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Visualization of Secondary Flow in the Reservoirs
of the Slotted-Wall Working Sections
of the A.R.L. 12 inch and 30 inch Water Tunnels

By

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VISUALIZATION OF SECONDARY FLOW IN THE RESERVOIRS OF THE
SLOTTED - WALL WORKING SECTIONS OF THE A.A.L.
12-INCH AND 30-INCH WATER TUNNELS

-by-

D. A. E. Leaver.

Abstract

The flow pattern in the reservoirs of the slotted-wall working sections of the 12-inch and 30-inch water tunnels has been studied by visual methods. Experiments with both original and modified bars show that the flow pattern exhibits marked axial asymmetry associated with the arrangement of the slots between the bars. It is thought that the results of this investigation may be of interest in connection with wind tunnel design as well as water tunnel design.

1. INTRODUCTION.

1.1. During acceptance trials of the 30-inch water tunnel severe vibration, in a radial direction, of the perspex bars forming the slotted-wall was observed at about 25 f.p.s. The amplitude of vibration of the bars increased as the speed was increased. Such vibrations of the bars had been observed in the 12-inch water tunnel but at a higher speed of about 61 f.p.s., and had limited the top speed at which the tunnel was run (Ref.1.). It was also observed that pressure pulses were travelling along the diffuser at about the speed of the water flow. When, in order that the 30-inch tunnel could be run at top design speed, the perspex bars were replaced by steel channels, it was found the severe longitudinal vibrations of the top limb of the tunnel, which rests on rollers, occurred at speeds greater than about 40 f.p.s. accompanied by severe pressure pulsations in the flow. It was thought that these vibrations originated at the downstream end of the working section at the entry to the diffuser. The purpose of the investigation described in this note was to visualize the flow in the reservoir of the slotted-wall working section of the 12-inch tunnel in the hope of finding the cause of the vibration.

1.2. Consultations of previously published work on the slotted-wall (Refs. 2, 3, 4.) does not reveal much about the nature of the flow in the reservoir. It was recognized that some of the fluid "moving in the tunnel enters the reservoir through the gaps between the bars", and that "near the end of the working section, it has to leave the reservoir again for reasons of continuity" (Ref. 3.). It was also recognized that "a back flow along (the reservoir's) outer boundary" could occur. These considerations together with the discovery of a pressure drop at the entry to the diffuser (Ref.4.) influenced the final design of the working sections of the 12-inch tunnel (Ref. 1.) and the 30-inch tunnel. A comparison of some of the more important features of the two working sections is given in Table 1 and Figures 1 and 2. It is convenient to express many of the dimensions in terms of D_0 the internal diameter of the slotted-wall.

2. VISUALIZATION OF FLOW IN SECTIONS WITH ORIGINAL BARS.

2.1. The slots in the original perspex cages of the 12-inch and 30-inch tunnels were arranged horizontally and vertically, rather than radially, to reduce their interference with optical observations (Refs. 1, 4, 5.). The result of this arrangement of the slots is that the cross-sectional shape of each of the sixteen bars forming the cage depends upon its position. The four different cross-sectional shapes required are shown in Figure 2. Section C is merely the reflection of section A. Four bars of each shape are required and are arranged as shown in Figure 4.

2.2. It is possible to run the 12-inch tunnel as a wind tunnel. The initial experiments were done in this way. The wind speed determined by a pitot-static tube aligned along the axis of the mainstream was about 28 f.p.s. corresponding to a Reynolds number of 1.8×10^5 (based on D_0). The whole of the outside of the perspex cage and the wall of the reservoir was explored with a single nylon filament threaded through a needle at the end of a stick. It was found that fluid entering the reservoir through the gaps between the bars entrains from the reservoir a sheath of fluid around the cage which moves in the same direction as the main stream. The entrainment of reservoir fluid commences at a distance of approximately $\frac{1}{2} D_0$ downstream from the beginning of the slotted-wall. The combined flow meets the wall of the contraction at the downstream end of the reservoir and divides, some entering the diffuser along with the main stream, the rest returning along the wall of the reservoir where it must, for reasons of continuity, continuously replace the entrained fluid. Thus a strong circulation of fluid exists in the reservoir. At the upstream end of the reservoir a weak counter circulation appears to exist.

2.3. The picture obtained so far (Fig. 3.) agreed with previously published work (Refs. 3, 5.). It was observed, however, that the flow in the reservoir was not axially symmetric. The nylon filament indicated a strong flow, in the downstream direction over the bars of section A, section C and section D, but the flow over the whole length of the bars of section B was random in direction, frequently reversing. Moreover the flow over the

reservoir wall was directed upstream opposite the bars of section B, but was random opposite the bars of section A, section C and section D. This behaviour of the flow was confirmed in both the 12-inch and 30-inch tunnels, when filled with water, by sticking large numbers of tufts of nylon or silk thread on the outside of the bars and on the wall of the reservoir. The stagnation position where the flow divided on the reservoir contraction was also determined by tufts. Rows of equally spaced tufts were fixed along radial lines on the face of the reservoir contraction. In the 30-inch tunnel the tufts were 1 inch long, spaced at intervals of 1 inch, and in the 12-inch tunnel they were $\frac{1}{2}$ inch long, spaced at intervals of $\frac{1}{2}$ inch. Rows of tufts were placed opposite the centres of the bars of section D and section B, and also opposite some of the slots. On running the tunnel it was seen that the stagnation position varied, having a maximum diameter opposite the bars of section D and a minimum diameter opposite the bars of section B. The diameters of the stagnation positions are given in Table II. No difference could be seen between the diameter of the stagnation position opposite a bar and opposite an adjacent slot.

2.4. From the above observations it was concluded that the flow in the reservoirs was axially asymmetric. Due to the arrangement of the slots between the bars, most of the entrained flow occurred along the bars of section A, section C and section D. Most of the return flow occurred along the reservoir wall opposite the wide backs of the bars of section B. To test this conclusion a wire screen of about 1 inch mesh, with 1 inch tufts, was placed across the reservoir of the 12-inch tunnel and attached to the upstream side of the middle spider which supports the bars. This conclusively showed the asymmetric flow. The streams moving upstream and downstream extended almost right across the reservoir from bars to wall, the division between them being quite sharply defined (Fig. 4. and Plate 1). This type of flow extends for almost the whole length of the reservoir, from the place at which entrainment commences, to the entry to the reservoir contraction. The rings and struts forming the three spiders, which support the cage of bars, seem to have very little influence on the nature of the flow pattern.

2.5 In order to simplify the flow pattern in the reservoir of the 12-inch tunnel it was decided to replace the bars of section A, section B and section C with perspex bars of rectangular cross-section. The original perspex bars of the 30-inch tunnel had already been replaced by steel bars of U-section. The cross-sections of these modified bars are shown in Figure 2. It was thought that the radial arrangement of the slots between these bars would produce an axisymmetric flow in the reservoir. This supposition was confirmed by means of tufts attached to the bars and reservoir wall in the 30-inch tunnel, and by means of the tufted screen in the 12-inch tunnel. The entrained and returning flow were concentric with the main stream (Fig. 4). The diameter of the stagnation position indicated by the tufts on the reservoir contraction was also constant.

3. VISUALIZATION OF FLOW IN SECTIONS WITH MODIFIED BARS.

3.1. At an early stage in the investigation, it was suggested that a collector ring, similar to those used in open jet wind tunnels would form a better diffuser entry. It was decided to fit a simple form of collector ring to the 30-inch tunnel. The ring was in the form of a tapering sheet metal cone. It seemed reasonable that the minimum diameter of the cone should correspond with the stagnation position on reservoir contraction. The steel bars fitted to the 30-inch tunnel were 9 inches longer than the original perspex bars. The diameter of the stagnation position determined by tufts was $1.45 D_0$ and this value was used in the design of the cone. Before the cone was fitted, however, the bars were cut to the original design length. It was discovered later that this had the effect of decreasing the diameter of the stagnation position to $1.32 D_0$. Observation of tufts on the reservoir contractions had shown a strong fluctuating component of the flow in a circumferential direction. It was thought that it might prove beneficial to try to suppress this circumferential flow by a system of radial splitters. Therefore, the cone was made in sixteen sections supported by sixteen radial splitters. Each splitter was attached to the centre of the back of a bar (Fig. 5.). This arrangement produced a marked improvement in

the tunnel performance and enabled the acceptance trials to be completed. A higher speed was reached before severe vibration commenced and the energy ratio was improved. It was not clear, however, whether the cone or the splitters or both were causing this improvement. The cone was separated from the reservoir contraction wall by a gap of about $\frac{1}{2}$ -inch. It has been shown (Refs. 6, 7.) that such a gap downstream of the collector ring will damp pulsations in an open-jet wind tunnel.

3.2. In order to obtain more information about flow directions, in a plane containing the axis of the reservoir, to assist in the more accurate design of a collector ring, a single splitter was fixed to the centre of the back of a bar in the 12-inch tunnel. The splitter which was in a horizontal plane, was covered with a titanium oxide flow visualizing paint (see Appendix). Plate 2 is a photograph of the flow pattern produced by running the tunnel. The flow pattern is quite different from that expected on the assumption that the flow into the reservoir contraction is axisymmetric. To assist in interpreting the pattern a similar splitter was made covered with $\frac{1}{2}$ -inch silk tufts. Figure 6 shows the flow directions indicated by the tufts. This flow pattern can be accounted for in the same way as that produced by the original bars. The strong combined flow opposite each slot meets the reservoir contraction and spreads out in all directions, some of it returning opposite the backs of the bars. The weaker entrained flow along the back of the bar is reversed by the strong return flow. To test this conclusion a flow pattern was obtained with the splitter in the radial plane through a slot (Plate 3.). This pattern again is difficult to interpret. It must be remembered that the paint shows the boundary layer flow on the splitter and not the flow in the main body of the fluid. It is thought that the white band represents a line of separation of the boundary layer due to the pressure rise on approaching the stagnation point (Ref. 8.) The most convincing evidence of the nature of the flow was obtained by painting the reservoir contraction with the titanium oxide paint. Plate 5 shows two photographs of the resulting flow pattern, taken from opposite sides of the working section of the 12-inch tunnel. The stagnation points formed opposite the slots between the bars can be clearly seen. The fluid flowing outwards from adjacent slots meets opposite the centre of each bar, forming a different type of stagnation point. Thus the flow is divided into cells, parallel to the axis of the reservoir, by 32 dividing stream-planes passing through the 32 stagnation points formed on the reservoir contraction (Fig. 7.). Some distortion of the flow pattern is attributed to the presence of five struts protruding from the upper part of the contraction. Similar results were obtained in the 30-inch tunnel using lamp-black paint. Plates 7 and 8 show the flow pattern on a single splitter in the horizontal plane (the other splitters and cone were removed) and should be compared with Plates 2 and 4. Plate 6 shows two photographs of the flow pattern on the reservoir contraction and should be compared with Plate 5.

3.3. The flow patterns on the reservoir contractions (Plates 5, 6.) were obtained at the same Reynolds number 2.0×10^6 corresponding to a main stream water speed of 25 f.p.s. in the 12-inch tunnel and 10 f.p.s. in the 30-inch tunnel. The paint flow pattern enables the diameter of the circle on which the stagnation points are situated to be measured directly. The diameters were $16\frac{7}{8}$ inches ($1.41D_0$) for the 12-inch tunnel and $39\frac{5}{8}$ inches ($1.32D_0$) for the 30-inch tunnel. The discrepancy has not been explained. It is thought that the small differences in the reservoir contraction geometry (Fig. 1.) cannot account for it. The 30-inch slotted-wall is relatively longer than the 12-inch slotted-wall, but this should make the stagnation diameter greater in the 30-inch tunnel. It has been shown that the length of the gap between the end of the slotted-wall and the throat of the diffuser can influence the diameter of the stagnation position (paragraph 3.1.), but the gap in the 12-inch and 30-inch tunnels is the same ($0.342 D_0$). It seems likely that the discrepancy is due to the difference in the geometrical opening ratio which is 24.5% for the 12-inch tunnel and 19.4% for the 30-inch tunnel. The effective opening ratio probably depends on the thickness and cross-sectional shape of the bars. The variation of effective opening ratio around the original slotted-wall should account for the variation in stagnation position described in paragraph 2.3.

3.4. In paragraph 3.2. it was necessary to assume that the flow in the radial plane through a slot was modified by the presence of a splitter. In order to justify this assumption it was necessary to show that, in the absence of the splitter, the combined flow opposite the slot moves right up to the reservoir contraction surface before it divides. Attempts to visualize the flow in this region by injecting coloured water were unsuccessful, as the dye was quickly dispersed by the very turbulent nature of the flow. With the 12-inch tunnel running very slowly (about 3 f.p.s.) drops of oil, mixed to a specific gravity of one, were introduced through a tube opposite the centre of a slot, level with the outside of the bars and 13.5 inches upstream from the end of the slotted-wall. Many of the drops were seen to travel up to the stagnation point opposite the slot and move out along the flow lines indicated by the titanium oxide paint which still adhered to the reservoir contraction. It was observed that a few drops were drawn through the slot into the main stream. When the tube was moved inwards so that the orifice was level with the inside of the bars, most of the drops were carried along with the main stream inside the slotted-wall, but a few emerged through the slot into the reservoir. Thus it seems that fluid passes both ways through the slots. When the orifice was positioned opposite and close to the centre of the back of a bar the drops were rapidly drawn alternately towards one or other of the adjacent slots. An earlier experiment in which the back of the bar in this region had been sprayed with titanium oxide paint, had shown that the flow lines diverged sharply in the downstream direction, showing that the fluid is drawn outwards from the centre of the bar into the region of the slots.

3.5. It appears that a stagnation point must be formed near the centre of the bar tip where the returning fluid impinges on it. (see Fig. 6 and Plates 2, 4.) The fluid must spread out in all directions over the bar tip, that which proceeds in the upstream direction meeting the weaker entrained flow along the back of the bar and forming another stagnation point. Attempts to obtain the flow pattern on the bar tip by the paint flow technique were unsuccessful. A row of silk tufts along the centre line of the tip showed that the flow frequently reversed in this region indicating that the stagnation points are unsteady. In order to determine if the loss of energy in the wake of the strut supporting the bar tip might be influencing the position of these stagnation points, the supporting strut was removed, but the flow pattern was substantially the same (Plate 4.). Some experiments were carried out in the 12-inch tunnel with a wire screen of $\frac{1}{2}$ -inch mesh cut to the same shape as the splitter. Silk tufts half-inch long were tied to each intersection of the wires. The behaviour of the tufts was observed with the splitter in the slot plane, in the plane through the centre of the bar, and in two intermediate positions spaced at intervals of $3\frac{3}{4}^{\circ}$. The tufts indicated the direction of the component of the flow normal to the splitter. The direction of the normal component was seen to be reversing violently along the centre of the back of the bar tip and between this position and the stagnation point on the contraction wall opposite, i.e. in the region where the entrained flow along the bar divides and the return flow from adjacent slots meets. Elsewhere the fluctuations were less violent but in general the normal component of the flow was less steady than the component in the plane of the splitter. The flow directions observed agreed with the picture already built up.

3.6. The discovery of the 32 dividing stream-planes suggested trying 32 splitters lying along these planes in the 30-inch tunnel. Such an arrangement with no cone but braced by tie bars was tried and produced no improvement in tunnel behaviour. It was confirmed by means of tufts that the boundary layer flow on these splitters was the same as had been observed on single splitters and was not modified by the presence of the other splitters. Later a cone made in 32 sections and having the same dimensions as the one previously employed was fitted. This arrangement of 32 splitters and cone produced the same improvement as the former arrangement of 16 splitters and cone.

4. CONCLUSIONS

It is concluded that the general nature of the flow pattern in the reservoirs of the 12-inch and 30-inch slotted-wall working sections is the same within the range of Reynolds number covered by the investigation. This

is to be expected since the flow is very turbulent. The Reynolds number, based on the internal diameter of the slotted-wall, ranged between 1.3×10^5 and 2.0×10^6 . It has been shown that the arrangement of the slots between the bars has a marked influence on the nature of the flow pattern. It is considered desirable to simplify the flow pattern in the reservoir by constructing the slotted-wall from equally spaced bars of identical shape. The improvement in the performance of the 30-inch tunnel produced by the cone-splitter assembly suggests that further investigation of its action should be made. The present investigation has shown that the cone is indispensable (Paragraph 3.6), but it has not shown if the splitters or the gap downstream of the cone (Paragraph 3.1) are necessary.

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APPENDIX

5. SOME NOTES ON THE METHODS OF FLOW VISUALIZATION EMPLOYED.

5.1. The speed of flow in the reservoir varies considerably with position. Along the slots between the bars and at the entry to the reservoir contraction the speed of the entrained fluid approaches that of the main stream. Near the walls and at the upstream end of the reservoir the speed is much lower. Tufts of silk or nylon thread give excellent indication of flow direction in the boundary layer because of the large forces in water even at low speeds. In some cases the behaviour of tufts was compared with that of coloured water injected into the stream. It was observed that the tufts followed changes in flow direction almost as rapidly as the coloured water. The tufts were fixed to the walls with "Lassovic" tape which remained firmly attached even after prolonged immersion in water.

5.2. In order to study the flow in the main body of the fluid a stream of air bubbles was injected into the reservoir, but it was found that they rose too quickly in the slowly moving water to give a reliable indication of flow direction. It was therefore decided to use drops of oil mixed to a specific gravity of one. A mixture of benzene and carbon tetrachloride is suitable.

5.3. The titanium oxide paint was made to a formula, for a paint for wind tunnel work, due to K. W. Newby of the R.A.E.

Titanium oxide (TiO_2)	100 grammes.
Diesel oil.	135 c.c.
Oleic acid (a dispersion agent) about	2 c.c.

The TiO_2 and some diesel oil are worked to a thick smooth paste. The oleic acid is then added, and after further thorough mixing, the remaining oil is added. The paint was applied by spray gun. Some dilution with diesel oil may be necessary. Care must be taken in filling the tunnel since the surface tension of the water can spoil the uniformity of the paint surface. During the test run the tunnel speed should be attained as quickly as possible. The flow pattern develops slowly and after several minutes changes no further. Even prolonged running does not seem to remove all traces of the pattern. Where possible, the pattern should be photographed without removing it from the water. A similar paint made with lampblack was used on the white surface of the 30-inch tunnel.

TABLE I

DIMENSIONS OF THE SLOTTED-WALL WORKING SECTIONS

	<u>12-inch tunnel</u>		<u>30-inch tunnel</u>	
Internal diameter of slotted-wall.	12 in	1 D _o	30 in	1 D _o
Internal diameter of reservoir.	30 in	2.5 D _o	75 in	2.5 D _o
Diameter of throat of diffuser.	13.2 in	1.1 D _o	33 in	1.1 D _o
Length of slotted-wall.	66 $\frac{1}{8}$ in	5.51 D _o	171 $\frac{1}{16}$ in	5.72 D _o
Length of gap between end of slotted-wall and diffuser throat.	4.1 in	0.342 D _o	10 $\frac{1}{2}$ in	0.342 D _o
Thickness of bars.	0.750 in	0.062 D _o	1 $\frac{1}{2}$ in	0.050 D _o
Trailing edge angle of bars.	15°		12°	
Opening ratio (original bars).	21.2 $\frac{1}{8}$		19.4 $\frac{1}{8}$	
Opening ratio (modified bars).	24.5 $\frac{1}{8}$		19.4 $\frac{1}{8}$	
Whole angle of diffuser.	7°		6°	

Geometrical opening ratio = 1 - $\frac{\text{Sum of widths of internal faces of bars.}}{\pi \times \text{Internal diameter of slotted-wall.}}$

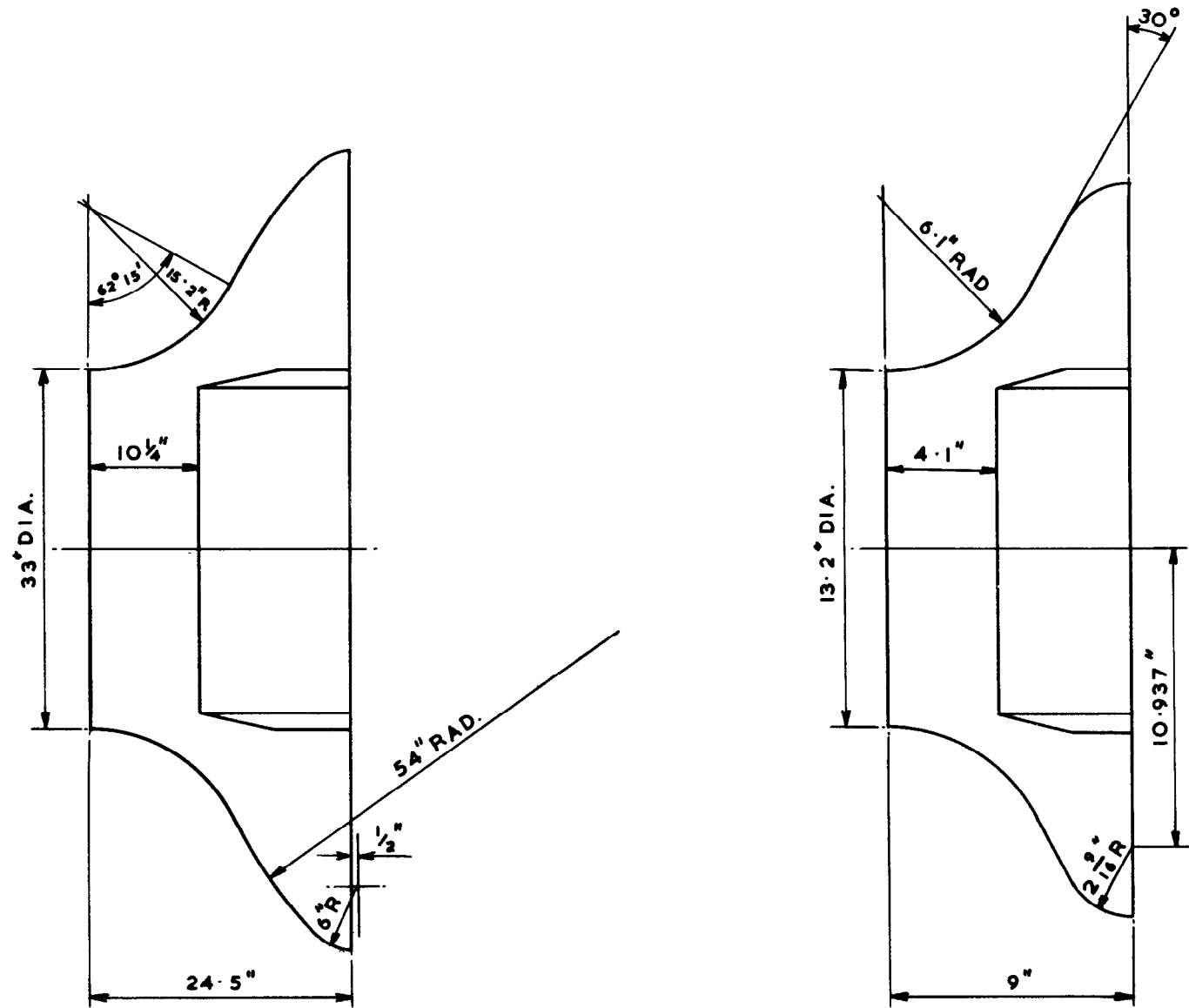
The main contractions of the two tunnels are geometrically similar in shape but in the 12-inch tunnel there is a parallel section 5 $\frac{7}{8}$ inches (0.490 D_o) long between the nozzle and the slotted-wall.

TABLE II

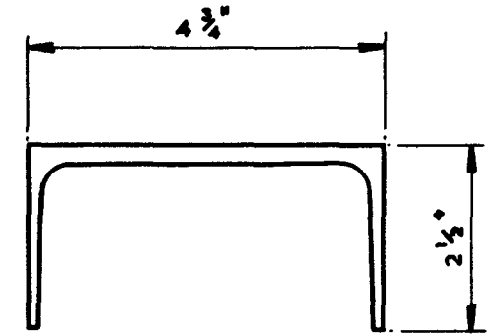
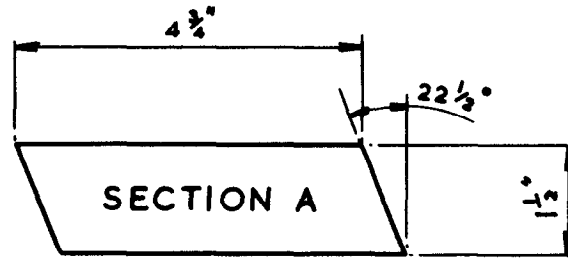
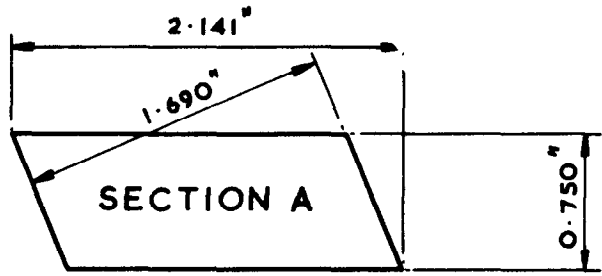
DIAMETERS OF THE STAGNATION POSITIONS

Original bars.	12-inch tunnel.	30-inch tunnel.
Opposite the bars of section D.	1.47 D _o	1.40 D _o
Opposite the bars of section B.	1.30 D _o	1.21 D _o
Modified bars.	12-inch tunnel	30-inch tunnel
Independent of position.	1.41 D _o	1.32 D _o

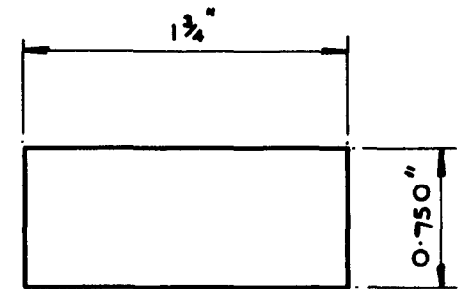
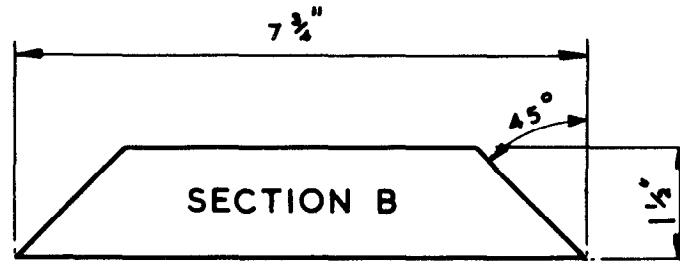
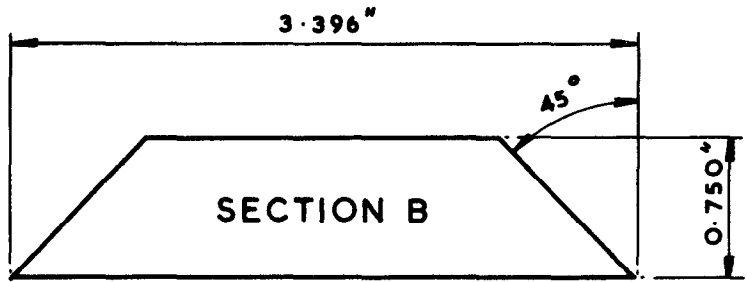
FIG. 1



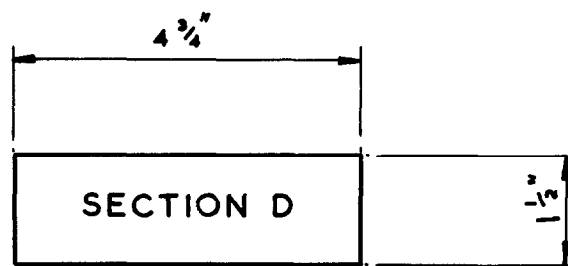
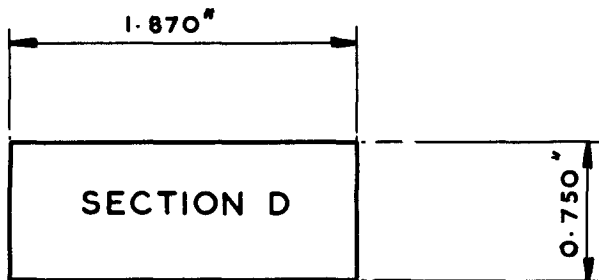
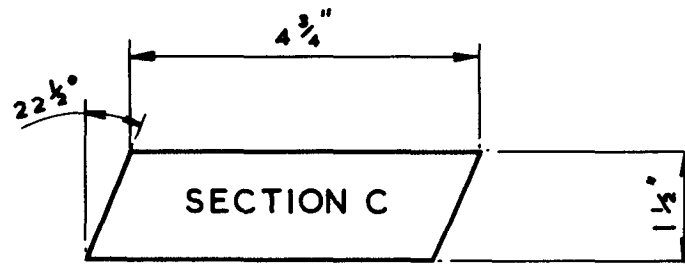
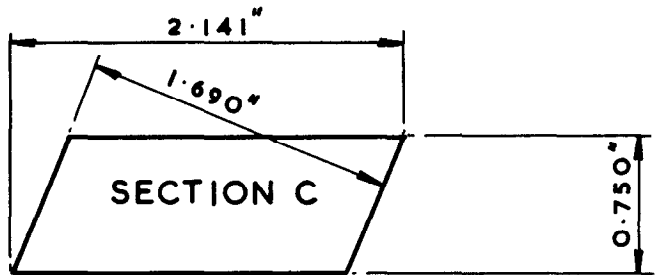
RESERVOIR CONTRACTION GEOMETRY.



30 INCH TUNNEL
MODIFIED BAR.
SCALE 1:2.5



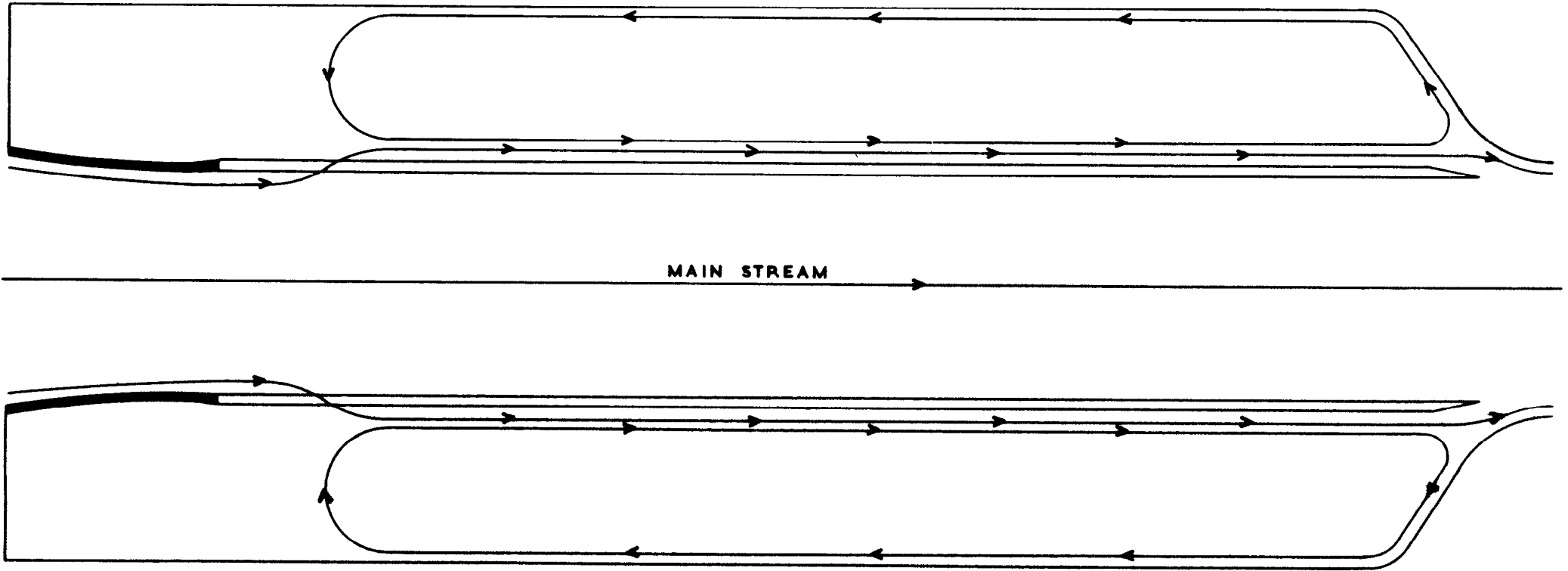
12 INCH TUNNEL
MODIFIED BAR.
SCALE 1:1



12 INCH TUNNEL ORIGINAL BARS.
SCALE 1:1

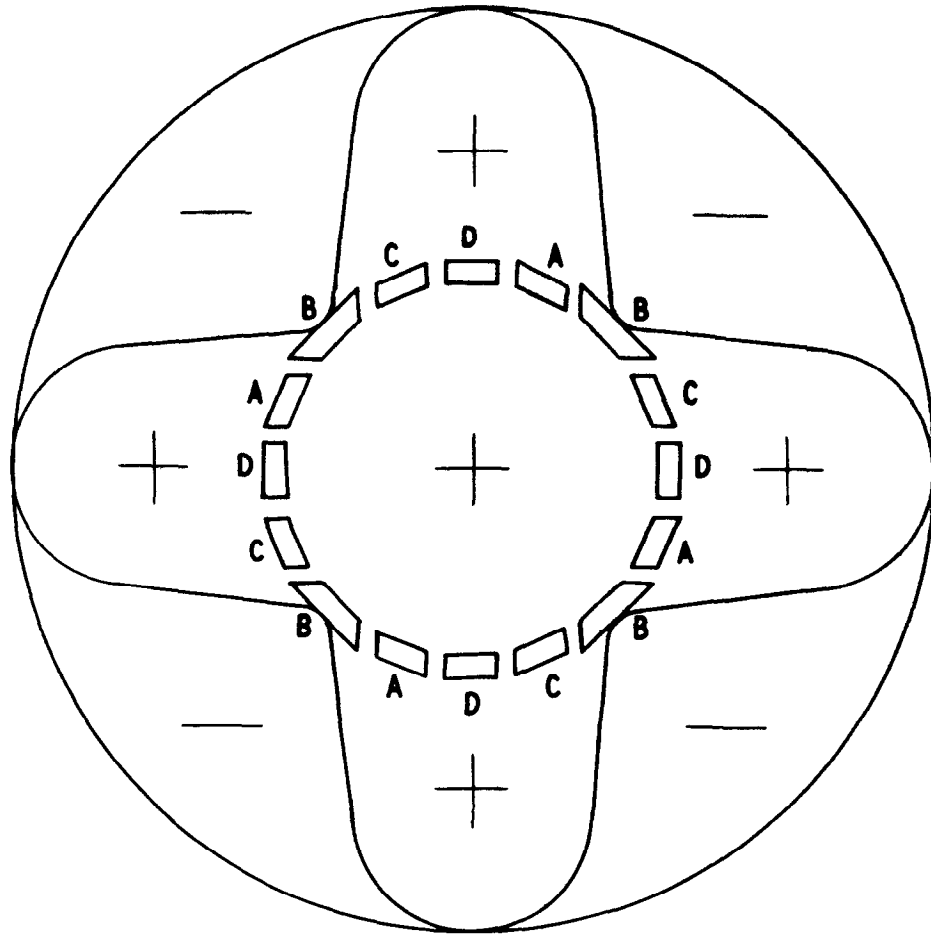
30 INCH TUNNEL ORIGINAL BARS
SCALE 1:2.5

FIG. 2

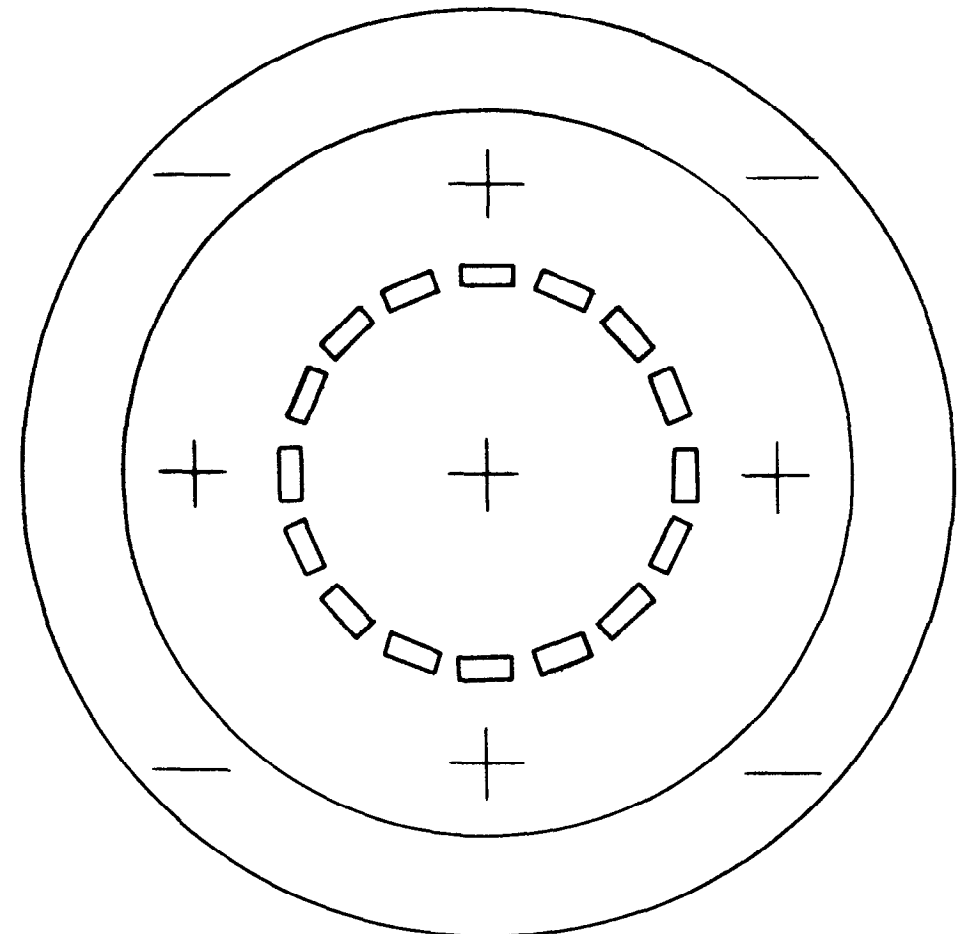


SIMPLIFIED PICTURE OF FLOW IN THE TUNNEL RESERVOIR.

FIG. 3



ORIGINAL BARS

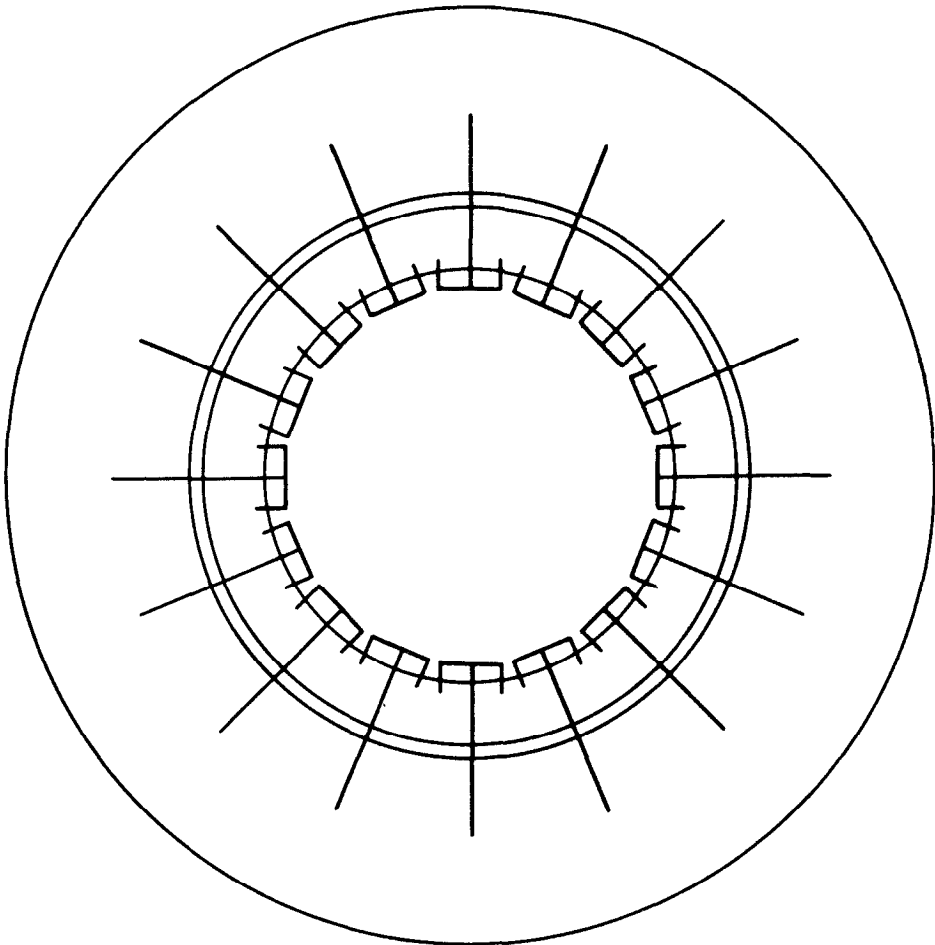
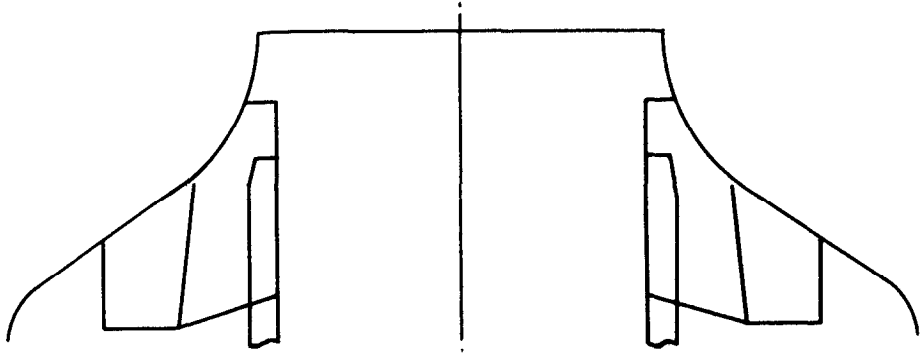


MODIFIED BARS.

CROSS SECTION OF FLOW PATTERN IN TUNNEL RESERVOIR (SCHEMATIC).

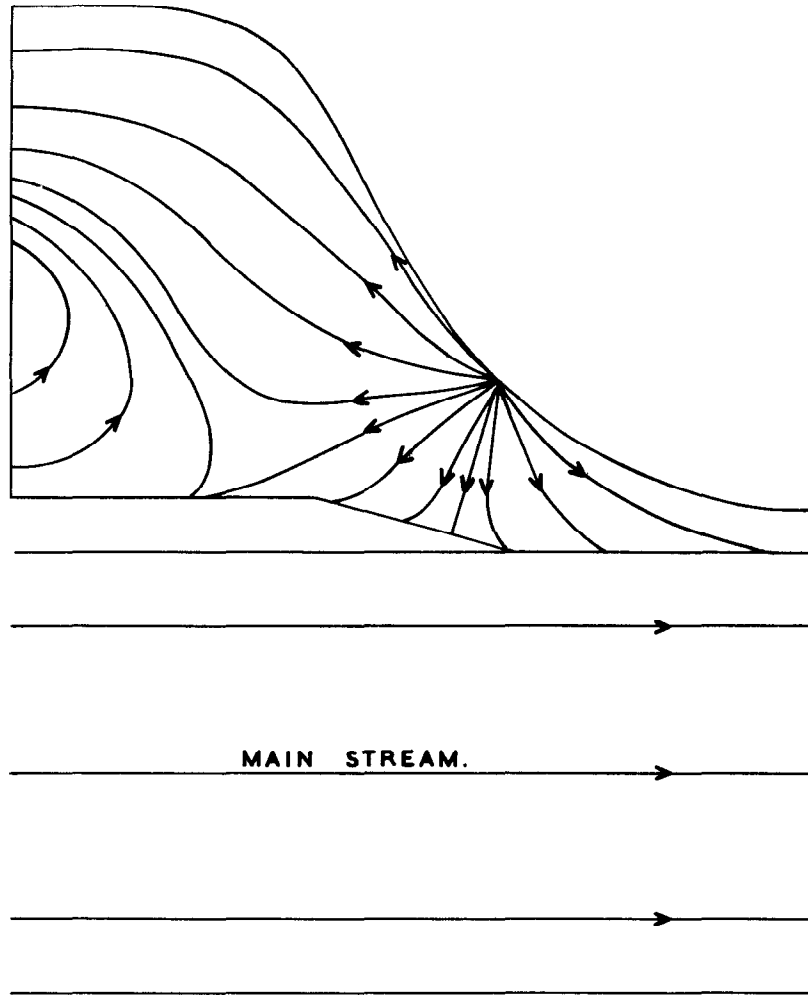
+ INDICATES FLOW IN THE DIRECTION OF THE MAIN STREAM.

FIG. 4

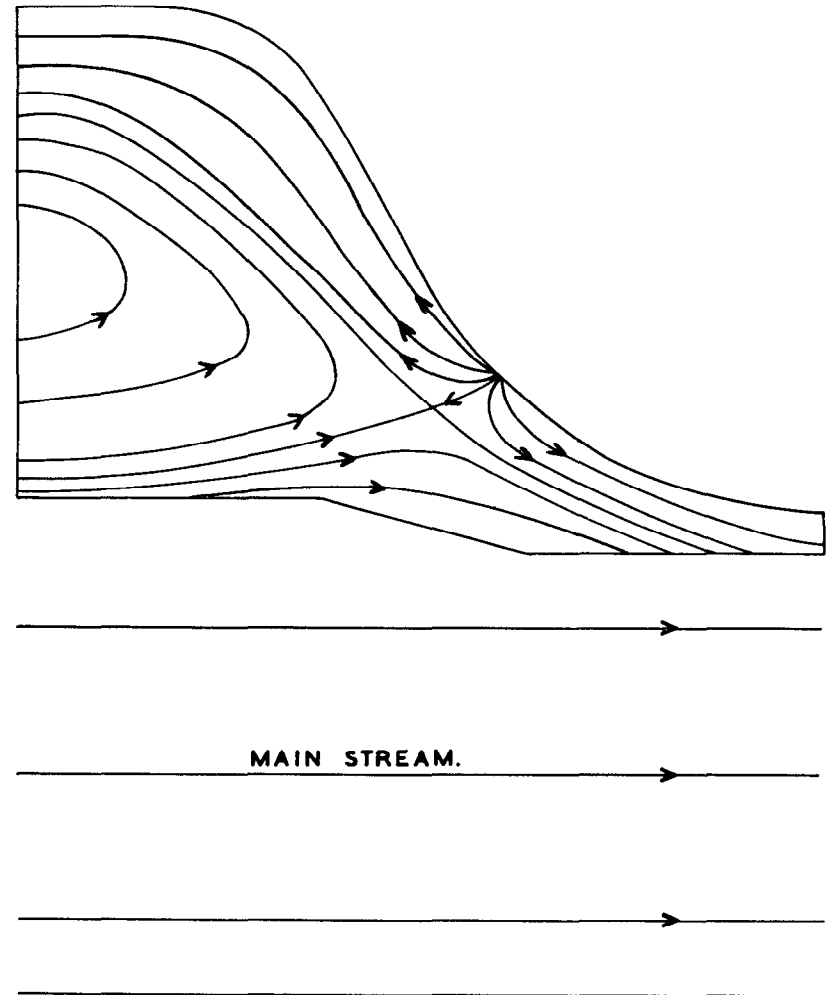


30 INCH TUNNEL CONE - SPLITTER ASSEMBLY.

FIG. 5



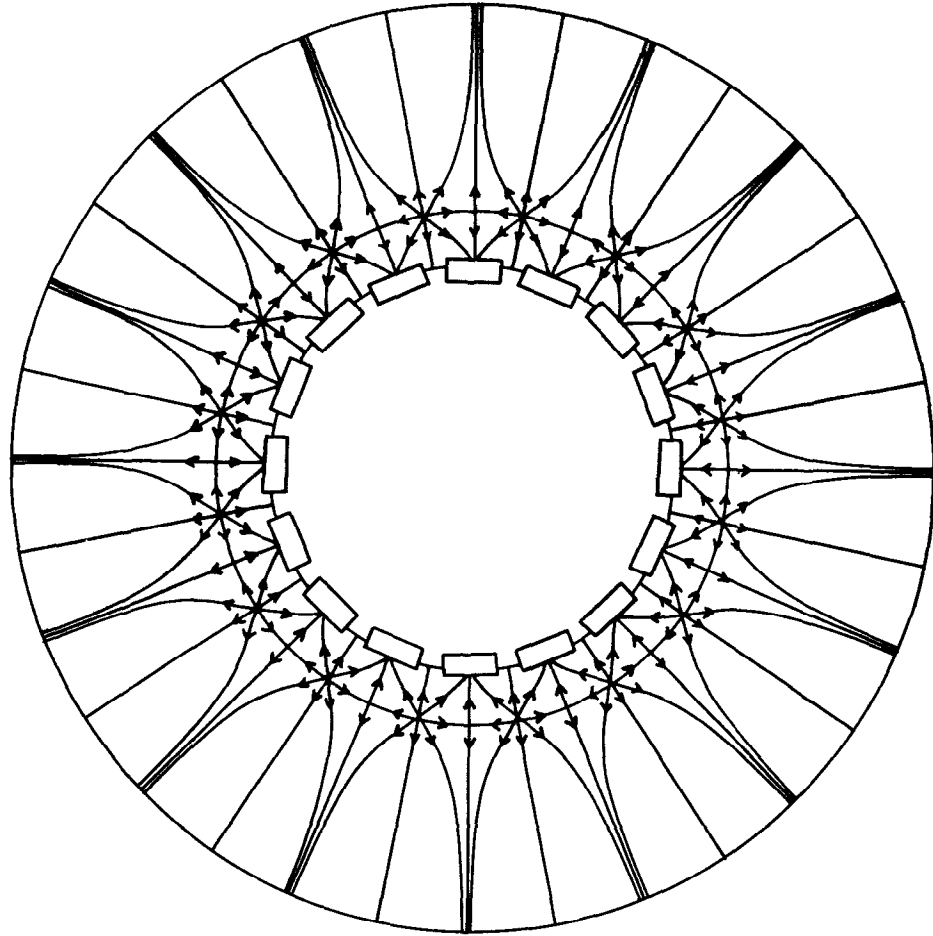
BAR PLANE



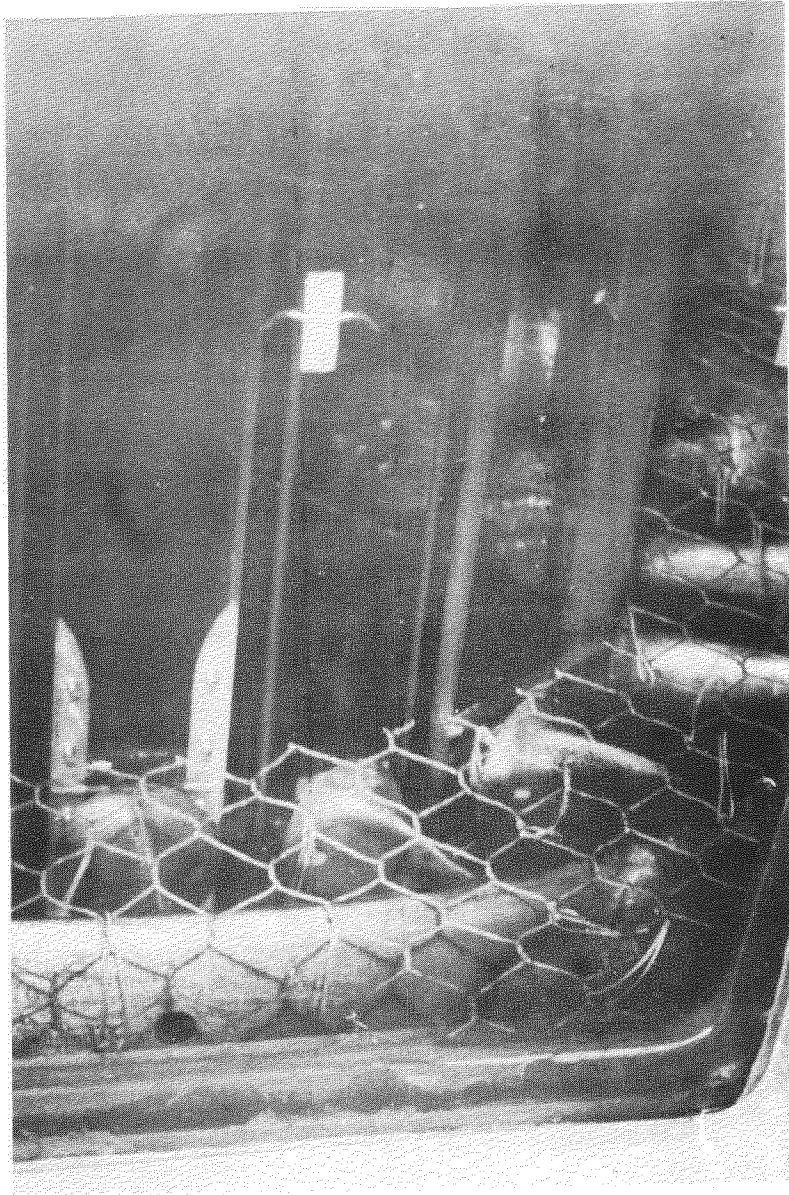
SLOT PLANE

BOUNDARY LAYER FLOW ON SPLITTERS IN THE 12 INCH TUNNEL (SCHEMATIC).

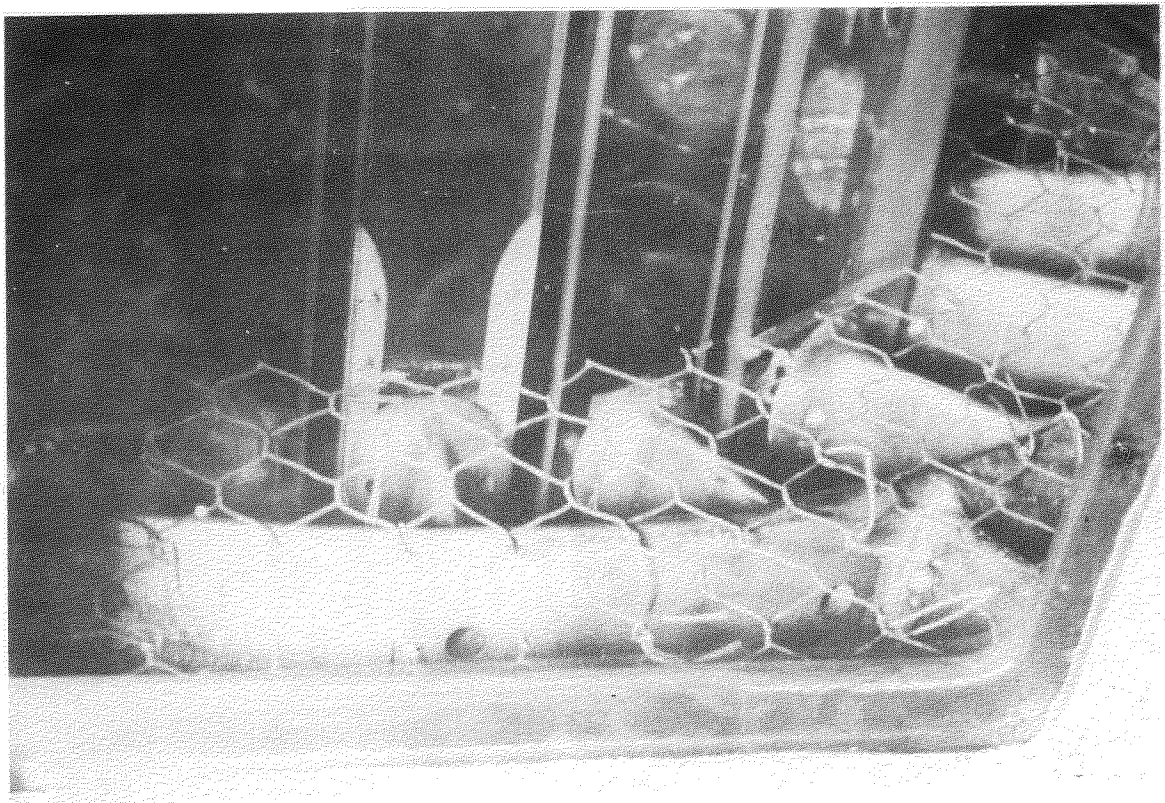
FIG. 6



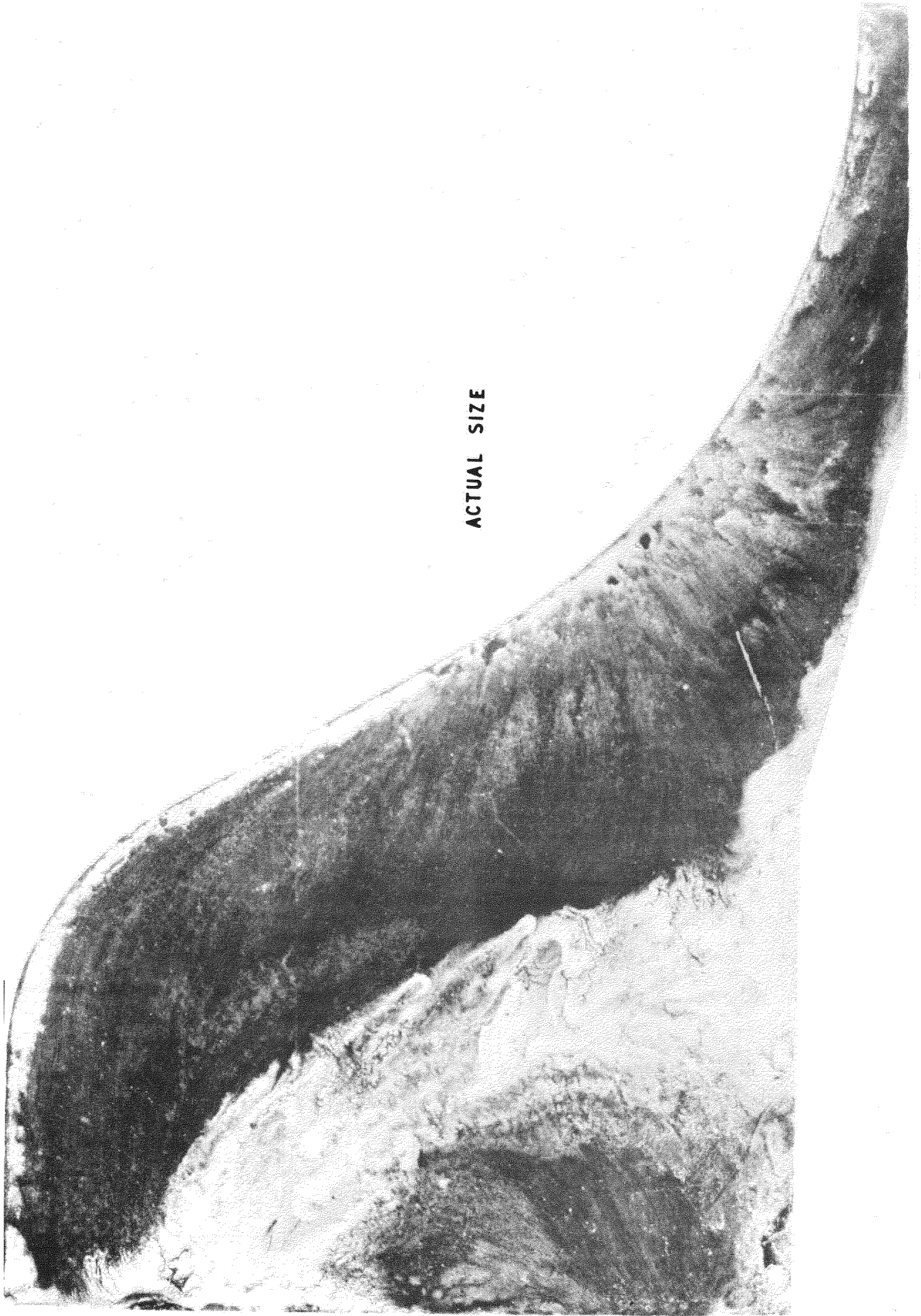
BOUNDARY LAYER FLOW ON SURFACE OF RESERVOIR CONTRACTION (SCHEMATIC).



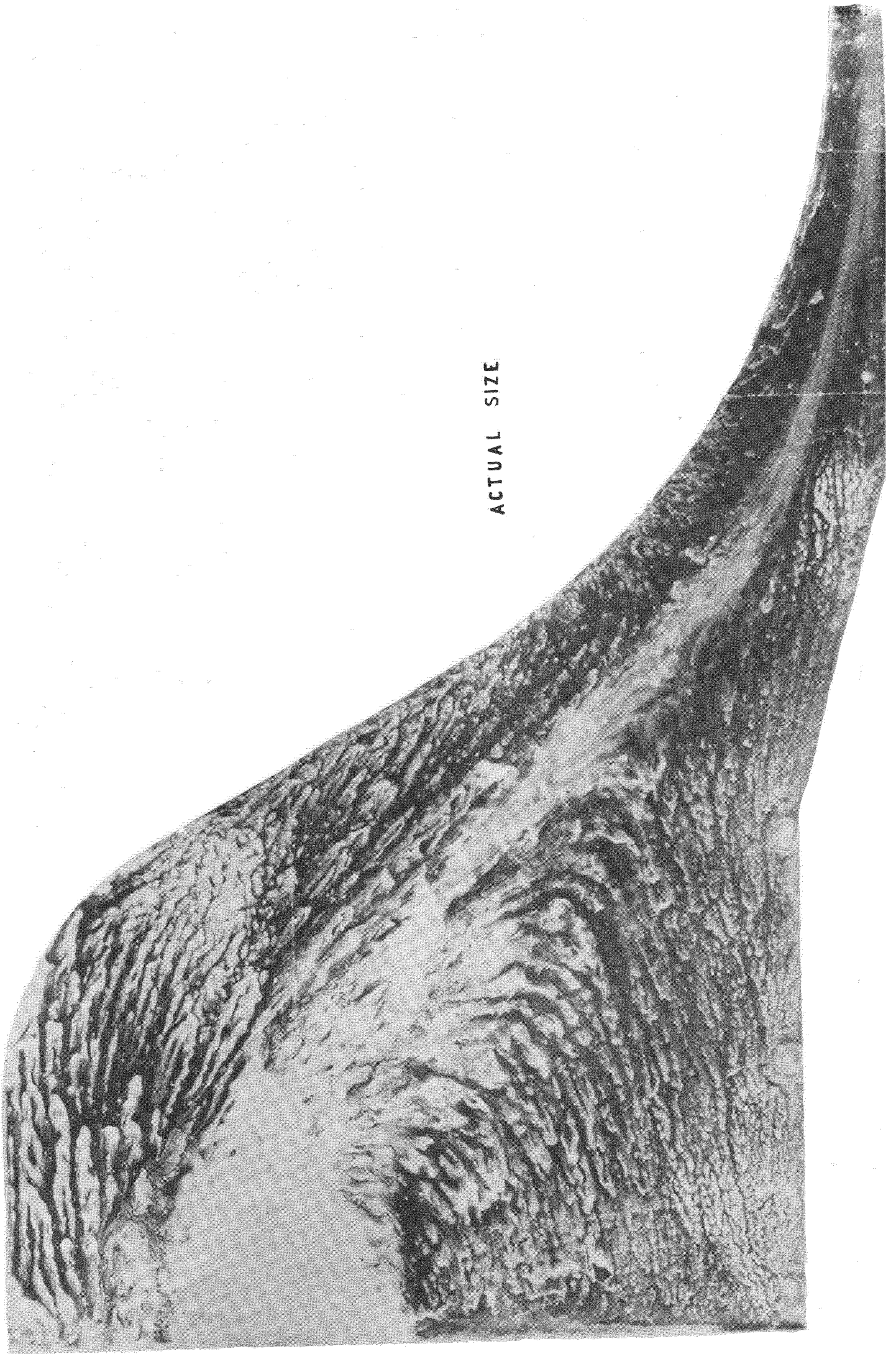
DIRECTION OF MAIN STREAM FLOW.

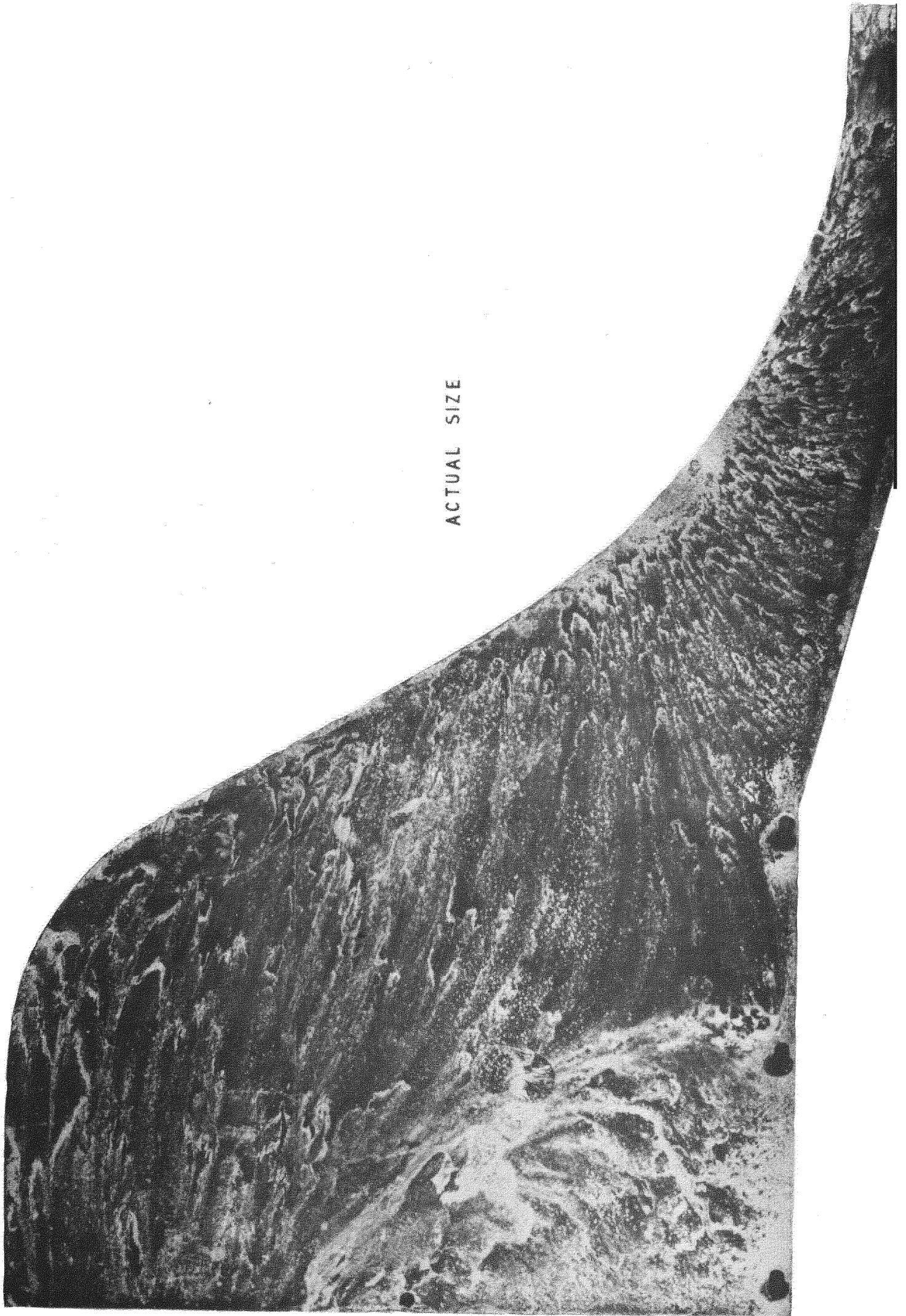


ACTUAL SIZE



ACTUAL SIZE





ACTUAL SIZE

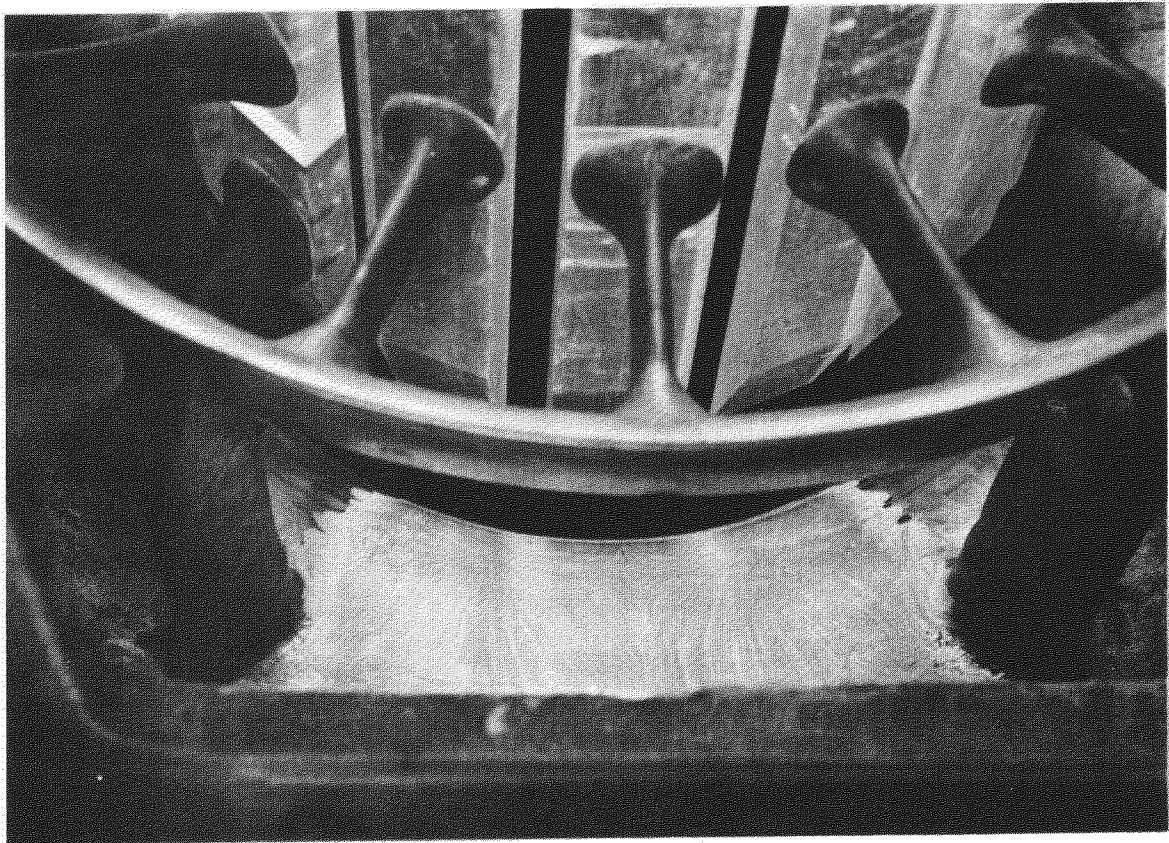
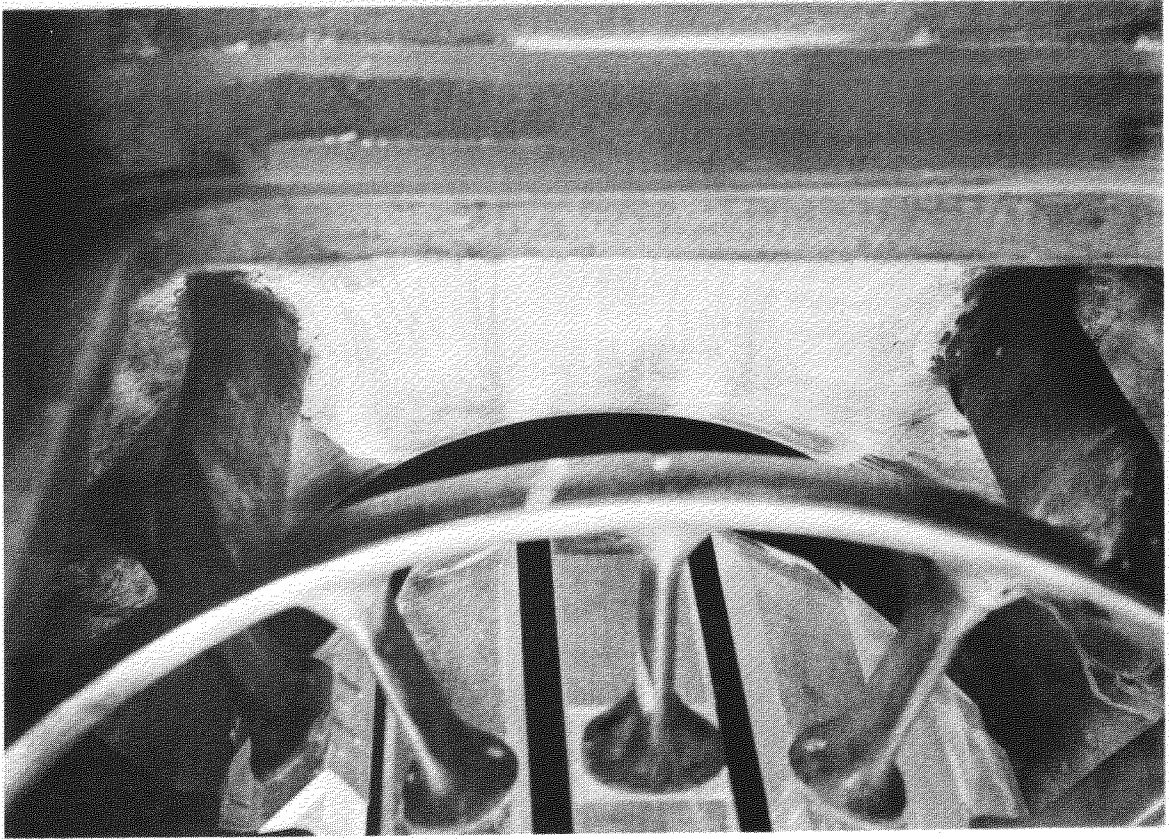


PLATE 5

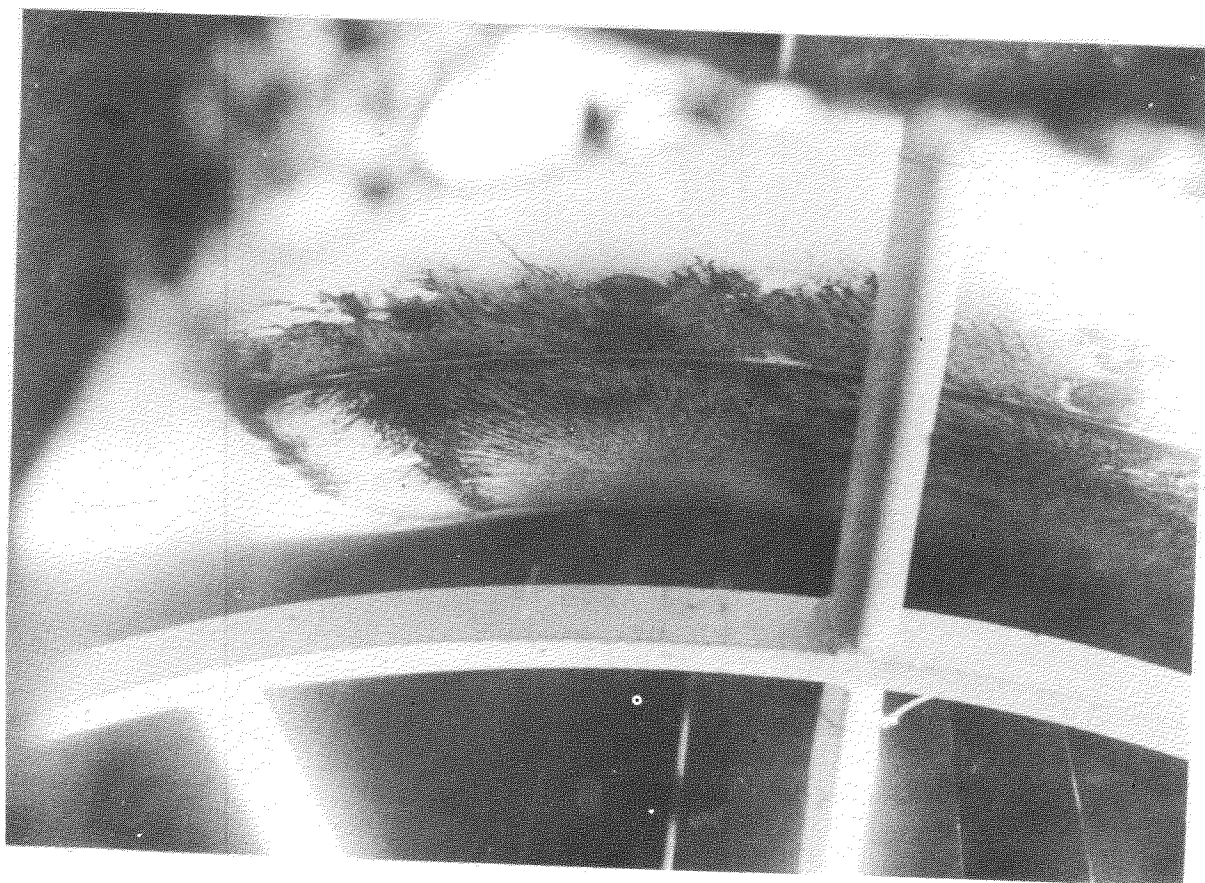
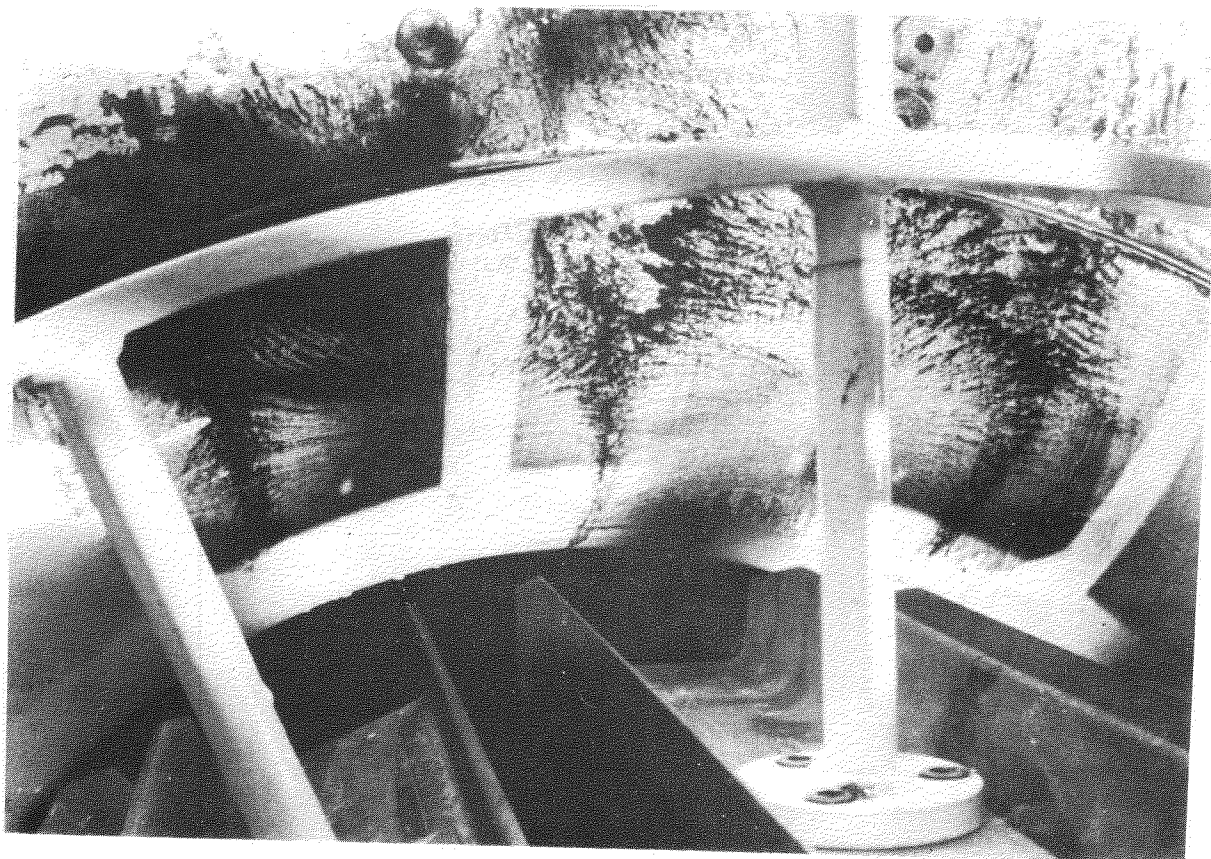


PLATE 6

2/5 ACTUAL SIZE

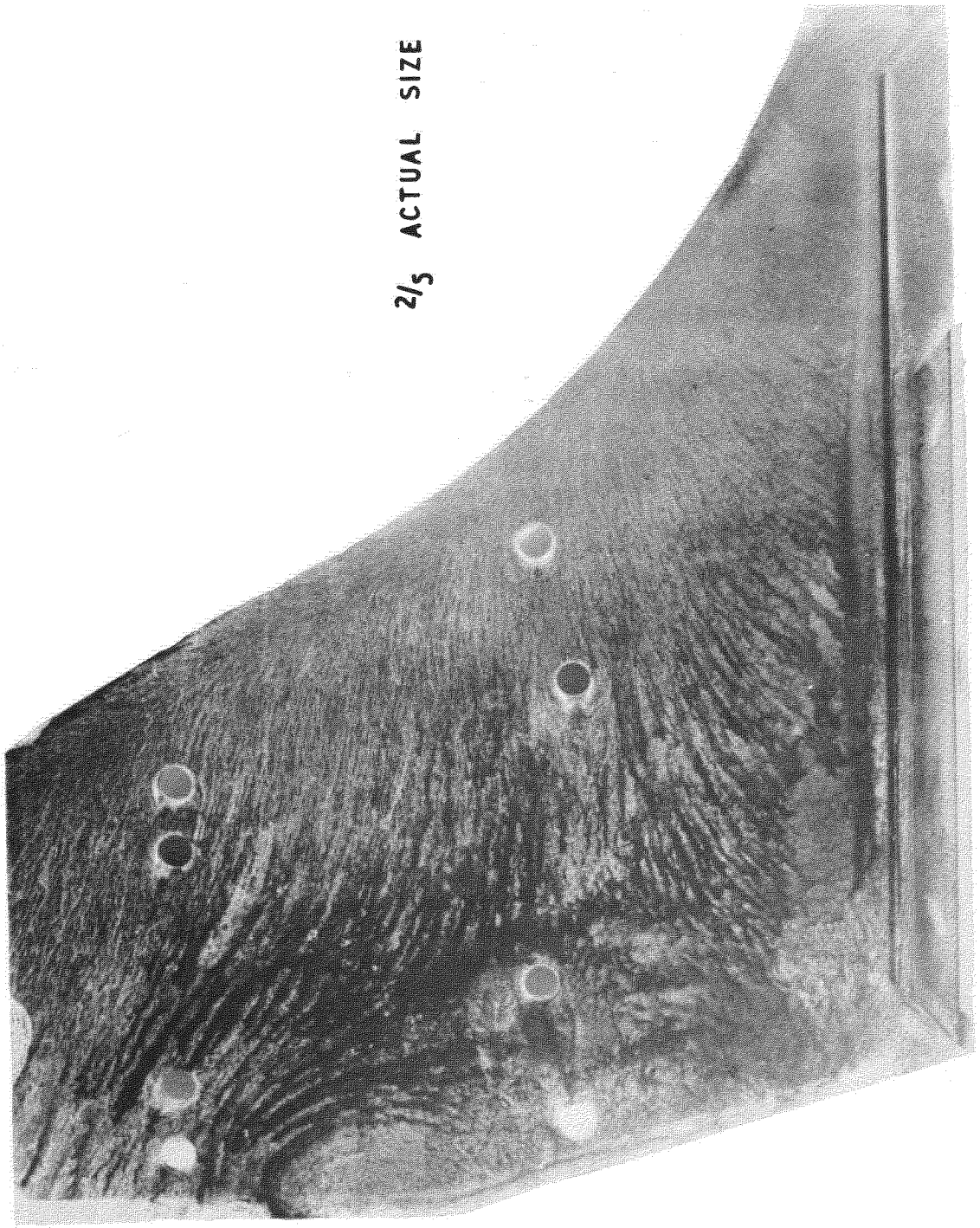


PLATE 7



A.R.L./N2/G/HY/4/1

PLATE 8

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