MEASUREMENTS AND DATA REDUCTION PROBLEMS BEHIND THE ROTOR OF A TRANSONIC AXIAL FLOW COMPRESSOR IN THE HUB REGION

by

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Experimental results are presented, for the hub region, downstream of a transonic compressor. The measurements are resolved in the relative frame of reference in order to provide informations on some aspects of the secondary flows.

Apart from the usual influence of the vortex motion on the relative flow angle, we have observed an unexpected increase of the rothalpy on the streamlines near to the wall.

These results have left open the question of the accuracy of temperature measurements with thermocouples, in unsteady flows. But also with the help of recent theoretical studies, they may be used to put some light on the influence of secondary flows in a rotor.

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1 - INTRODUCTION

An extensive experimental work has been realized in the Ecole Centrale de Lyon, in order to provide informations on the secondary flows in a transonic axial flow compressor.

The continuous developments of highly loaded compressors have put into light the needs for better understandings of the three-dimensional nature of the flow in a turbomachine.
The flow downstream of a rotor has been studied by LAKSHNINARAYANA and his coworkers ([1, 2]), KOOL [3] who were mainly interested in the velocity field downstream of the rotor. Also, the importance of viscous effects has been demonstrated inside the blade row by DRING, JOSLYN and HARDIN [4] in a low speed compressor.
Numerous works on the secondary flows in fixed blade cascades has already been published (see for instance [5, 6, 7]). In this paper, we present some experimental results for the hub region, downstream of an axial compressor rotor.
In the following, we shall present the experimental set-up.
And then, the experimental results will be discussed.

2 - DESCRIPTION OF THE EXPERIMENTAL SET-UP

Test facilities.

The experiments have been realized on the high-speed compressor test facility of the Ecole Centrale de Lyon. A full description of this facility may be found in reference [8]. A 1000 H.P. electric motor is used to drive the compressor rearwards. The speed of rotation may be continuously regulated up to 12000 R.P.M. The air is provided from outside and comes axially into the compressor. A throttle valve is used to modify the circuit characteristics, in order to cover a wide range of mass flow rates, which are measured by a ventury arrangement.

The transonic axial flow compressor.

A schematic view of the compressor is given figure 1. It is a transonic single stage axial flow compressor with inlet guide vanes(I.G.V.), a rotor and a stator.
The main characteristics of the compressor, under standard conditions, and at nominal point of operation, are :

- stage pressure ratio 1.38 ;
- mass flow 16 kg/s ;
- speed of rotation 11150 R.P.M. ;
- external diameter 0.55m ;
- hub-to-tip radius ratio 0.78.

Instrumentation and data reduction.

We shall only describe here the instrumentation used directly in our secondary flows studies. The choosen measuring planes are shown schematically in figure 1. Wall static pressure taps are disposed in these stations at different circumferential positions.

At stations 1, 4 and 5, probe traverses are performed at only one circumferential position. At stations 2 and 3, a circumferantial movement is added. Rotation of the probe around its axis is also allowed.

Two different types of probes were used in each stations in order to cover the whole radial positions (fig. 2). A full description of these probes is given in [9]. The "cylindrical" probe is able to give the desired information only from the tip up to 0.20 of the blade height. The "cobra" type probe supplies the desired information for the whole channel width and especially near the hub. An overlapping part exists, so that we can compare the measurements produced by the two probes. These two kinds of probes were calibrated in pitch and yaw angles as well as for various Mach numbers.

Flow quantities are obtained in the following way. We first use a null method. The probe is fixed in radial and circumferential positions. Then the probe is rotated around its axis, equalizing the pressure readings obtained on two opposite taps. An approximative flow angle α is then obtained. Individual pressures are measured. Then, interpolating in previous calibration curves at different Mach numbers, the corrected flow quantities are obtained.

The temperature is also corrected for a static effect and for a Mach number effect.

The accuracy of static pressure measurements have been often questioned when a cobra probe is used [10]. We have done many tests to validate such a probe (see for instance [9]). From these results, we have concluded that the accuracy of a cobra probe is similar to that of a cylindrical probe for such a blade height, excepted very near to the wall.

Another question which comes up frequently, concerns the response of a probe which is introduced in a non-stationary environment as in the stations 4 and 5. It seems that in our case, there is little influence of the non-stationary field on the probe pressure response, especially outside the wall shear layer regions. In our opinion, this result must be attributed to the small size of the probe pressure tube diameters used (0.3 mm). This fact is confirmed by the mass flow rate conservation measured by the two probes in each station, both upstream and downstream of the rotor which compares with the mass flow measured by the Venturi, with an accuracy of ± 0.50 %.

The validity of the following discussions is supported by the credit we give to the measurements. We shall see that a lot of controls are possible to check the coherence of the measurements. First of all, the good agreements between the two probes (cylindrical and cobra) (fig. 2) allow to check the slope of distributions of flow quantities along the radius. Let us repeat that the confidence for this point is reinforced by the fact that, because of their different geometries, the two probes have a completely different response (excepted for the nonstationary response which is only indirectly checked). The agreement between the static pressure taps at the wall allows to check the pressure level. The proper levels of the angle and stagnation temperature distributions may be checked when considering the agreement with the venturi's mass flow. Also the conservation of the mean rothalpy may be verified accrpss a moving blade row at least at mid-span. Finally, an analysis of the axial evolution of measurements and a comparison with theoretical results are the final tests. These points will be devoted to the chapter 3.

Aerodynamic testing conditions.

The compressor has been operated at 0.95 Nn, with a mass flow of 14.9 ± 0.2 kg/s and a pressure ratio of 1.32. Such operating conditions have been choosen in order to avoid strong interaction between the shear layers and the shock system in the rotating blade row.

3 - PRESENTATION AND ANALYSIS OF EXPERIMENTAL RESULTS

We shall present here the radial evolution of flow quantities behind the rotating blade row in the hub region, for the station 4 in figure 1. The difficulties in analysing the flow in station 4 are that the measurements are made in a stationary frame of reference, while the hypothesis concerning the flow behaviour are more easily made in a relative one. We shall then analyse the flow according to the relative quantities. The measurements with the cobra and cylindrical probes are given by the square and cross symbols respectively. For comparisons, some inviscid flow computations are also given. These results have been obtained with the help of blade-to-blade and meridional flow computations.Boundary layer effects on the blades have been taken into account for the estimation of the "inviscid" losses. Also the influence of the secondary flows is introduced, on the inviscid flow computation, by added mass-flows at the hub and tip boundaries.

Consider now the relative flow angle distribution (fig. 3). We notice the agreement between inviscid flow computations and the measurements for $h > 35$ %.
In the hub region, the $\overline{\beta}$ angle evolution has the classical shape, as observed in fixed blade cascade (see [7] for instance). This $\overline{\beta}$ distribution may then be considered as a direct consequence of a passage vortex. For comparison, the shifted distribution in station 3, upstream of the rotor is also given.

The prediction of the inviscid losses in relative stagnation pressure $\overline{\text{Por}}$ is well reproduced by the computational methods, up to 15 % of the blade height. (fig. 5). Very near to the wall, we notice that the $\overline{\text{Por}}$ evolution may not be reproduced by a classical boundary layer profile, as observed in a fixed blade cascade (see [7]).
Considering the static pressure evolution $\overline{\text{Ps}}$ (fig. 4), excepted very near to the hub, we can see that $\overline{\text{Ps}}$ is mainly imposed by the inviscid flow.

The stagnation relative temperature $\overline{\text{Tor}}$ is given figure 6. We observe an important increase of $\overline{\text{Tor}}$ over the inviscid flow curve, in the hub region, (especially for $h < 0.15$), while a good agreement is given everywhere else. Notice that we can estimate that error measurements on the stagnation absolute temperature $\overline{To}$ are here of the order of 1° K, in a stationary flow.

The reasons for such an evolution are difficult to find. We just want to suggest some ideas for future reasonings.
First of all, the accuracy of the measurements with our probe in strong three-dimensional unsteady flow has not been checked. Indirect informations on this subject may be given when we consider the agreement between measurements and predictions outside of the wall shear layer. However, the "unsteadiness" of the flow may be greater near the wall than outside. More experimental works are then needed.
Secondly, we may consider an heat transfer through the wall. In fact, we have observed an increase of 3° K of $\overline{To}$ in station 3, very near to the wall. However, this effect must not have any direct counterpart in an increase of $\overline{Por}$ in the rotor.
Thirdly, we could assume that the increase of $\overline{Tor}$ in station 4 over the inviscid values is associated with a corresponding increase of $\overline{Por}$, by some isentropic process. Then, using the solid squares in figure 6 for $\overline{Tor}$, we should obtain the corresponding symbols in figure 5 for $\overline{Por}$. It can be seen then, that this "experimental" evolution of $\overline{Por}$ in figure 5, is nearer to the classical boundary layer picture we have observed in fixed blade cascade (see [9]).

In the frame of this third hypothesis, it remains to imagine some way in order to increase $\overline{Por}$ (or $\overline{Tor}$) over the values given by the classical law of conservation of the mean rothalpy $\overline{I}$ on a streamline.
As noted by DEAN [11], if the relative flow is unsteady (, due to disturbances of stationary upstream blades), the rotating observer will see work done. A variation of the rothalpy $\overline{I}$ along the particule path may then be induced according to

$$\frac{D\overline{I}}{Dt} = \frac{1}{\rho}\frac{\partial P_s}{\partial t}$$

Such a situation may occur in our case because of the existence of the leakage flow effect in the hub region of the I.g.V (fig. 1), which distorts the Ps field up to station 3 in the leading edge region of the rotor (fig. 7).

Finally, according to SEHRA and KERREBROOK [12], the classical "conservation" of the mean rothalpy $\overline{I}$ along the particule path (for stationary and adiabatic upstream conditions) is again an oversimplification because of the variation of the velocity vector along the circumferential direction. This introduced additional stresses associated with the spatial fluctuating velocities. Some work may then be added to (or substracted from) the mean flow by these additional stresses, especially where highly 3D flows are observed (e.g. secondary flow regions).

CONCLUSION

Some measurements have been presented for the hub region downstream of the rotor of a transonic compressor. The experimental results were resolved in a relative frame of reference in order to check the hypothesis associated with the secondary flow study. The classical effect of a passage vortex has been observed on the relative flow angle distribution $\overline{\beta}$. Also, the static pressure distribution $\overline{Ps}$ was very well predicted by inviscid flow computation.

Finally, an unexpected increase of $\overline{Tor}$ has been observed over the value given by the inviscid flows computation. No definite explanations of this phenomenon have been given.

The unsteady response of the probe in strong three-dimensional flow remains to be checked, especially for the temperature measurements.

However, the classical laws of "conservation" of the mean rothalpy may be perhaps corrected in our case, according to upstream unsteady disturbances or owing to the high local three-dimensionality of the flow in this region.

It is believed that more work is needed to refine our knowledge on the flow in this area.

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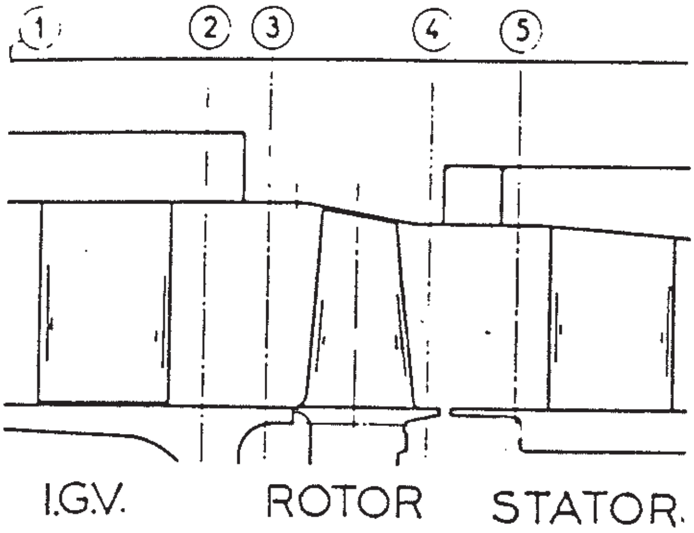
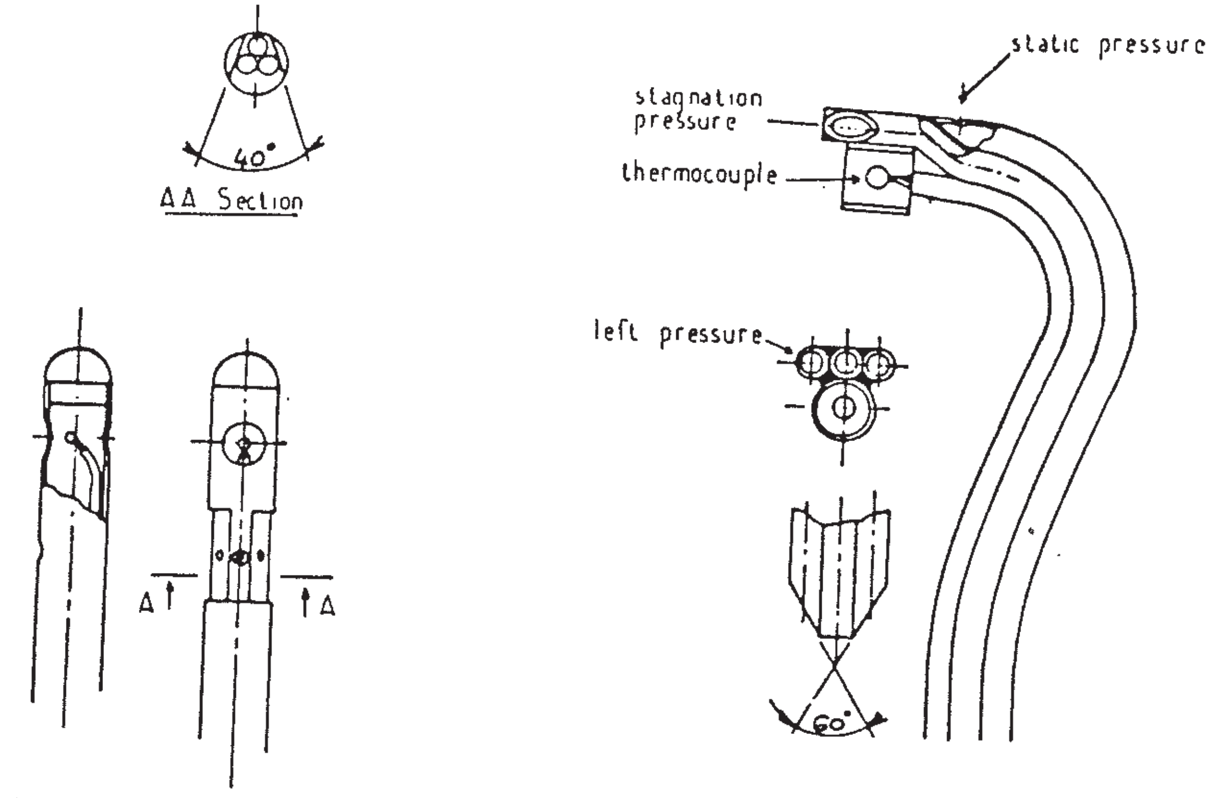
FIGURE 1

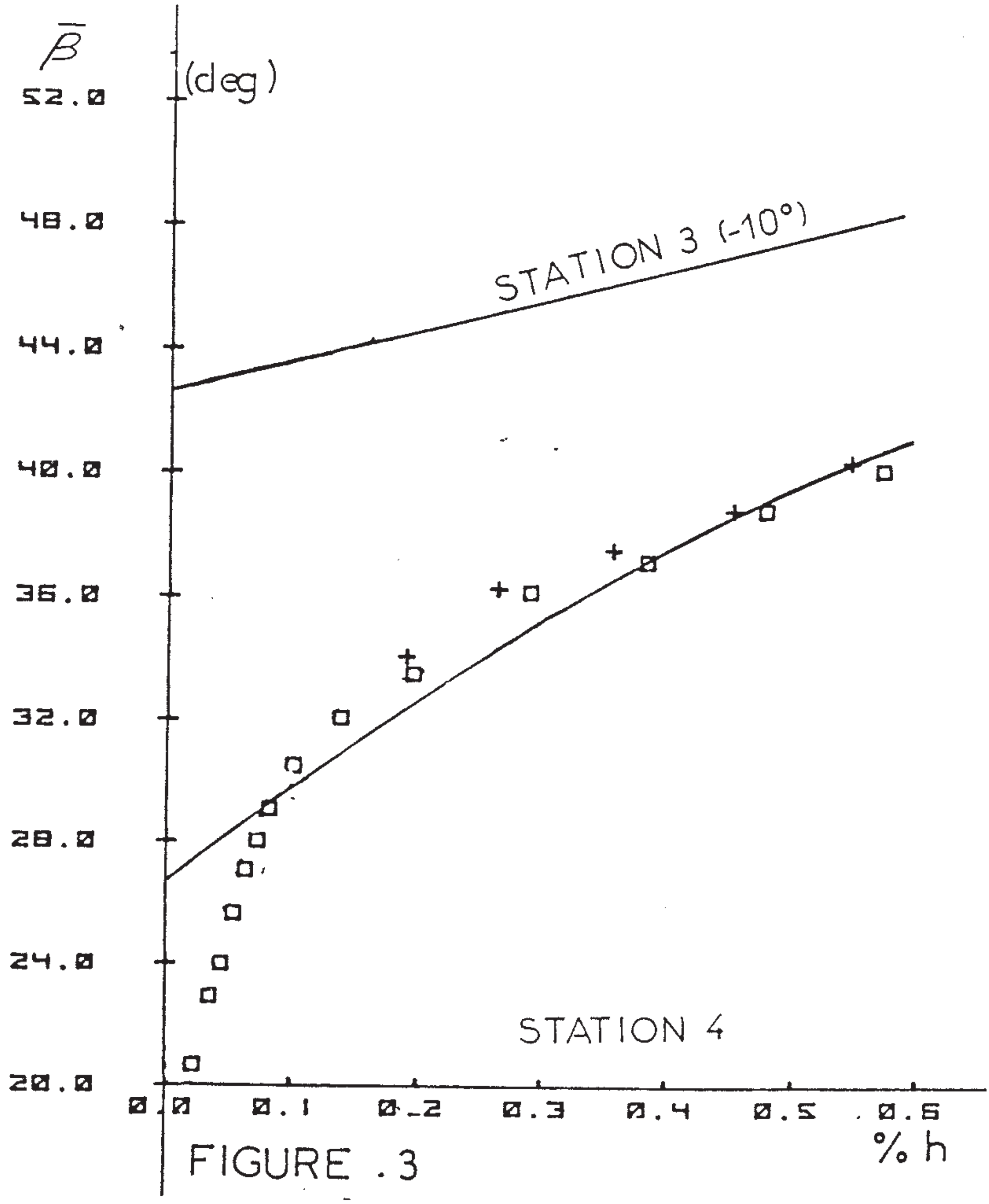




cylindrical probe

cobra type probe

FIGURE 2 Pressure probes.



$\bar{\beta}$ (deg)
52.0
48.0
44.0
40.0
36.0
32.0
28.0
24.0
20.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
% h
STATION 3 (-10°)
STATION 4

FIGURE .3

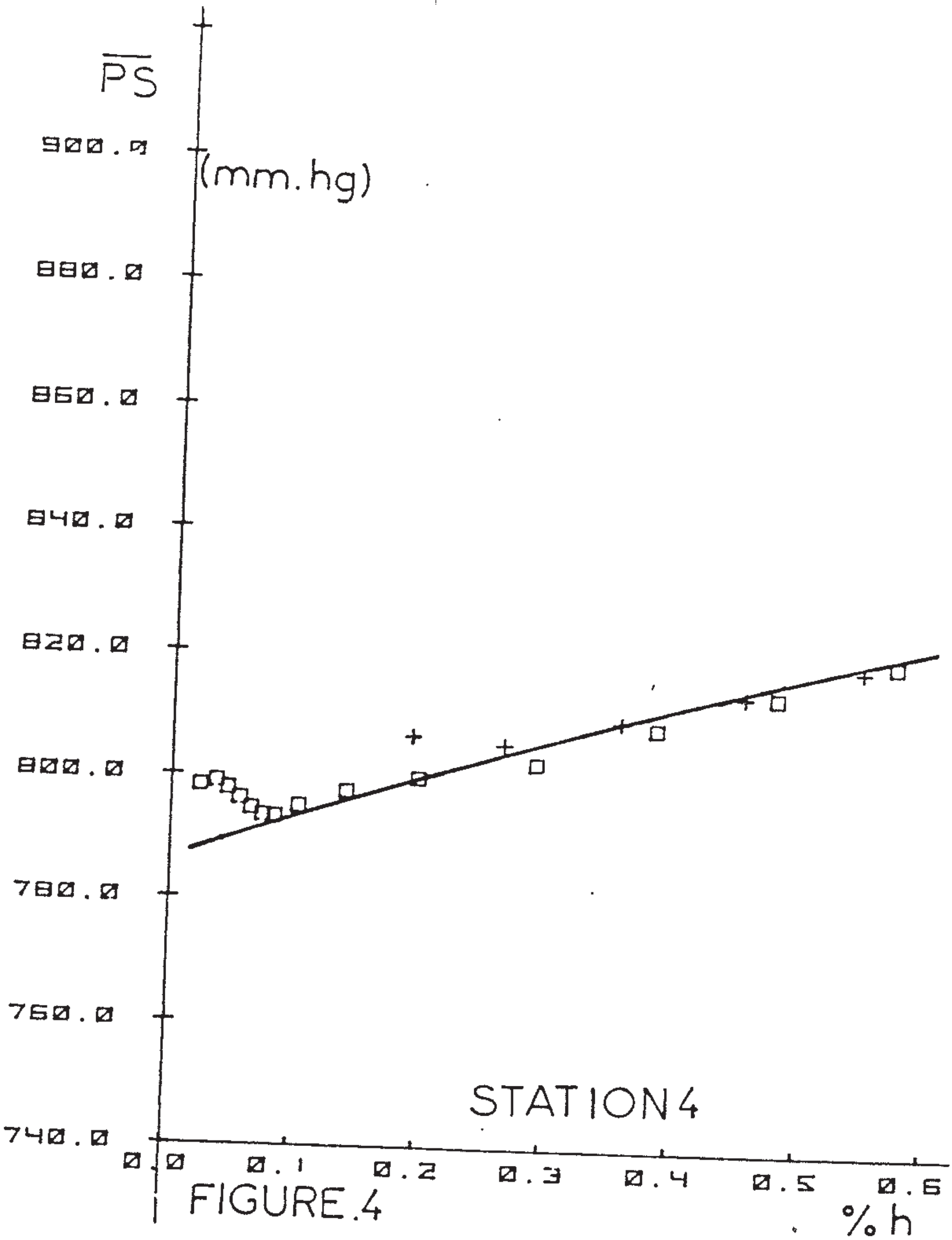

PS
(mm.hg)
900.0
880.0
860.0
840.0
820.0
800.0
780.0
760.0
740.0
STATION 4
0.0
0.1
0.2
0.3
0.4
0.5
0.6
%h

FIGURE.4

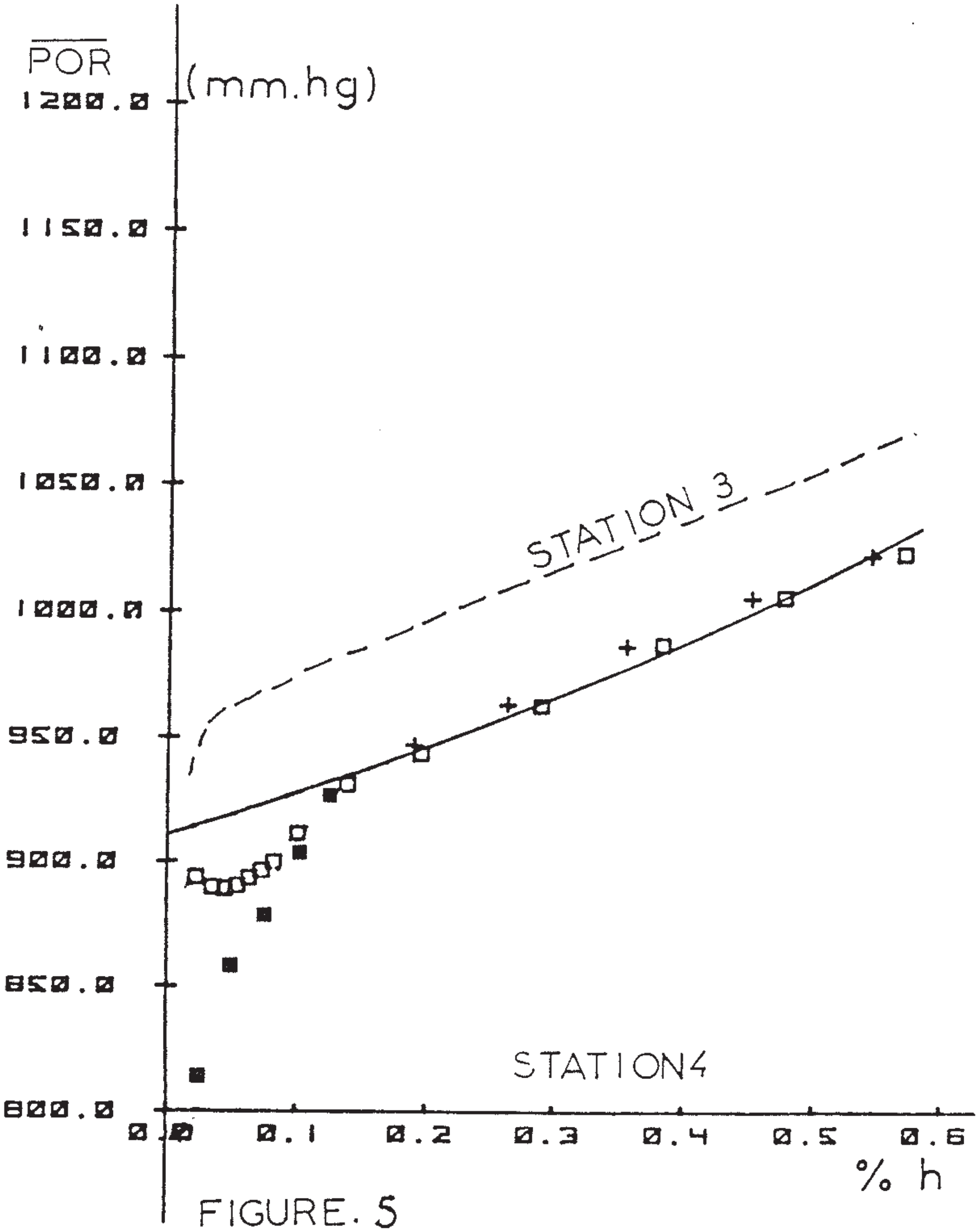

$\overline{\text{POR}}$
(mm.hg)
1200.0
1150.0
1100.0
1050.0
1000.0
950.0
900.0
850.0
800.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
% h
STATION 3
STATION4

FIGURE. 5

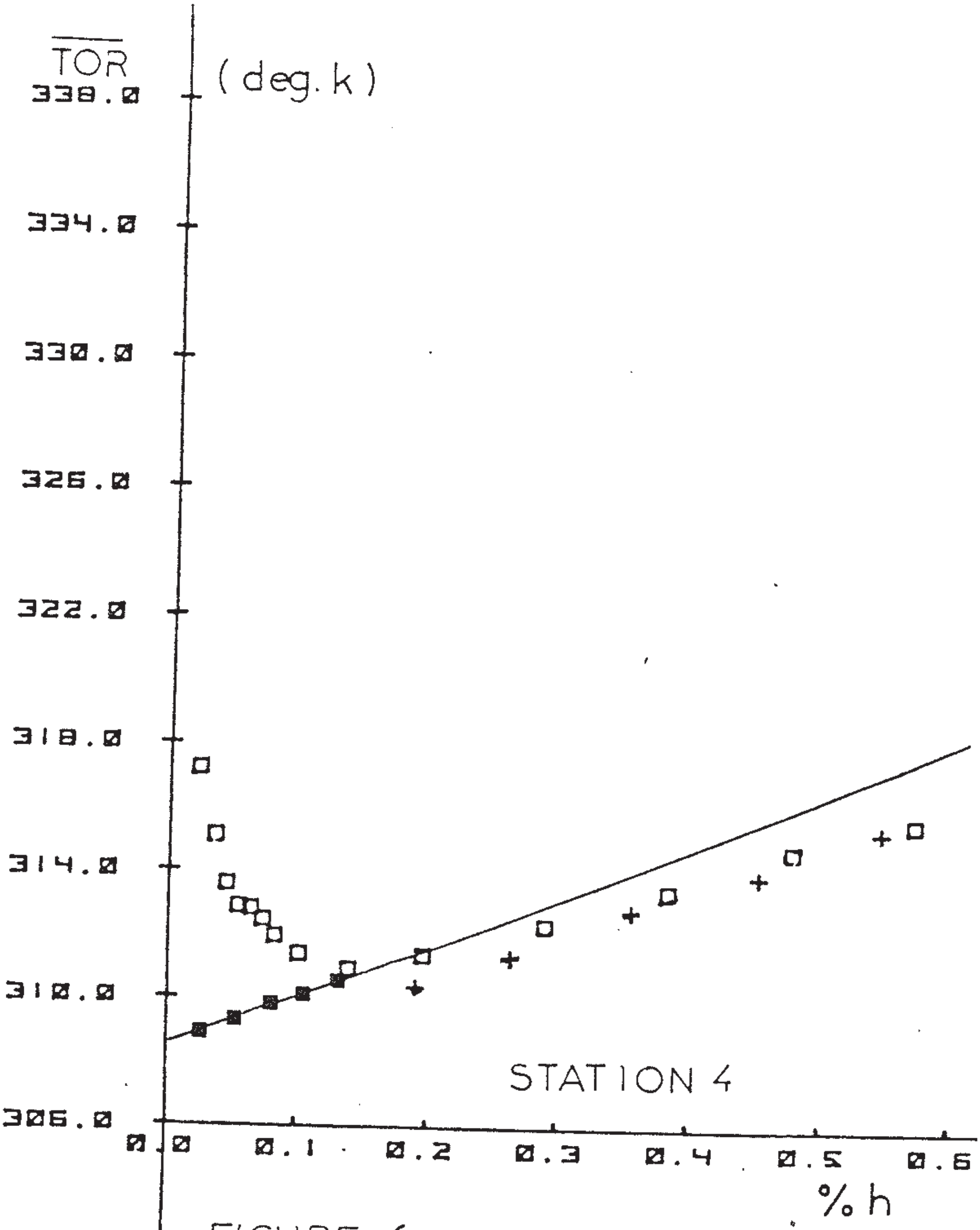

$\overline{TOR}$ (deg. k)
338.0
334.0
330.0
326.0
322.0
318.0
314.0
310.0
306.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
% h
STATION 4

FIGURE. 6

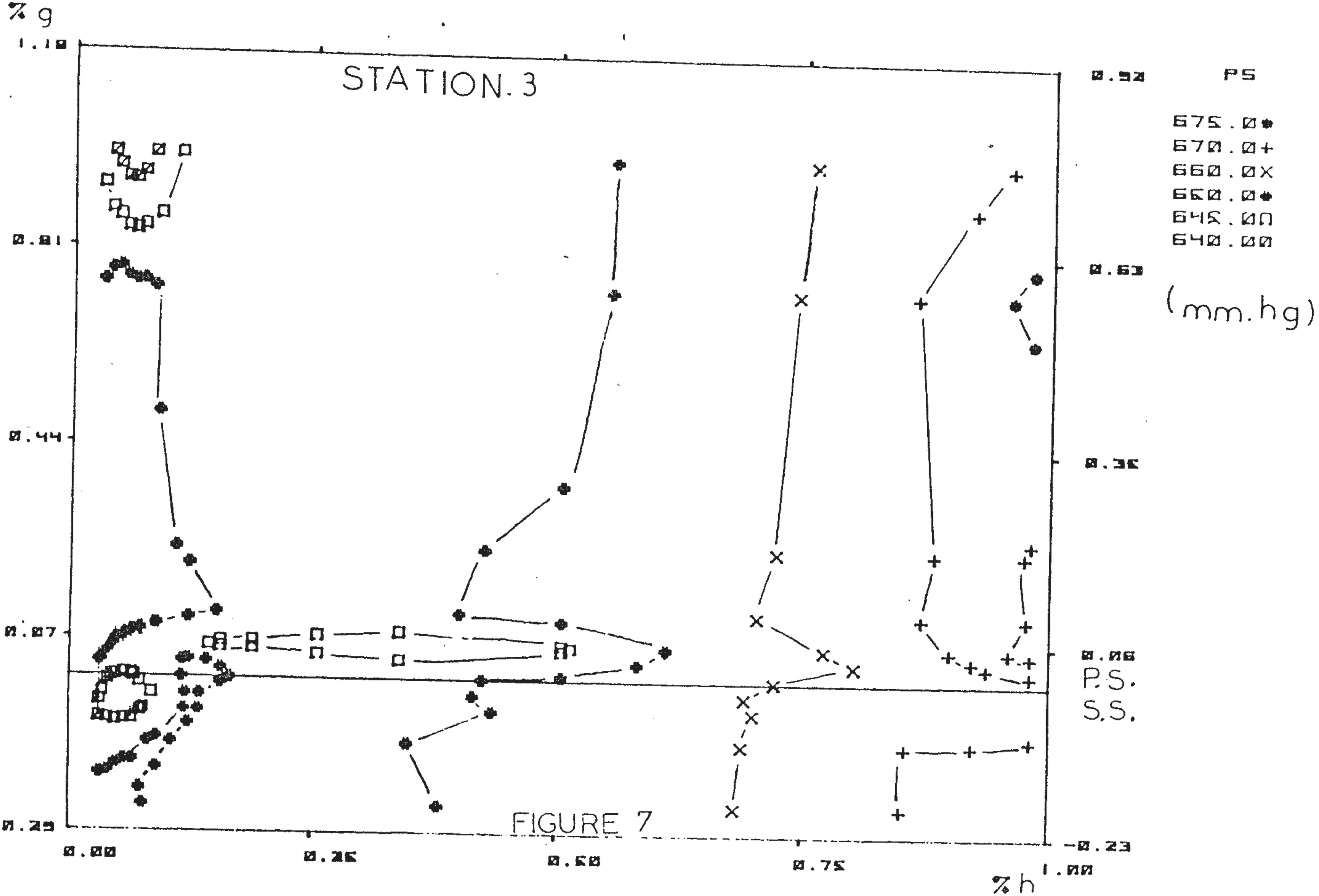

% g
1.10
0.81
0.44
0.07
-0.25
STATION. 3
0.00
0.25
0.50
0.75
1.00
% h
0.92
0.63
0.36
0.06
-0.23
P.S.
S.S.
PS
675.0 ●
670.0 +
660.0 X
650.0 ●
645.0 □
640.0 □
(mm.hg)

FIGURE 7