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THE EXISTENCE OF THREE-DIMENSIONAL PERTURBATIONS IN THE REATTACHMENT OF A TWO-DIMENSIONAL SUPERSONIC BOUNDARY-LAYER AFTER SEPARATION

by

Jean J. GINOUX.

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ABSTRACT

The reattachment region of a laminar boundary-layer after separation has been investigated in TCEA facilities at a Mach number of 2.16. Two-dimensional compression-corners and backward or forward facing step models were used. The case of interaction between a shock-wave and a laminar boundary-layer was also considered.

Surface flow was observed by a sublimation technique and detailed span-wise surveys were made in the reattachment region of the flow with total-head probes.

Strong, regular and repeatable span-wise perturbations were observed in the boundary-layer; these could not be explained by irregularities either in the air-flow upstream of the models or in the models themselves. It was found in all cases that street-like flow perturbations existed up to the point where transition occurred.

A systematic investigation was made on backward facing steps in order to find out the effects of step height and boundary-layer thickness on the wave-length of the flow perturbations.

INTRODUCTION

Work done by many other investigators has shown that whereas a laminar separated region is unstable at low speeds, the stability increases greatly with Mach number and becomes surprisingly stable at hypersonic speeds.

The current considerable interest in separated flow studies at hypersonic speeds stems from the fact that the heat-transfer rate from a separated mixing layer is less than that from a corresponding attached layer and could be reduced to a substantially zero value by the use of gas injection, assuming that the stability of the flow does not deteriorate (2). As there are large regions of laminar supersonic flow over many practical wing designs, operating at free-stream hypersonic speeds, the interest in separated flow at these speeds is extended to the supersonic speed range.

In the course of an experimental investigation on supersonic separated flows, strong, regular and repeatable span-wise perturbations were observed in the reattachment region of the flow (3). As far as the author is aware such phenomenon had not been observed in supersonic flow before. In an investigation under similar conditions, Chapman (1) concluded that the flow was strictly two-dimensional; but, in his case, no detailed span-wise surveys were made. As there was some doubt about the origin of these disturbances, a careful experimental analysis was made to check the influence of possible irregularities in the air-flow upstream of the model or in the model itself and also to verify whether the phenomenon existed only on the particular model that was used or if it was more fundamental.

The research was sponsored by the Air Research and Development Command under U.S. Air Force contract n° 61(514)-993, through its European Office, ARDC.

DESCRIPTION OF THE EQUIPMENT

Wind Tunnels

S-1 Tunnel : Most of the experiments were conducted in the TCEA 40 x 40 cm^2 (16" x 16") supersonic wind-tunnel. This tunnel was operated continuously with dry air at a Mach number of 2.16. The stagnation pressure was below atmospheric and could be varied from 90 to 220 mm of mercury absolute.

S-2 Tunnel : A few tests were made, for comparison, at the same Mach number, in a 15 x 15 mm^2 (0.6" x 0.6") supersonic wind-tunnel. Tunnel S-2 was operated continuously with dry air, using the vacuum pump of tunnel S-1 and its auxiliary dryer. The stagnation pressure was slightly below the atmospheric pressure. The nozzle was asymetric; only one block was contoured, the other one being flat.

Both tunnels were equipped with conventional optical systems using parabolic mirrors and a spark light source.

Models

The geometry, dimensions and designations of the various models that were used in tunnel S-1 are given in figure 1. Most of the models were formed by assembling together a number of interchangeable pieces. The leading-edge thickness was equal to 0.1 mm (0.004 inch) with the exception of model S-6 which was 0.02 mm thick. Models completely spanned the 40 cmstest section except compression-corners (CC-models) and models S-6, S-7, S-18, S-19 having a 150 mm span. Model S-8 had a 250 mm span. The models were mounted on a double support allowing for the adjustement of the angle of attack. Figure 2a shows model S-1 in the test section of tunnel S-1. In tunnel S-2, backward-facing steps were directly machined in the flat wall of the nozzle as shown in figure 2b.

Test Techniques

The flow on the surface of the models was observed by the sublimation of azobenzene. Detailed surveys were made with total-head probes. The probes were located against the model surface. One was fixed and used as a reference while a second one was moved in a span-wise direction. In the early tests it was manually operated by steps using a micrometric device. Later, the probe was moved at a constant and low speed using an electric motor, the pressure difference between the fixed and the moving probes being measured by a pressure transducer and a Brown recorder.

PRELIMINARY TESTS

In the initial phase of a research made on supersonic separated flows, some doubt arose about the possibility of getting a perfectly two-dimensional flow over a model with a backward-facing step which completely spanned the tunnel. It was therefore decided to investigate carefully the flow on the model surface using a sublimation technique; the indicator was azobenzene. Using this technique, span-wise (i.e. three-dimensional) perturbations were found to be present in the reattachment region of the flow when transition was located downstream of reattachment. They appeared in the form of regular striations, where the sublimation rate was high. The test was remade several times and consistently similar striation patterns were found on each occasion. The result is shown in figure 3a which was obtained after a 3-hours run of the tunnel.

EFFECT OF POSSIBLE PERTURBATIONS IN THE FREE-STREAM OR IN THE MODELS

A series of tests, made for various free-stream conditions and on different models, showed that possible free-stream perturbations or model irregularities could not explain the existence of strong, repeatable and regular span-wise perturbations in the boundary-layer.

The influence of the quality of the flow upstream the nozzle was checked in tunnel S-1, by placing three 13-mesh screens (0.5 mm diameter) followed by two 55-mesh screens (0.2 mm diameter) in the settling chamber. Tests were also made with humid air. The model was then mounted in a vertical plane instead of horizontal as in all the other tests. Two models having the same geometry but machined in different materials (copper and steel) and in different workshops were tested and compared. Finally the angle of attack of the model was varied from 1°30' to -1°30'.

In all cases the same pattern of surface flow was observed (3). The results were later confirmed by the tests made in tunnel S-2. Furthermore, the increased roughness of the surface owing to the azobenzene crystals was found to have no influence on the phenomenon. With a clean model, the same flow perturbations were detected by transverse total-head surveys made in the reattachment region, as detailed below.

The effect of leading-edge thickness was considered. No influence was found when it was reduced from 0.1 mm to 0.02 mm on a particular model (model S-6, figure 3g). Tests were made on models having identical cross-sections but different spans (models S-5, 7 and 8) equal to 40, 25 and 15 cms. There was no appreciable effect on the flow pattern. The result obtained on model S-8 is shown in figure 3i.

RESULTS ON VARIOUS TYPES OF SEPARATED AND UNSEPARATED FLOWS

Various types of laminar separated flows were examined in relation to the existence of span-wise perturbations. The tests were made in tunnel S-1.

A separated flow was obtained by interacting a laminar boundary-layer with two-dimensional oblique shock-waves. The shock strengths were so chosen that separation occurred with a laminar reattachment as shown in figure 4a. Figure 3b shows that a striation pattern existed downstream of reattachment.

The flow around an upstream-facing step (model DS-11) was also investigated. A 0.6 mm step height was used. Figure 4g is a schlieren picture of the flow around model DS-11. The result of a test made with the sublimation technique is given in figure 3m; it shows the existence of span-wise perturbations in the flow downstream of reattachment.

Finally, separated flow was studied on a body of revolution in which a "backward-facing step" was formed by a sudden decrease in the diameter (figure 1). Figure 3(o) shows the existence of essentially similar perturbations to those found in the earlier models.

A test was made in tunnel S-2, using the sublimation technique, to visualize the flow on the surface of the contoured nozzle wall in the presence of a laminar boundary-layer. Figure 3p shows that three-dimensional perturbations again existed in the boundary-layer upstream of transition.

All the surface flow pictures shown in figure 3 were obtained after several-hours running time of the tunnel. This is thus an indication that the flow perturbations were essentially located at fixed positions on each model.

DETAILED MEASUREMENTS ON STEP MODELS

A detailed study of laminar separated flows was started in tunnel S-1, on backward-facing steps and on compression corners. At present, only the effect of boundary-layer thickness (δ) and step height (h) on the spacing (or so-called "wave-length" λ) of the flow perturbations has been examined. A few tests were also made when reattachment occurred on convex surfaces. The models that were used are shown in figure 1. δ and h were varied within the following ranges :

$$0.1 < \delta < 3 \text{ mm}$$
$$0.3 < h < 21 \text{ mm}$$

where δ is the boundary-layer thickness at separation; it was computed assuming an adiabatic flat plate with zero leading-edge thickness. δ was varied by using different lengths L for the flat plate and by changing the tunnel stagnation pressure. The leading-edge angle of the models was kept below 10°; in these circumstances, it was found difficult to get separation of very thin boundary-layers and still have an acceptable range of step heights. The difficulty was overcome by using compression-corners located at a small distance behind the leading-edge of a flat plate; the models (CC-models) are shown in figure 1. By varying the angle of the compression corner and its position on the flat plate, separation could be obtained very close to the leading-edge, thus giving small values of δ . An example is given in figure 4h, which is a schlieren picture of the flow around model CC-1.

The radius of curvature of the surface upon which reattachment occurred was variously chosen as 1000 mm and 250 mm as shown in figure 1 (SR-models) and by the shadowgraphs given in figures 4b and 4c.

Measurements were also made in tunnel S-2 on backward-facing steps located in the flat nozzle wall. The boundary-layer was laminar and its thickness at separation was equal to 0.6 mm; this value was measured by surveying the boundary-layer with a small circular total-head probe.

Shadowgraphs and schlieren pictures were taken of each flow to locate the position of transition; examples are given in figure 4. A chemical technique was used to obtain a qualitative picture of the flow on the surface of the various models; the scale of the various pictures given in figure 3 is not the same, due to the fact that a certain number of models did not completely span the working section of tunnel S-1. For quantitative information, detailed surveys were made using a total-head probe which was moved across the model at a constant distance (x) from the step-base. The same cylindrical probe was used for all the various flow conditions and models. It had an external diameter of 1 mm and an internal diameter of 0.5 mm; the probe was always moved in contact with the model surface. The difference in the readings (Δp) of the moving probe and of an identical fixed probe, located at the same distance (x), was recorded by a pressure transducer and a Brown recorder. Values of Δp shown in the graphs are given in millimetres of water.

Using this technique, span-wise variations of Δp were found in the region of reattachment. There existed peaks and valleys in the pressure distribution, which were almost precisely equally spaced, although of very irregular magnitude. The repeatability of the measurements was very good; this is shown in figure 5 for model CC-1, at $\alpha = 0$ and $x_c = 20$ mm. Two successive surveys were made at $p_o = 200$ mm Hg and two others at $p_o = 146$ and 116 mm Hg.

Tests were made in order to compare the results of both techniques. Good agreement was always found; each pressure peak (or valley) corresponded to a stria where the sublimation rate was high (or low). Figure 6 shows a typical example of such a comparison made for model S-1; the striation pattern which is schematically shown was obtained from figure 3a.

Not much attention was given on the recorded amplitudes of the pressure peaks because of their irregular form. The strongest peaks were found to exist on compression-corners (CC-models); (Δp)s of about 300 mm of water were measured (figure 5); figures 3e and 3f show the flow pattern obtained on models CC-1 and CC-2.

On the other hand, for small values of (h) on step models, the total-head probe gave no indication of pressure variations (within the accuracy of measurement, i.e. a few mm of water) although a striation pattern was clearly indicated by the azobenzene as shown for example by figures 3ℓ and 3n for models DS-8 and DS-9 having a 0.8 mm backward-facing step. In these cases, quantitative information, such as the wave-length of the perturbations, was taken directly from the pictures of surface flow.

In all cases, the striation pattern existed up to the point where transition occurred, except on models S-18 and S-19 where the flow perturbations seemed to vanish well upstream of transition; this is shown in figures 3h and 3j. The sublimation technique gave no indication of a striation pattern in the turbulent region of flow. Such a pattern seemed to vanish when transition was reached (as determined from the shadowgraphs). However, surveys made with the probe in that region on model S-1 did show pressure variations over a certain distance downstream of transition. The results are shown in figure 6, the striation pattern being also indicated; x is the distance from the step base. A shadowgraph of the flow is given in figure 4f.

DISCUSSION OF THE RESULTS

Table I summarizes the results obtained on the various types of models. The distance between successive pressure peaks ("wave-length") was not exactly constant on each model, but varied within the range indicated. Also given in table I is the tunnel stagnation pressure (p_o in mm of mercury) which was used, together with the length (L) given in figure 1, to compute the boundary-layer thickness (δ).

Except for compression-corner models (CC-models), for which h could not be accurately defined, non-dimensional quantities such as λ / δ and h/δ were introduced and plotted in a diagram as shown in figure 7. A mean wave-length defined as the ratio of a certain basic span-wise length divided by the number of pressure peaks recorded along that length is also indicated on the graph.

Figure 7 shows that a good correlation was obtained between the experimental results by using these non-dimensional quantities. λ / δ increased when h/δ was increased from zero to about 3; then stayed constant for h/δ up to 8 and then increased again for higher values of h/δ . Correspondingly, transition moved upstream when h/δ was increased. It reached the point of reattachment for h/δ between 8 and 13.

Figure 7 also shows that λ / δ did not tend towards zero as h/δ approached zero. This result was confirmed as a striation pattern was observed incidently on the flat surface of model S-17 upstream of the step after a 9-hours run of the tunnel; the surface flow on the complete model is shown in figure 3c whereas a detailed portion of the model where the phenomenon appeared is given in figure 3d. There was no indication of a boundary-layer separation in that region of the flow; weak perturbations were present in the wind-tunnel, one being created by a rubber joint which was not correctly fastened to the model side. λ / δ was found to be within 1.2 to 1.4 in that case; this range of values is plotted on the vertical axis of figure 7.

It was found occasionally that very irregular, weak and localised striations existed on the model surface upstream of the step, although these were not very clearly indicated (3). It might be thus possible that three-dimensional perturbations existed initially in the laminar boundary-layer and as the flow separated and reattached, the perturbations corresponding to a given wave-length were amplified, the selected wave-length being related to the boundary-layer thickness. The perturbations then travelled for a certain distance, function of the ratio h/δ before transition appeared.

The effect of the streamline curvature, related to the positive pressure gradient that always existed at reattachment, is presently being investigated. The importance of the flow curvature has been pointed out by

Görtler in a theoretical investigation on incompressible boundary-layers (4,5). However, three-dimensional perturbations have been detected experimentally at low speeds by Hama et al (6), and also by Klebanoff (7), that could not be attributed to streamline curvature. Moreover, the tests made on the SR-models showed that the flow perturbations still persisted when the boundary-layer was flowing along convex surfaces (figures 4b and c, figure 3k).

CONCLUSIONS

1. Strong, regular and repeatable span-wise flow perturbations were found to exist in the reattachment region of a laminar boundary-layer on two-dimensional models that could not be explained by irregularities either in the air-flow upstream of the models or in the models themselves.

2. On backward-facing steps, at a given Mach number, the ratio of wave-length of the flow perturbations to boundary-layer thickness was a function of the ratio of step height to boundary-layer thickness.

3. Similar perturbations were also detected in unseparated laminar boundary-layer before transition occurred.

4. The presence of three-dimensional perturbations seems to be related to the general question of boundary-layer stability.

* *

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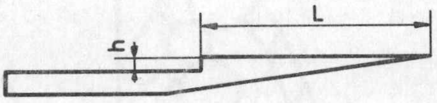
*

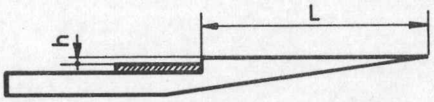
TABLE I

Model	δ (computed) from L & p_o	Range of λ (measured) mm	p_o mm Hg abs
S-1	2.08	3.5-6	220
S-2	1.5	3-5	220
S-3	2.47	4-7	181
S-4	1.49	3-5	223
S-5	1.04	2-3.5	213
S-6	1.10	2-4	195
S-7	1.07	2.5-4	212
S-8	1.05	2-3.5	211.4
S-11	2.19	4-9.3	193.3
S-12	1.58	-	195.3
S-13	2.16	5-up	198.9
S-14	1.6	6-10	193.2
S-15	2.16	8-18	200
S-16	1.57	-	197.7
S-17	3.07	-	200
S-18	0.50	0.5-1	200.3
S-19	0.72	1.5-2	195.5
DS1	1.48	2-5	225.4
DS2	2.23	4-6	185.3
DS3	1.53	2.5-4	210.7
DS4	2.07	3-5	213.6
DS5	1.53	3-5	209.4
DS6	2.22	4-6	188
DS7	1.58	1.2-2	198
DS8	1.59	1.5-3	195
DS9	2.2	1.7-3.5	206
DS10	2.15	1.2-2.5	199
SR-1	2.05	4-7.5	220
SR-2	1.75	3-6	160
SR-3	2.12	2-5	205
SR-4	1.50	2.29	206
CC1 $x_c=20$ $\alpha = 0°$	≈ 0.4	1-2.5	200
$\alpha = 9°$	≈ 0.4	1.5-3	197
CC1 $x_c=10$ $\alpha = 0°$	≈ 0.3	≈ 1	198
CC2 $x_c=20$ $\alpha = 0°$	≈ 0.3	1.5-4.5	200



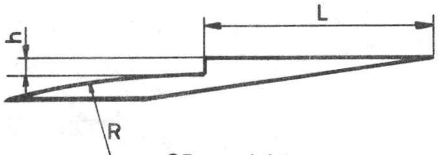
Single step (S-) models.

Model	h_{mm}	L_{mm}
S - 1	15	225
S - 2	15	120
S - 3	10	225
S - 4	10	120
S - 5	4	56
S - 6	3	59,6
S - 7	4	56
S - 8	4	56
S - 11	17	225
S - 12	17	120
S - 13	19	225
S - 14	19	120
S - 15	21	225
S - 16	21	120
S - 17	1	460
S - 18	0,5	12
S - 19	1	25



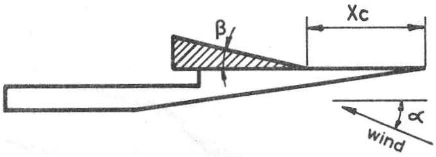
Double step (DS-)models.

Model	h_{mm}	L_{mm}
DS - 1	4	120
DS - 2	4	225
DS - 3	2	120
DS - 4	2	225
DS - 5	7	120
DS - 6	7	225
DS - 7	0,41	120
DS - 8	0,82	120
DS - 9	0,3	225
DS - 10	0,82	225



SR-models.

Model	h_{mm}	L_{mm}	R_{mm}
SR - 1	10	225	1000
SR - 2	10	120	1000
SR - 3	4	225	250
SR - 4	4	120	250



CC - models.

Model	β
CC - 1	14°
CC - 2	25°

Cone - cylinder

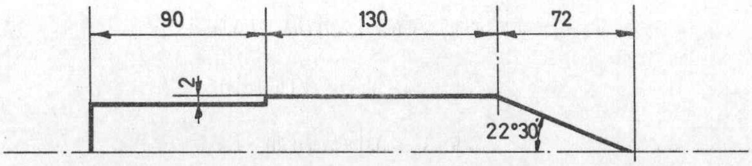
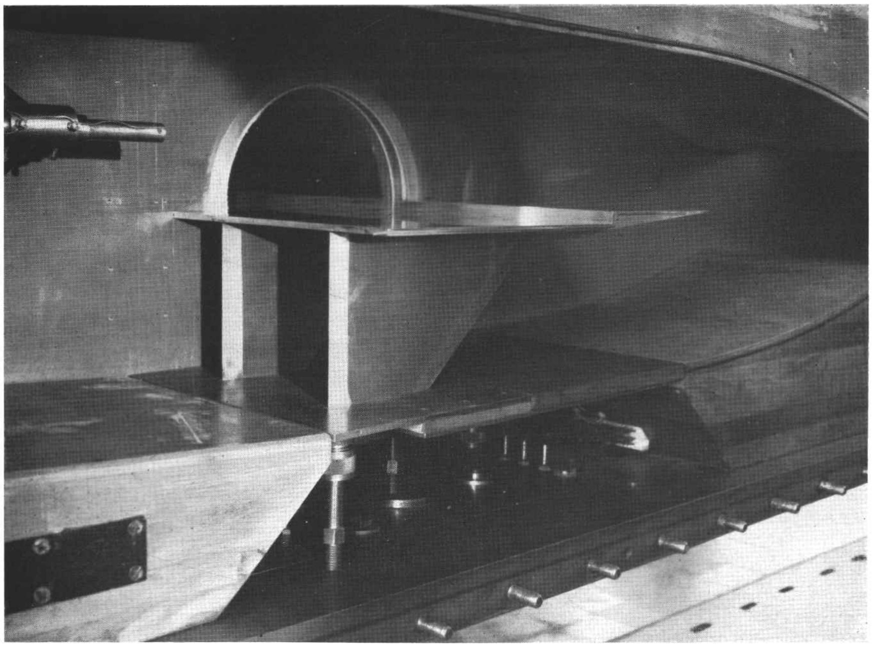
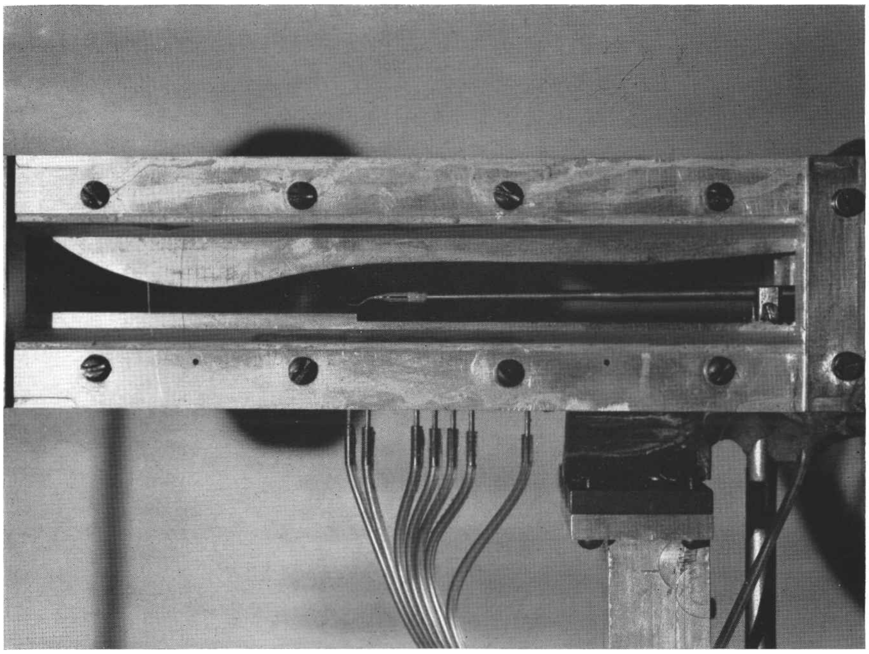


Figure 1 - Model configurations and designations.

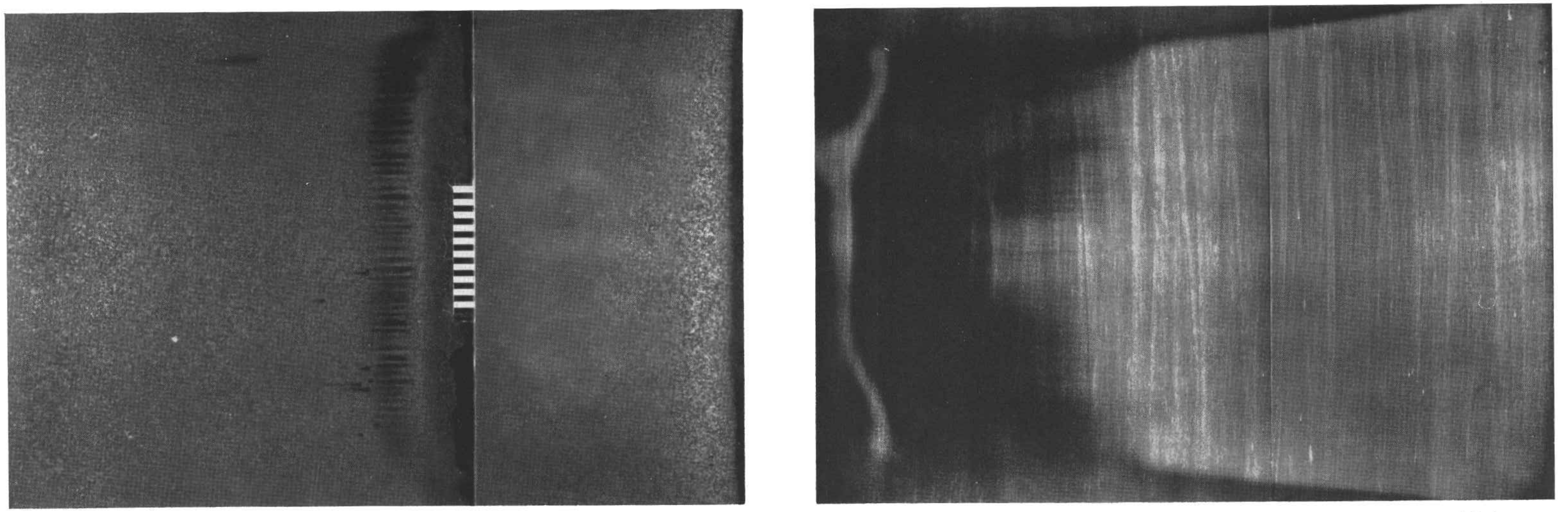


a) Tunnel S-1



b) Tunnel S-2

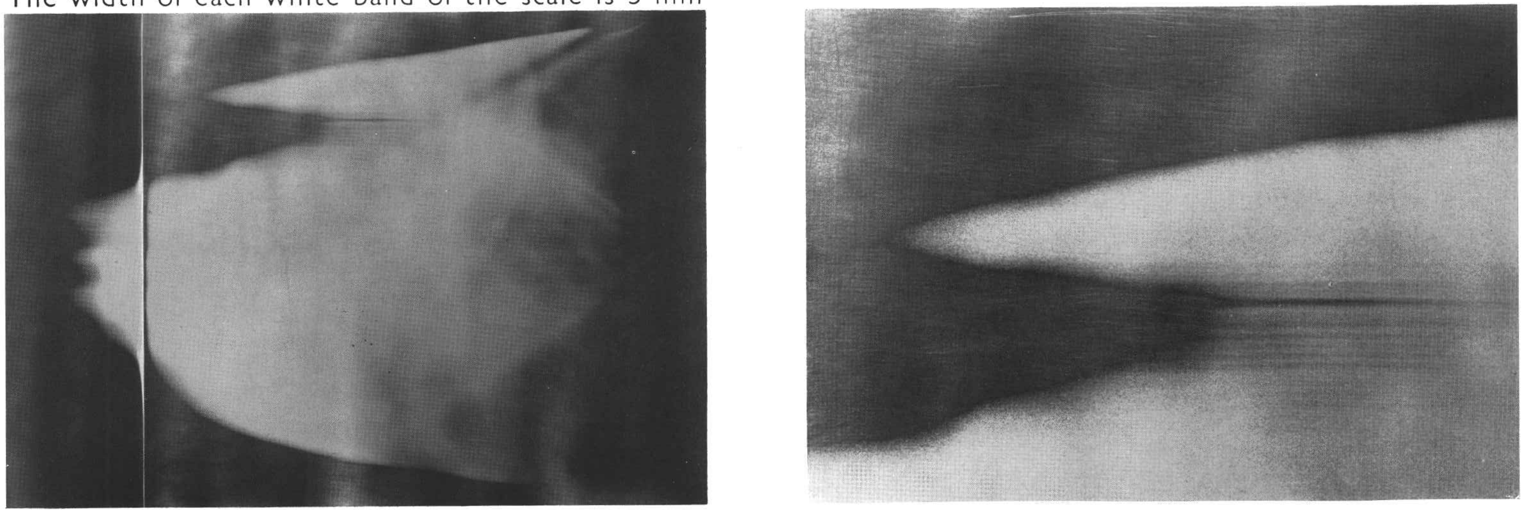
Figure 2. Tunnels S-1 and S-2



a) Model S-1 ; $p_o = 220$

The width of each white band of the scale is 5 mm

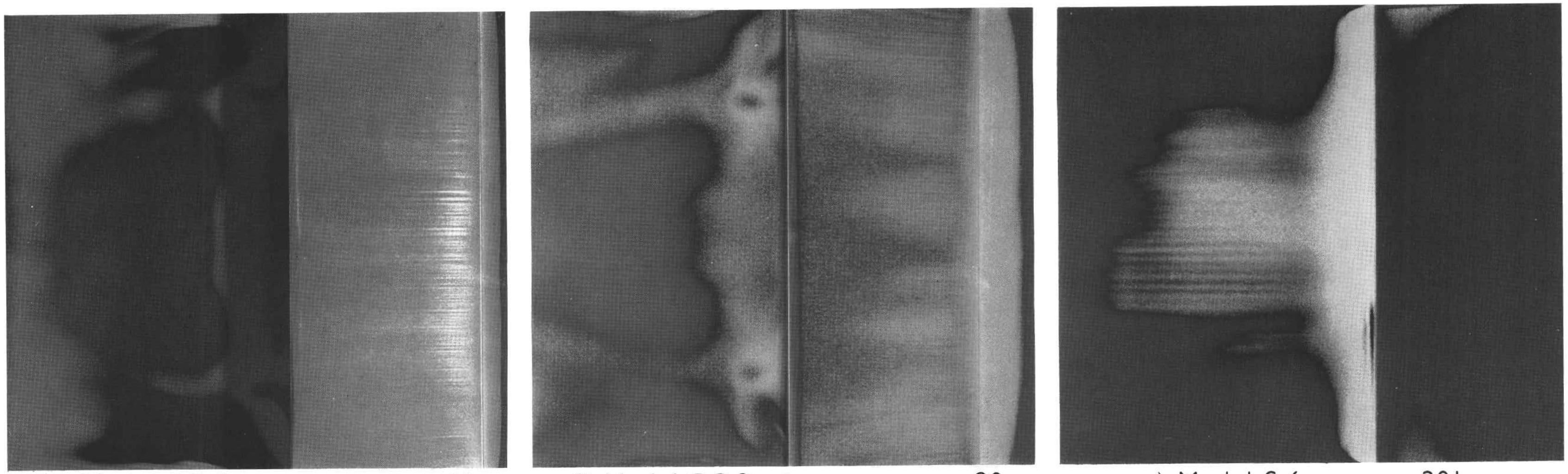
b) Shock-wave B.L. interaction ; $p_o = 126$



c) Model S-17 ; $p_o = 200$

d) Model S-17 - Details

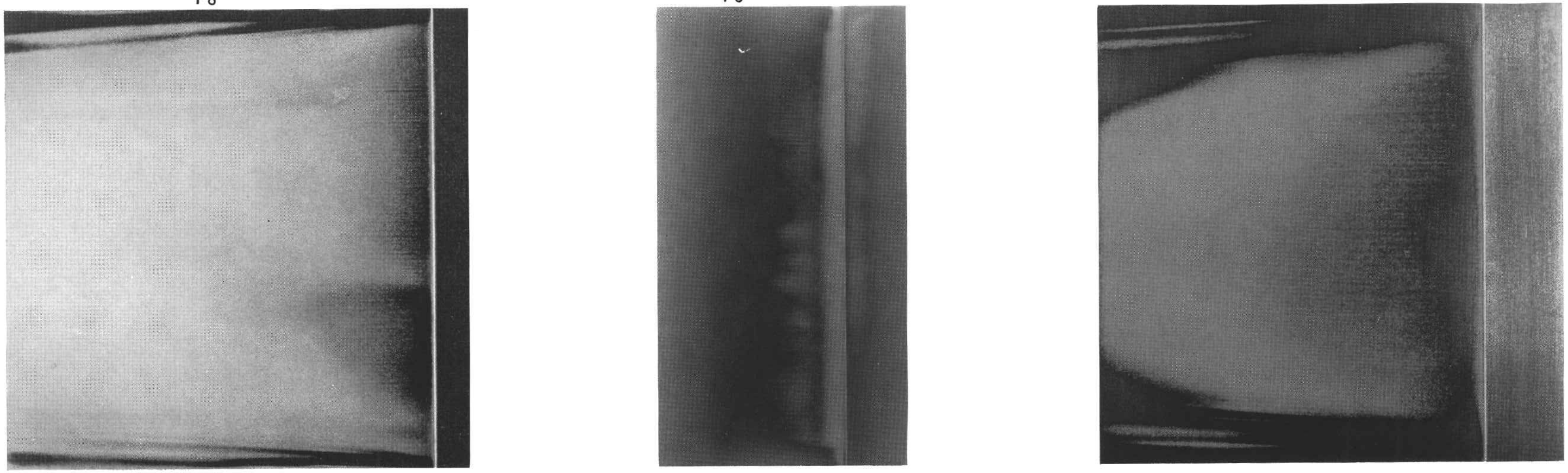
Figure 3. Sublimation technique



e) Model CC-1 - $\alpha = o$; $x_c = 10$ $p_o = 198$

f) Model CC-2 - $\alpha = o$; $x_c = 20$ $p_o = 196$

g) Model S-6 ; $p_o = 201$

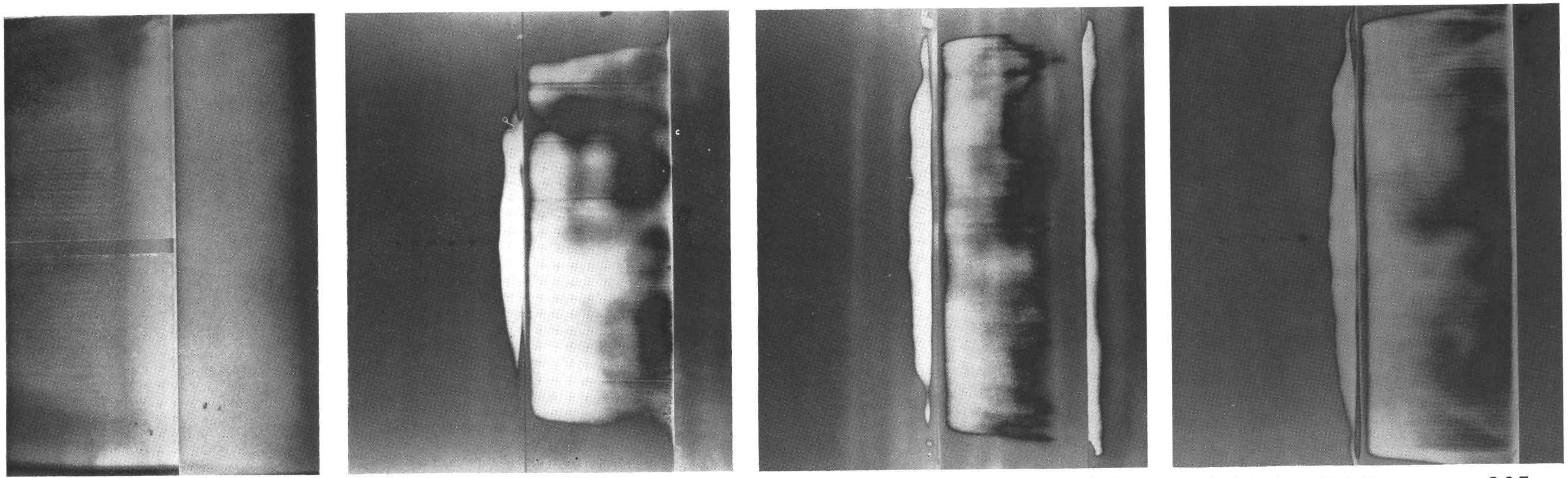


h) Model S-18 ; $p_o = 200$

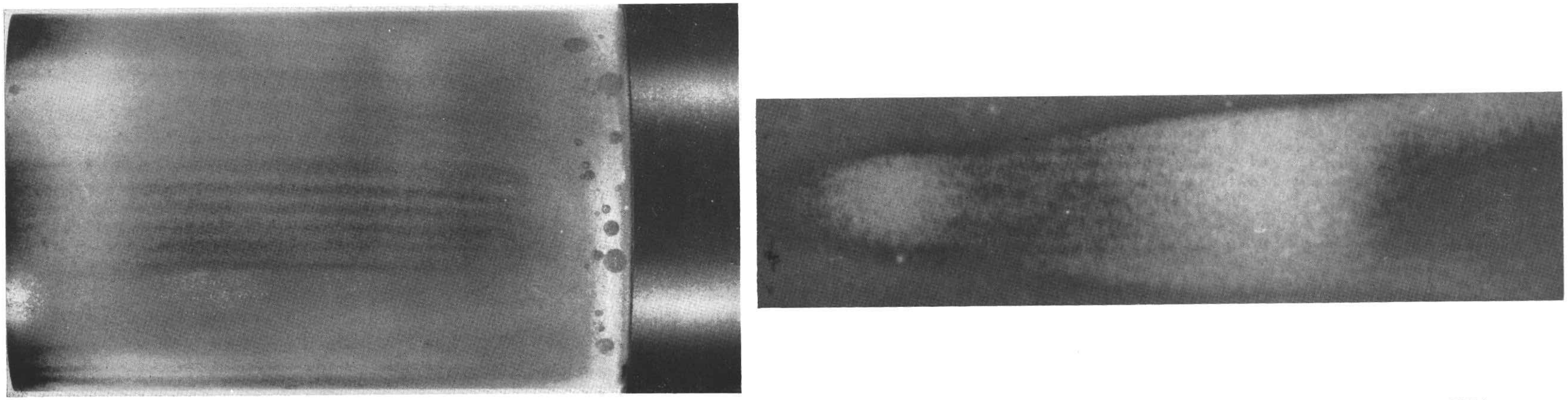
i) Model S-5 ; p_o 209

j) Model S-19 ; $p_o = 195$

Figure 3. Continued

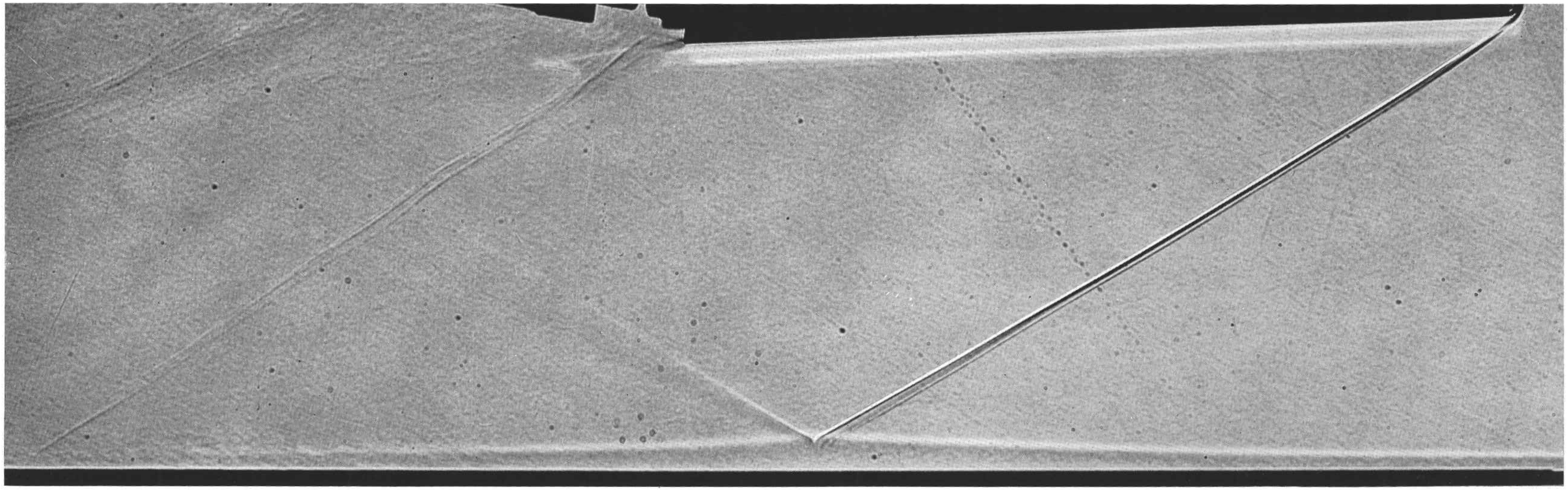


k) Model SR-2 ; $P_o = 162$ l) Model DS-9 ; $P_o = 206$ m) Model DS-11 ; $P_o = 198$ n) Model DS-8 ; $P_o = 205$

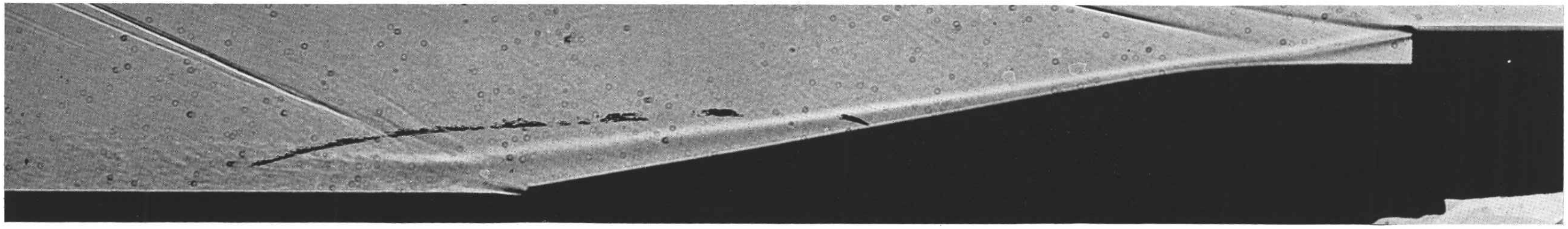


o) Body of revolution ; $P_o = 210$ p) Contoured wall of tunnel S-2 ; $P_o = 750$

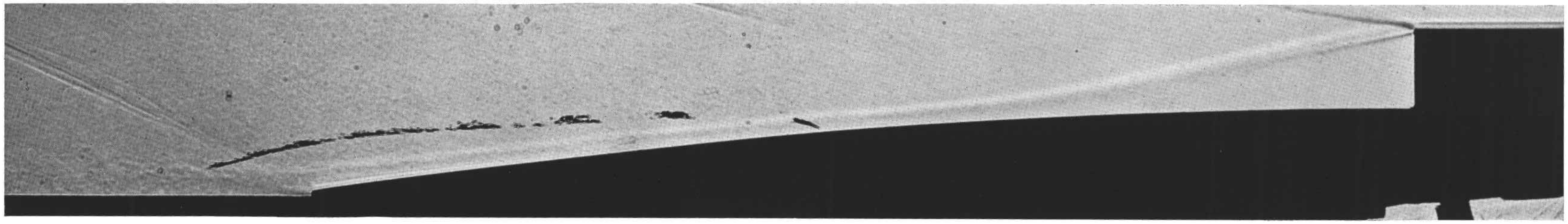
Figure 3. Continued



a) Shock-wave Boundary-layer Interaction ; $p_o = 126$

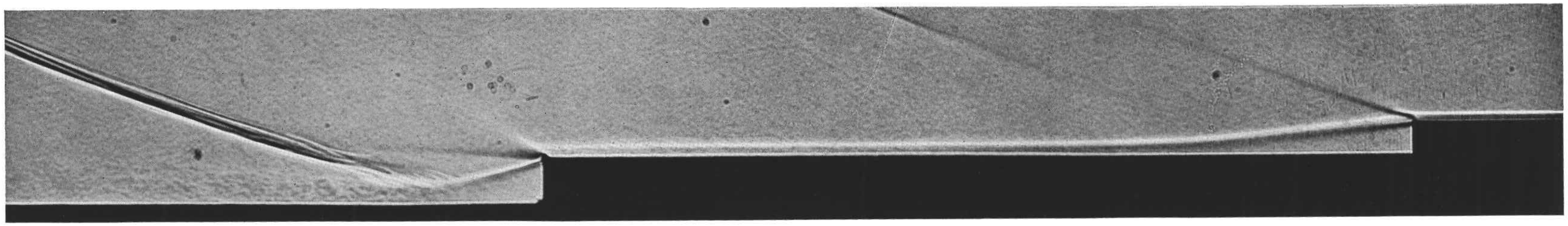


b) Model SR-4 ; $p_o = 197$

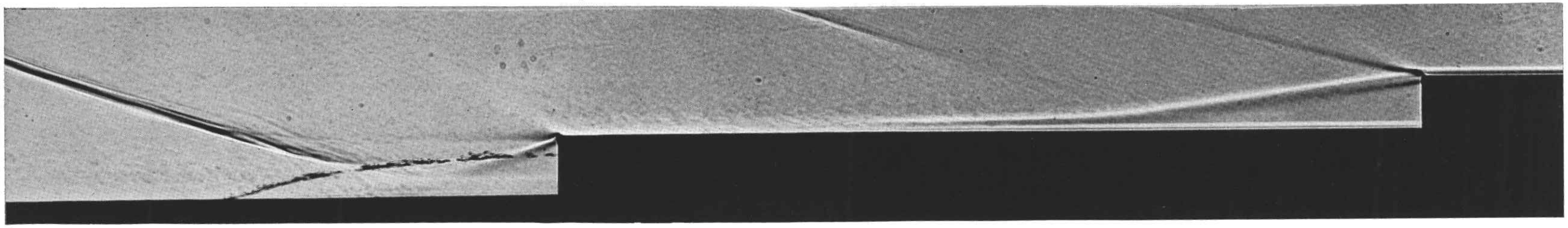


c) Model SR-2 ; $p_o = 134$

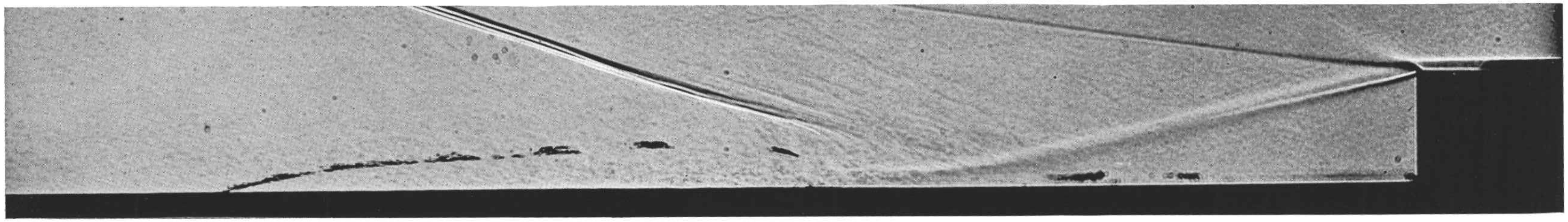
Figure 4. Shadowgraphs and schlieren pictures of separated flows



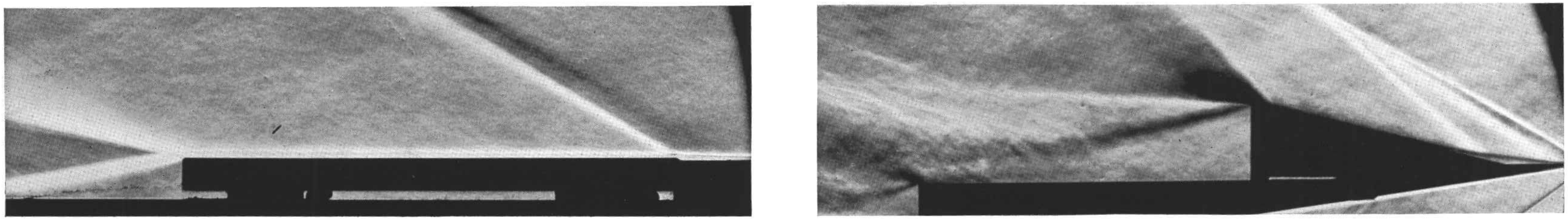
d) Model DS-1 $p_o = 213$



e) Model DS-5 $p_o = 191$



f) Model S-1 $p_o = 209$



g) Model DS-11 ; $p_o = 198$

h) Model CC-1, $\alpha = 0$, $x_c = 20$; $p_o = 115$

Figure 4. Continued

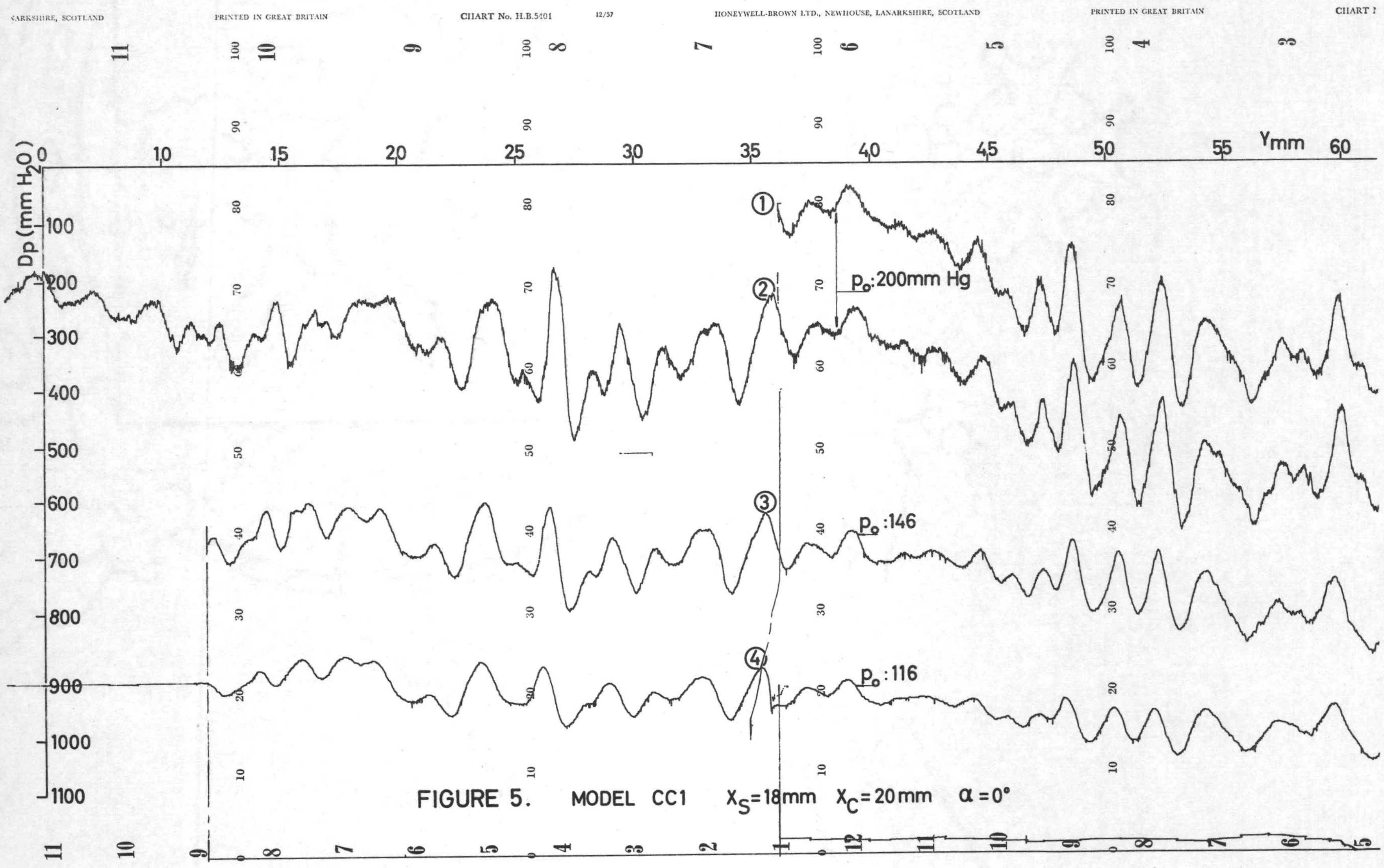


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CHART
Dp (mm H_2O)
0
100
200
300
400
500
600
700
800
900
1000
1100
Ymm
0
10
15
20
25
30
35
40
45
50
55
60
①
②
③
④
p_o:200mm Hg
p_o:146
p_o:116

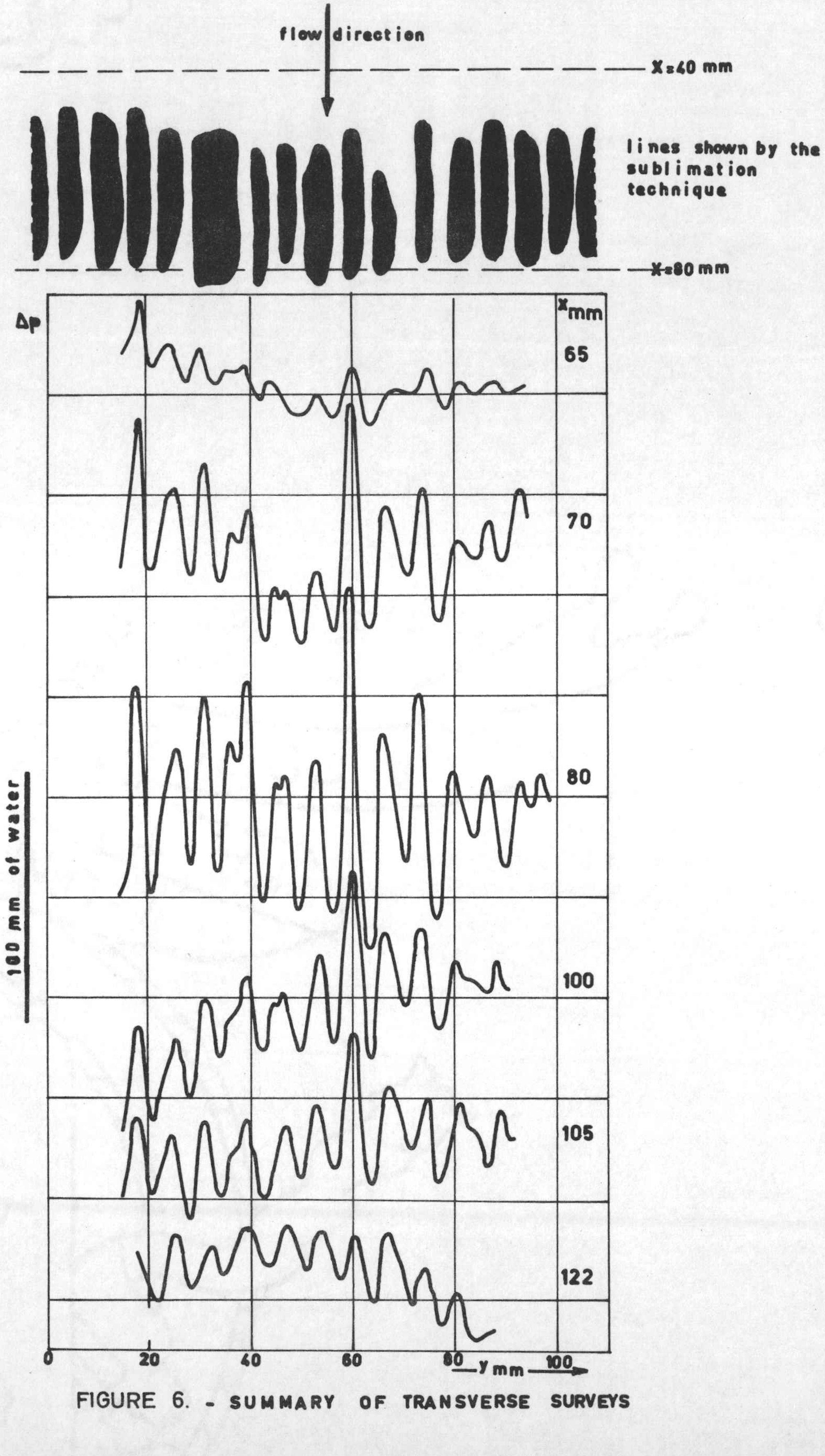


FIGURE 6. - SUMMARY OF TRANSVERSE SURVEYS

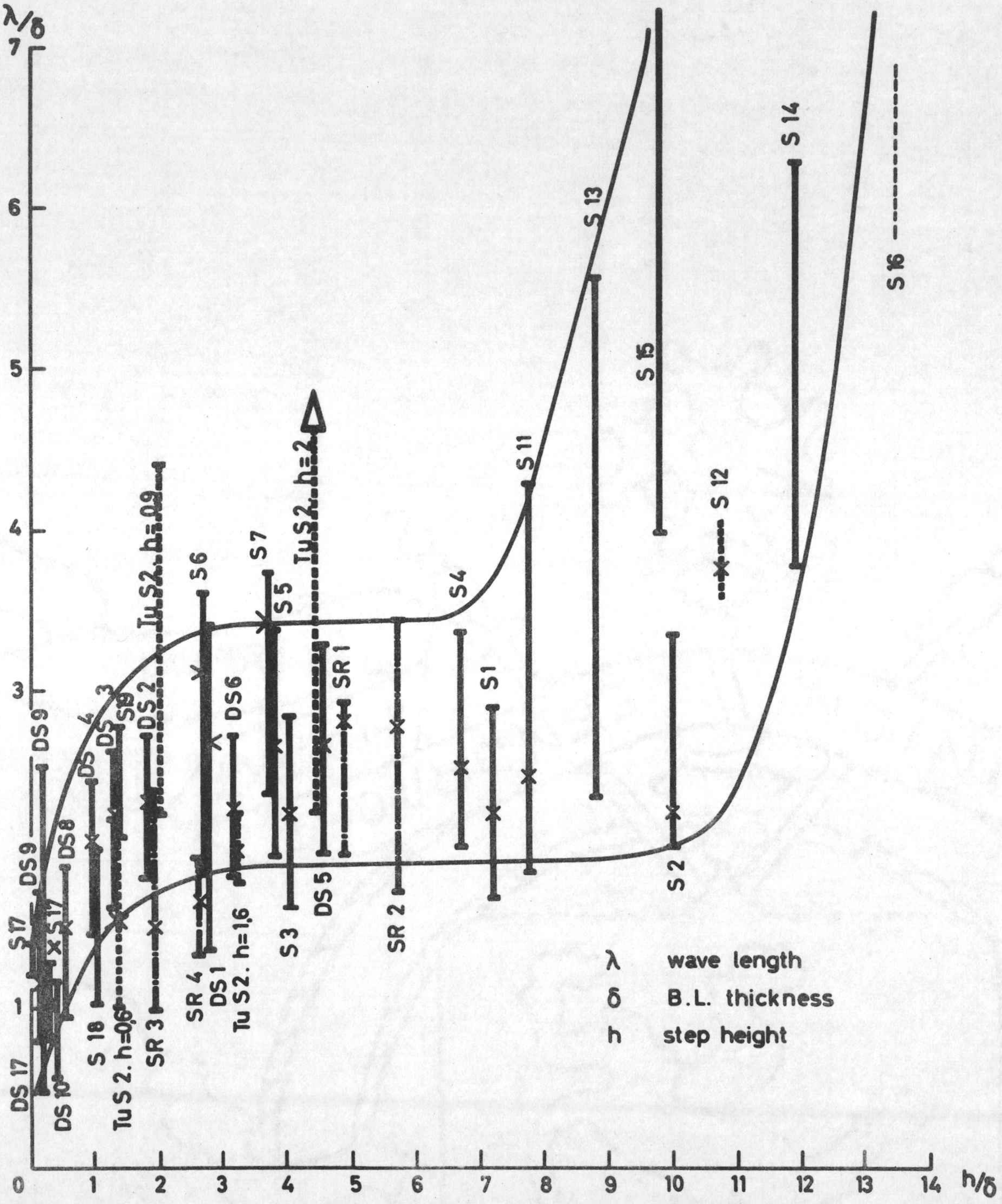
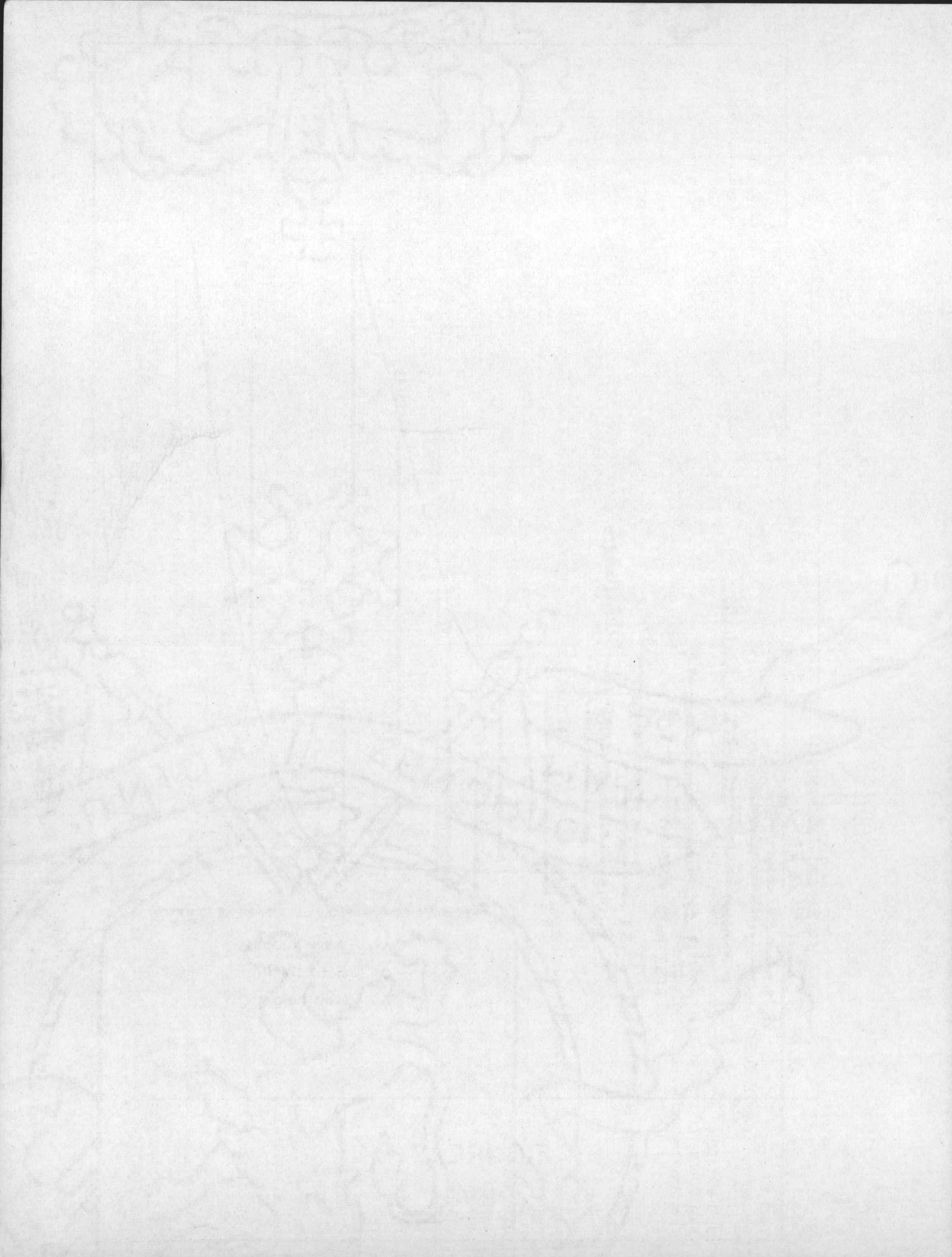

λ/δ
7
6
5
4
3
1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
h/δ
DS 17
S 17
DS 9
DS 10
S 17
DS 8
S 18
DS 4
DS 3
S 19
Tu S 2. h=0,6
DS 2
SR 3
Tu S 2. h=0,9
SR 4
DS 1
S 6
Tu S 2. h=1,6
DS 6
S 7
S 5
S 3
DS 5
Tu S 2. h=2
SR 1
SR 2
S 4
S 1
S 11
S 13
S 15
S 2
S 12
S 14
S 16
λ wave length
δ B.L. thickness
h step height

FIGURE 7.



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