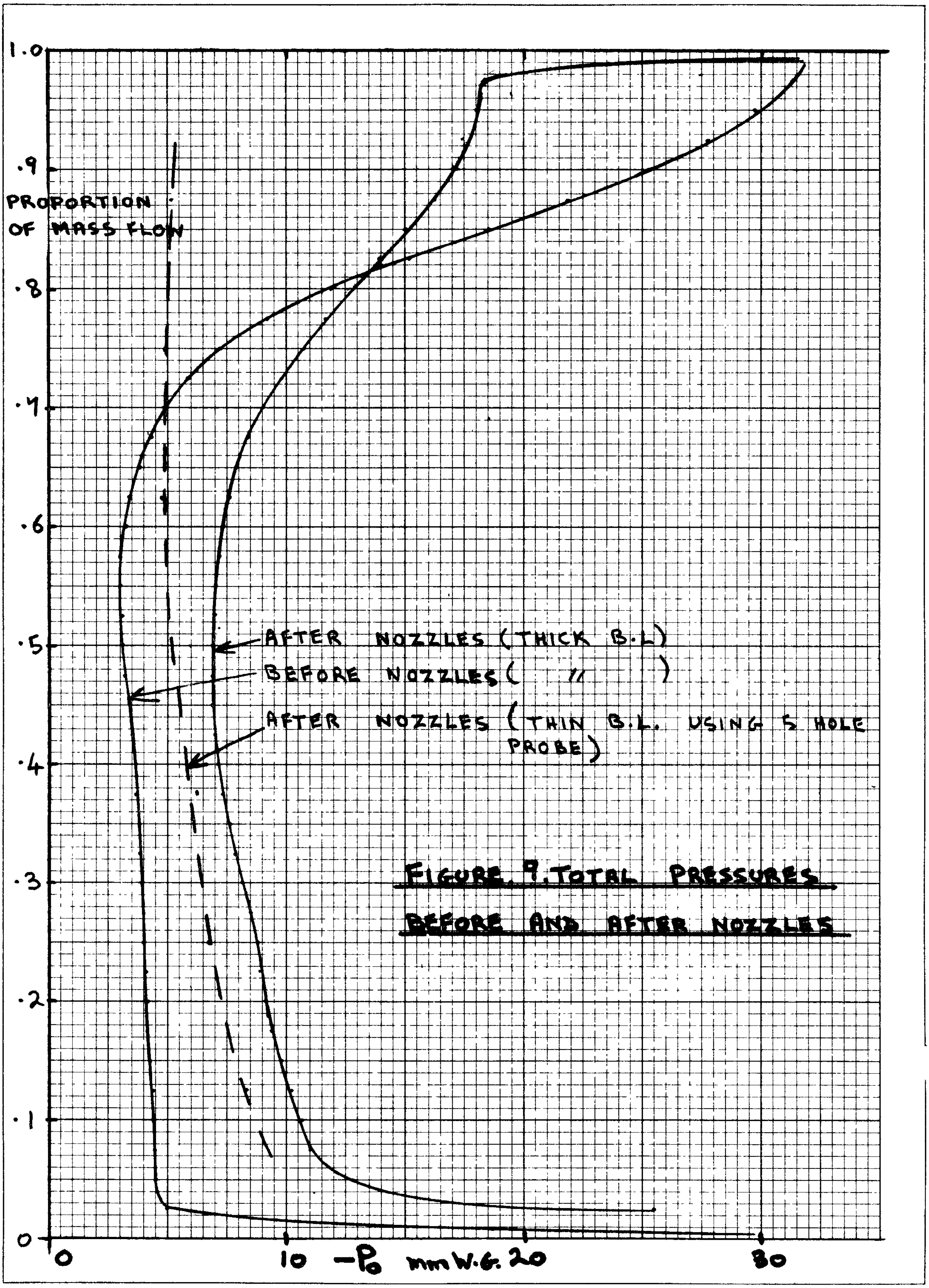

FIGURE 9. TOTAL PRESSURES BEFORE AND AFTER NOZZLES

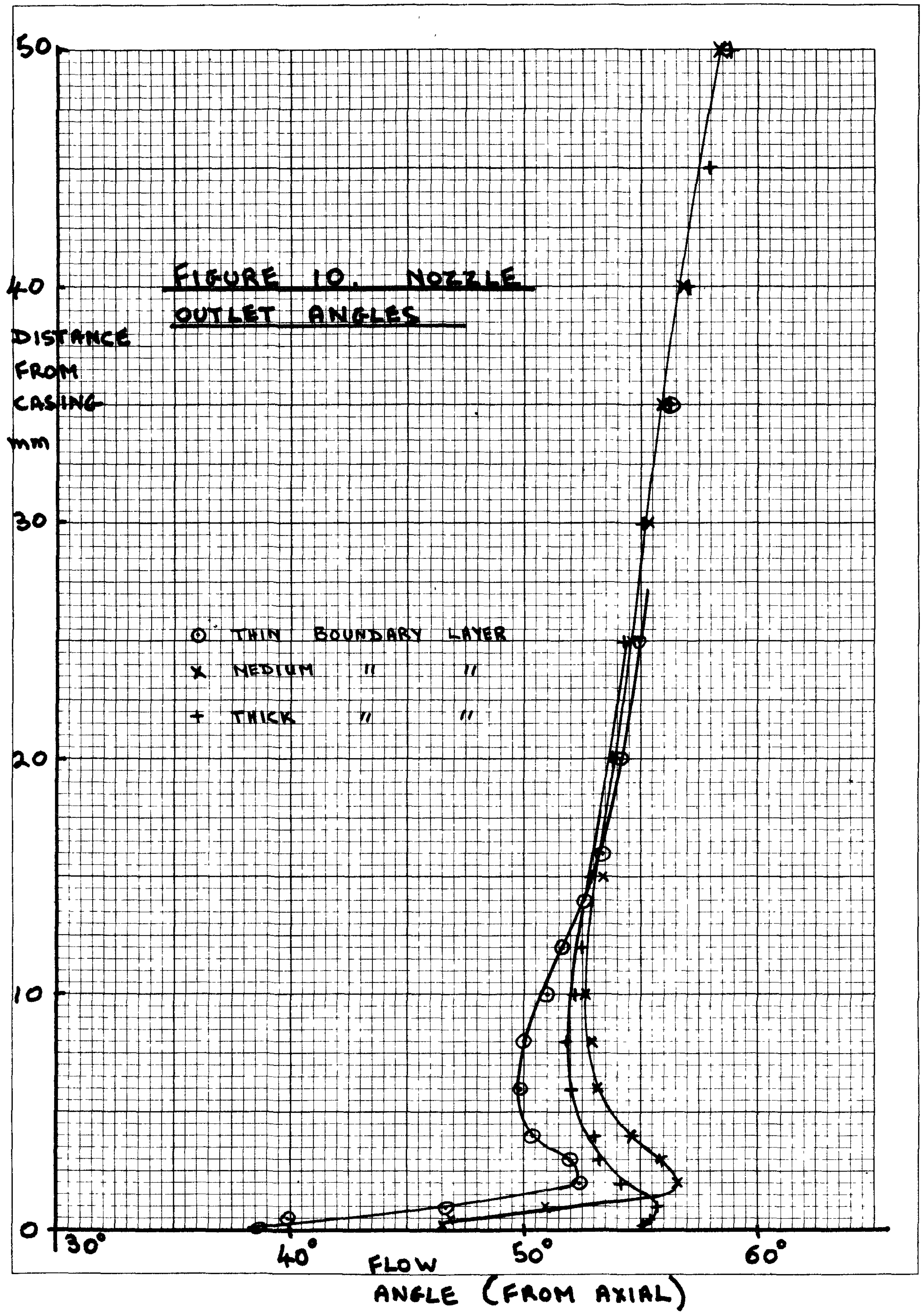

FIGURE 10. NOZZLE OUTLET ANGLES

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DETACHABLE ABSTRACT CARDS

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