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Laboratory Memorandum (National Research Council Canada. Division of Mechanical Engineering. Engine Laboratory); no. NRC-ENG-69, 1972-02

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FILE M2-17-13.C-19	DIVISION OF MECHANICAL ENGINEERING OTTAWA, CANADA	PAGE 1 OF 10
PREPARED BY HSF	LABORATORY MEMORANDUM	COPY NO. 29
CHECKED BY EPC	SECTION ENGINE LABORATORY	DATE February 1972

SECURITY CLASSIFICATION OPEN

SUBJECT The Performance of Slotted Blades in Centrifugal Fan Rotors, as Stall-delaying Devices

PREPARED BY H.S. Fowler, G.S. Bond, J. Carvish

ISSUED TO

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1.0 Introduction

An experimental investigation of the flow in centrifugal impellers has been in progress in the Engine Laboratory since 1963. It has become clear that the detachment of flow from the blade surfaces is one of the major influences on the poor distribution and stability of flow in the impeller channels. After a general exploration of this flow detachment, reported in Lab. Memo. NRC-ENG-62 (Ref. 1), it was concluded that slotted blades were the most promising means of delaying instability and flow detachment as flow-rate through the impeller was reduced.

Further experiments on an isolated blade in a static wind tunnel were carried out from mid-1969 to the end of 1970, to establish the optimum slot configuration for this application. This work is reported in NRC-ENG-68 (Ref. 2).

Since that date, comparative experiments on three sets of blading, without and with slots, have been carried out in an actual rotating impeller on the Low Speed Centrifugal Compressor Rig. These experiments are reported in the present Memo.

2.0 Aim of Investigation

It has been shown that slotted blades appear to present a practical method of delaying flow detachment and unstable flow in a centrifugal blower impeller. It was therefore necessary to assess quatitatively the capabilities of such a system, applied to an actual rotating impeller. The ultimate aim of the programme is to raise the efficiency and broaden the operating range of centrifugal blowers.

3.0 The Experimental Approach Used

A centrifugal impeller is usually considered as a group of rotating quasi-radial channels, but it is also valid to regard it as a group of aerofoils rotating in an airflow whose natural path relative to them is a spiral. The work done by the impeller is therefore characterized by the degree to which the aerofoil deflects the flow outwards from its undisturbed spiral path. The force doing this work is in fact the lift generated by the aerofoils.

In a word, the blower characteristic is determined by the maximum lift coefficient generated by the aerofoil blades, and the range of incidence angle (controlled by the incidence/RPM function) over which this lift-coefficient can be maintained.

The maintenance of high lift-coefficient over a wide range of incidence is achieved in normal aerofoil practise by using slots, and the experiments described in Ref. 2 defined the twin-slotted configuration which appeared to be the optimum compromise between wide range, high lift-coefficient, and low loss, for this application.

Three sets of blades were therefore designed for the LSCC Rig, to fit into an impeller which had already been extensively tested (see ME-237 and ME-238, Refs. 3 and 4).

Each of these sets of blades was built in duplicate, one set of solid blades and one set with slots, and the unslotted and slotted builds of each set were tested over the same series of rpm and outlet throttle settings, to establish blower performance curves to show the influence of slots on performance. Volume airflow and pressure rise were measured by detailed traverses, detailed exit speed profiles were measured by hot wire anemometer, which gave clear indication of flow stability, and slow-motion movies of the flow visualized with smoke were shot at all conditions.

This body of evidence is presented in the present report, with a brief analysis. A full analysis of the whole project will follow after a further set of experiments has filled in some areas of investigation pointed out by the present programme. The present Memo. is to be regarded as a progress report in the continuing programme.

4.0 Arrangements Tested

An index of the blades tested is given in Figure 2. Layouts of the impeller and the three sets of blades are given in Figures 3, 4, 5, and 6. Fan characteristics of the various builds are given in Figures 7, 8, and 9. The exit speed profiles and tracings from the flow visualization movies are presented in Figures 10 to 47.

4.1 Description of Blades and Impeller

The impeller was common to all three sets of blading, and is shown in Figure 3. It is in fact the impeller described in Ref. 4, which also describes the unslotted version of the first of the present three sets of blades, which are designated the V.B. Series.

The three sets of blading VB1, VB2, and VB3, in their unslotted (VB1a etc.) and slotted (VB1b etc.) forms, are shown in Figures 4, 5, and 6. In all cases the blades are of C-4 section (see Appendix "A") with max. thickness (at 30% C) of 10% C. The chord line varied in the three sets, being a circular arc in VB1 and VB3, and a straight line in VB2. The chord lengths were different in all three sets, and were determined by the inlet and outlet blade angles, and impeller inner and outer diameters, which did not vary. The blade inlet angle was the same for all three sets, but the outlet angle was different for each.

The blade of VB1 was identical to that shown in Ref. 4, and was a typical heavily swept-back curved blade.

The blade of VB3 had the same inlet angle, but was oppositely-curved, with a radial exit. This could be regarded as analogous to a "radial" impeller, with integral curved inducer blades.

The blade of VB 2 was intermediate between these two, having the same inlet angle, and a straight chord line extending from this.

This arrangement led inevitably to different chord lengths for the three sets, and the number of blades in each build was chosen to hold the pitch/chord ratio approximately constant, where the circumferential pitch of the blade leading edges was used as the "pitch" figure. This decision was an arbitrary one, based on axial compressor practise, and appears to have led to too small a number of blades in the VB 3 set, where the performance at low flows could probably have been improved by a larger number of blades.

The slots were designed in accordance with the method proposed in Ref. 2 and are shown in Figures 4, 5, and 6.

5.0 Experiments and Analysis

5.1 Experimental Procedure

For details of the experimental procedure, the reader is referred to Ref. 3 (ME-237). In addition to the measurements described there, a total pressure probe was inserted (for tests on VB2 and VB3 only) into the vaneless diffuser space outside the impeller, at 41.2" radius (12" outside the impeller tip). This probe was mounted at mid-height in the channel, to measure the total pressure rise across the impeller. The probe was aligned to the local airflow for each reading, and the pressures read on a micromanometer.

5.2 Analysis of Results

5.2.1 Flow Quantity

From the hot-wire traverses in the inlet duct, it was simple to plot the inlet velocity profile, divide the inlet into concentric annulae of equal area, and hence calculate accurately the volume-airflow through the machine. This is displayed, as a function of throttle opening (in inches) in Figures 7, 8, and 9 at various impeller speeds.

5.2.2 Blower Characteristic Curves

The flow quantity is also plotted against total pressure rise (VB2 and VB3) in curves 8a and 9a. The pressure rise across build VB1 is not at present available. The "Zero Incidence", "Stall", and "Surge" points marked on these curves are defined in the discussion of the following section.

5.2.3 Impeller Exit Speed Profiles

The speeds at the grid of points in the impeller exit plane occupied by hot wire probes rotating with the impeller are plotted in a "three-dimensional way in Figures 10 to 47.

Since these wires were stretched in a direction parallel to the impeller axis, they provide no information as to the direction of the flow in the plane of the impeller disc. This information must be gained from the flow visualization diagrams. The nature of the flow (Stable, Fluctuating, or Bistable-alternating between two semistable modes) is indicated on the plots. It must be appreciated that the speeds in each graph are plotted as percentages of the maximum speed found on that graph. This is done so that the patterns of distribution at the various running conditions may be compared easily, although the average speed actually varies greatly from one condition to another.

5.2.4 Flow Visualization Diagrams

From the motion pictures of the flow visualized by smoke filaments, diagrams of flow have been prepared, corresponding to the running conditions at which the impeller exit speed profiles were measured. This was done with the hot-wire probes removed. These flow diagrams are shown in Figures 10 to 47.

6.0 Discussion of Results

6.1 Definitions

The three following arbitrary definitions are used in this program.

(a) "Zero Incidence". The running point at which the calculated volume flow and RPM combine to give an air inlet angle at the blade leading edge radius which is the same as the blade inlet angle, so that the air flows onto the blade at zero incidence.

(b) "Stall Point". The running point at which the flow in the impeller channels is unsteady, even as far upstream as the blade leading edges. However, this only implies randomly unsteady flow, and does not include periodic flow reversals.

(c) "Surge Point". This is the running condition at which cyclic flow reversals appear, whose period is a function of impeller RPM, and which cause the flow to enter a channel, loop back, and then enter the next channel.

6.2 Results of Experiments

6.2.1 General Flow

The general description of the flow is similar in all three pairs of blading sets. At zero incidence, the flow is smooth and stable throughout the channel, is reasonably aligned to the blades at inlet, and leaves the channel with a relatively smooth speed profile, showing but little detachment and low energy wake from either suction or pressure wall.

At flows above the zero incidence point, the inlet velocity moves towards the radial direction, and there is some tendency to detachment from the pressure wall of the channel (the convex blade surface). In general the flow is still smooth and stable.

At flows below the working range, the inlet velocity moves towards the tangential direction, and detachment from the suction wall of the channel (trailing blade wall) is observed, starting at the blade trailing edge and moving upstream, leaving a region of eddies behind it, as the flow is further reduced. This instability spreading from the suction wall of the channel leads to general instability of flow in the channel, which moves progressively upstream as the flow rate is decreased. At any given point the instability appears first in a transitory fashion, with occasional flutters in the flow, and then becomes a continuous unsteadiness. As stated above, Stallpoint is defined here as the flow at which continuous unsteadiness is experienced in the flow as far upstream as the inlet of the channel.

The flow may be still further reduced, with even worse consequences. By the time stall is reached, the suction wall detachment area will contain strong eddies forming periodically and drifting downstream. At yet lower flows, these eddies will begin to pulsate up and downstream, in a cyclic manner, before drifting bodily away downstream. This pulsation, combined with the progressively flattening inlet angle, will cause the inlet flow periodically to miss the channel inlet, and flow into the following channel instead, until ultimately this will be accompanied by an actual upstream movement of the eddies near the channel inlet, which can even carry them upstream out of the channel, into the eye of the impeller, and back maybe into the following channel. The flow at which this process starts was defined above as the Surge Point.

6.2.2 Fan Performance

Although there is a general similarity between the flow ranges of the various blading sets, the curves of Figures 7, 8, and 9 show up certain definite and systematic differences.

Firstly, it is clear from Figure 7 that at the same throttle opening and speed, the flow (and by implication pressure rise) curves from the three sets of blading 1, 2, and 3 are in ascending order, as would be expected from the increasing exit angle and exit whirl of the three sets of blades which run from the heavily swept back Set 1 to the radial-exit Set 3.

Much more interesting is the difference between the unslotted (a) and slotted (b) blades of each set. This is also shown in Figure 7, but more clearly in Figures 8 and 9 for Sets 2 and 3 respectively.

From the point of view of pressure rise, the slotted arrangement is superior only over quite a restricted range of operation at low flows, where a 2-3% increase of pressure rise is obtained. However, it is also seen that Set 2 in particular has its stall and surge flows appreciably reduced (from 10 to 5 ft^3/sec on stall, the surge point of Set 2b could not even be found) by the presence of slots.

6.2.3 Airflow Patterns

It is at the low-flow region, where stall is normally caused by unstable detachment from the suction wall, that slots would be expected to be useful, as their action consists in taking high-energy air from the pressure side of a blade and injecting it into the low-energy boundary layer on the suction side, to stabilize it and delay detachment.

However, there is another effect which is difficult to present quantitatively, but is striking to the observer. The quality of the flow near the stall point, and the severity of stall and surge, are notably different between the unslotted and slotted blading of all three sets. As can be seen from the flow diagrams of all sets, the stabilizing effect of the slots not only delays the onset and severity of detachment, but also greatly reduces the instability and transitory nature of the flow pattern. The characteristic bistable flow patterns, associated with complete vortices moving along the channel, and the pulsating flow of the surge regime, are hardly to be seen in the slotted blading.

This reduction of the flow pulsation around the surge point of a compressor could be of great benefit in many applications, quieter operation at low flows might be most acceptable in air conditioning systems for example.

A further point which could be of importance in blowers or compressors incorporating a vaned diffuser is that it appears true in general that the slotted sets of blading produce a more uniform speed profile at exit than the unslotted sets. Even the exit speed "solid" graphs give this impression, although their lack of directional information somewhat masks the effect. However, studied in conjunction with the flow diagrams they give definite confirmation to this statement.

The sensitivity of diffuser flow is well known, and it is clear that anything which reduces the flow pulsations in a vaned diffuser channel, due to the passage of successive jets and wakes from the uneven distribution leaving the rotating impeller channels, will benefit the diffuser performance in the compressor.

6.2.4 Blade Loading

The number of blades in each Set was decided on the basis of keeping a constant value of pitch/chord ratio, as explained in Section 4.1 above. As the blade loading is increased with rising delivery pressure, from Set 1 to Set 3, it becomes apparent from inspection of the flow diagrams, particularly at low flows, that the blades cannot generate the required lift. The loading should be reduced by using greater numbers of blades, particularly in Set 3. This would avoid the state of affairs seen in the small throttle openings of Set 3, where the small flow streams diagonally across the channel, leaving large dead areas at the inlet pressure side and exit suction side. The presence of slots did control and stabilize this pattern, and prevented the pulsating of these dead areas up and down the channel as they did in the unslotted version. However, a greater number of blades would probably have improved the pattern as well as stabilizing it.

7.0 Conclusions

(1) The research on stabilizing the flow in centrifugal compressor impellers described in references 1 and 2 has been continued. A series of experiments on the application of the slots described in reference 2 to rotating impellers is described. Three sets of blades were tested at low speed without and with slots, and their performance is described in detail.

(2) It is shown that the presence of slots increases the pressure rise obtainable across the impeller at low flows, but may reduce it at higher flows.

(3) It is also shown that the presence of slots has a marked effect in stabilizing the flow, lowering the stall point, and reducing the severity of surge, if not eliminating it altogether.

8.0 Future Action

(1) Further low speed tests will be carried out to fill in some gaps in the present data, notably the absence of pressure rise measurements across the Set 1 blading.

(2) High speed tests at up to 6000 RPM on an 18" d. impeller, will be carried out on the Set 2a and 2b blading.

9.0 References

(1) Fowler, H.S. "Attempts to Delay Flow Detachment, with Potential Application to Centrifugal Compressor Rotor Blades" Lab. Memo NRC-ENG-62, April 1969.

(2) Fowler, H.S., Bond, G.S., Rudnitski, D. "The Effectiveness of an Isolated Slotted Blade in Delaying Detachment of Flow, with Potential Application to Centrifugal Compressor Rotor Blades" Lab. Memo NRC-ENG-68, June 1971.

(3) Fowler, H.S. "Aerodynamic Tests on a Centrifugal Fan Impeller Model with Swept-Back Blades" NRC ME Report ME-237, May 1971.

(4) Fowler, H.S. "Comparison of Thin Plate and Thick Aerofoil Blades in a Centrifugal Fan" NRC ME Report ME-238, August 1971

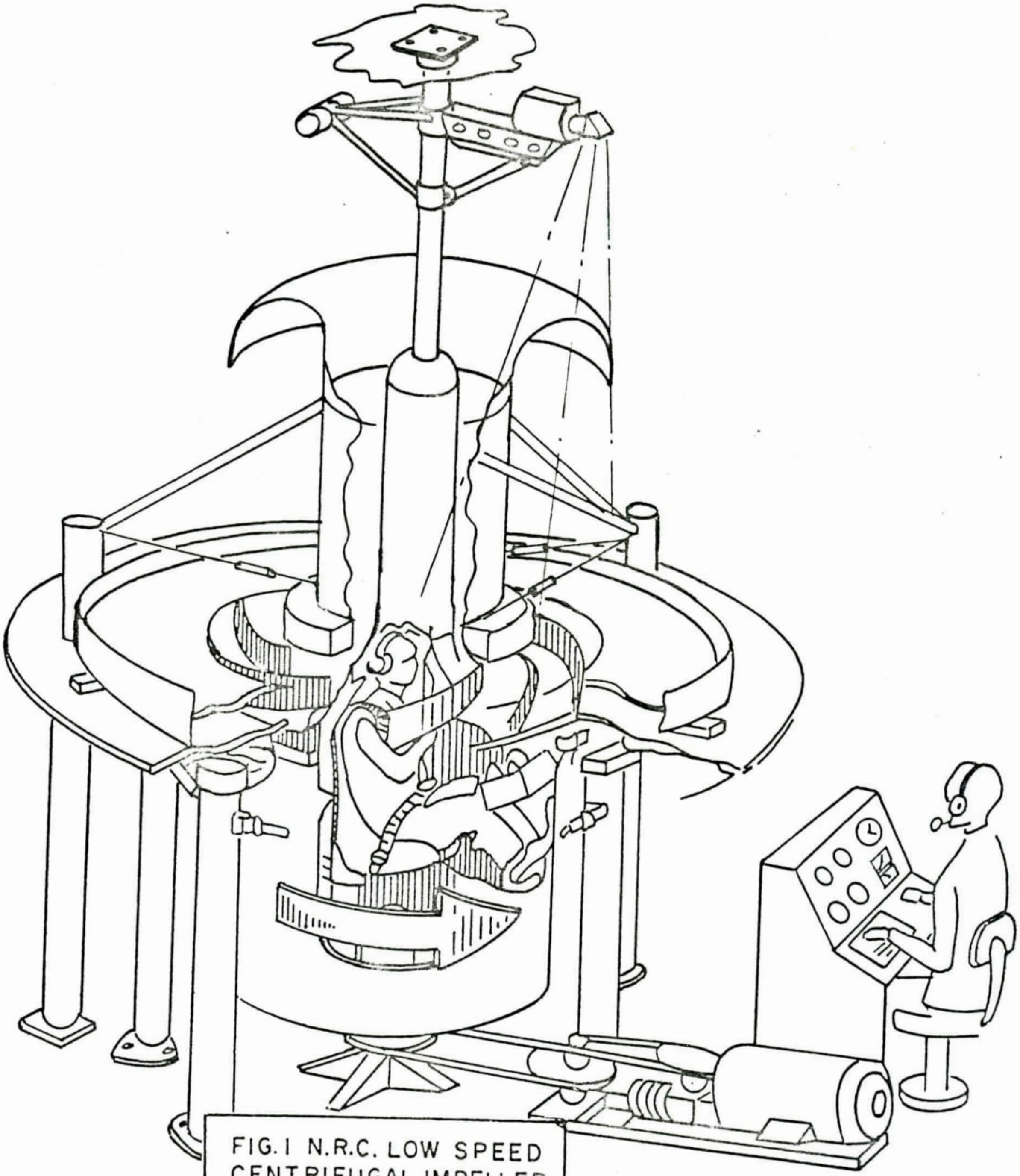


FIG. 1 N.R.C. LOW SPEED CENTRIFUGAL IMPELLER TEST RIG

FIG. 1.

Index of Blades Tested

All blades had the following features in common:-

Impeller blade leading edge pitch circle diameter = 33.0"
Impeller blade trailing edge pitch circle diameter = 58.4"
Blade inlet angle (to tangential direction) = 35°
Blade aerofoil section - C-4 (max. thickness/chord = 10%)
Blade height = 3.25"

There were three sets of blading, Nos. 1, 2, and 3. Each of these sets was first tested plain, and then tested again after two slots had been added to each blade, corresponding to Blade "E" of Ref. 2. The unslotted and slotted blades were identified as 'a' and 'b' respectively of each set 1, 2, or 3.

The distinctive features of the three sets of blades were:-

Set	No. of Blades	Camberline	Outlet Angle
1	8	Circular Arc	30°
2	11	Straight	62.5°
3	13	Circular Arc	90° (Radial)

Figure 2

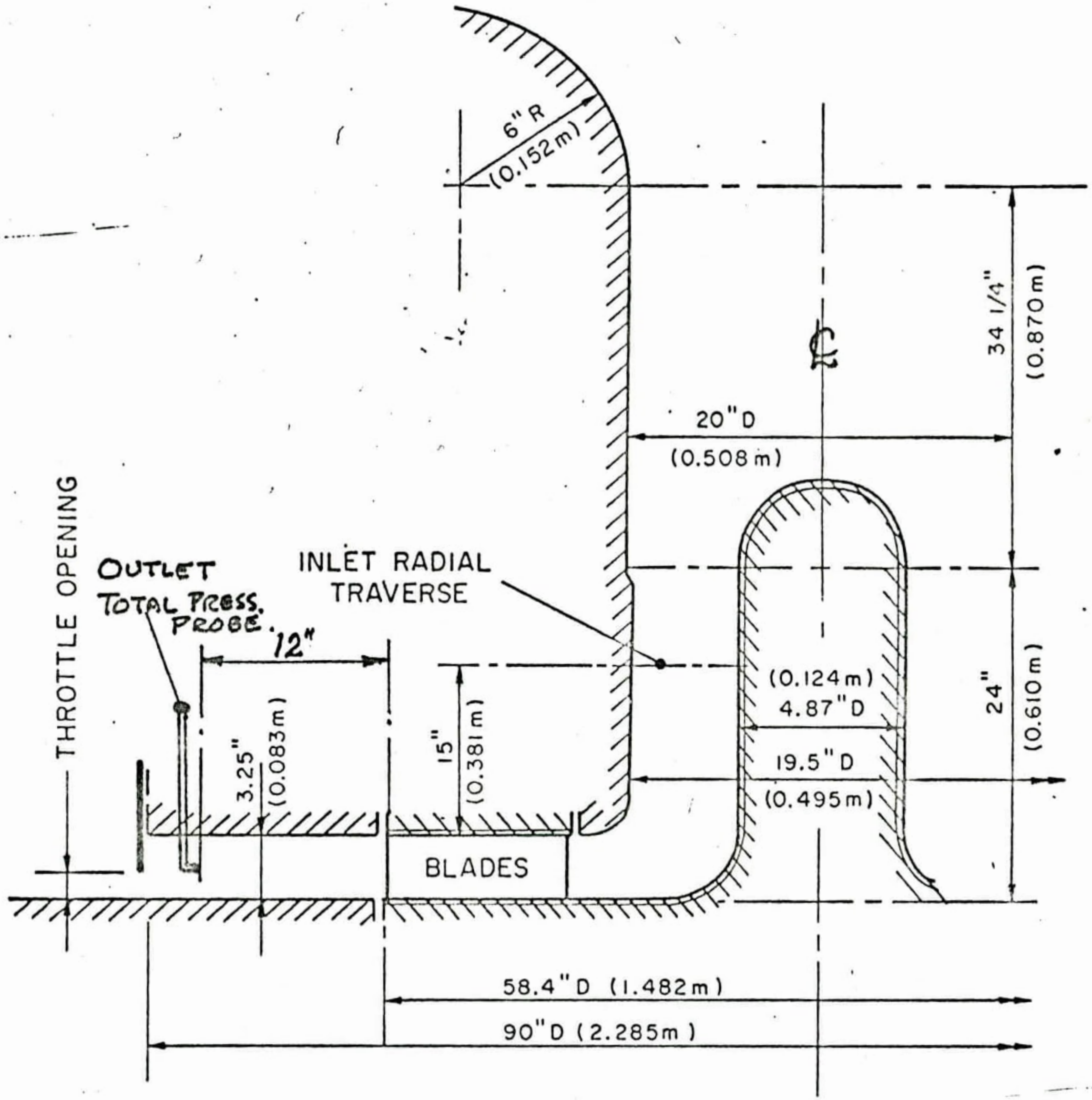


Fig. 3.

FIG. 3 : ROTOR AND AIR PASSAGE PROFILE

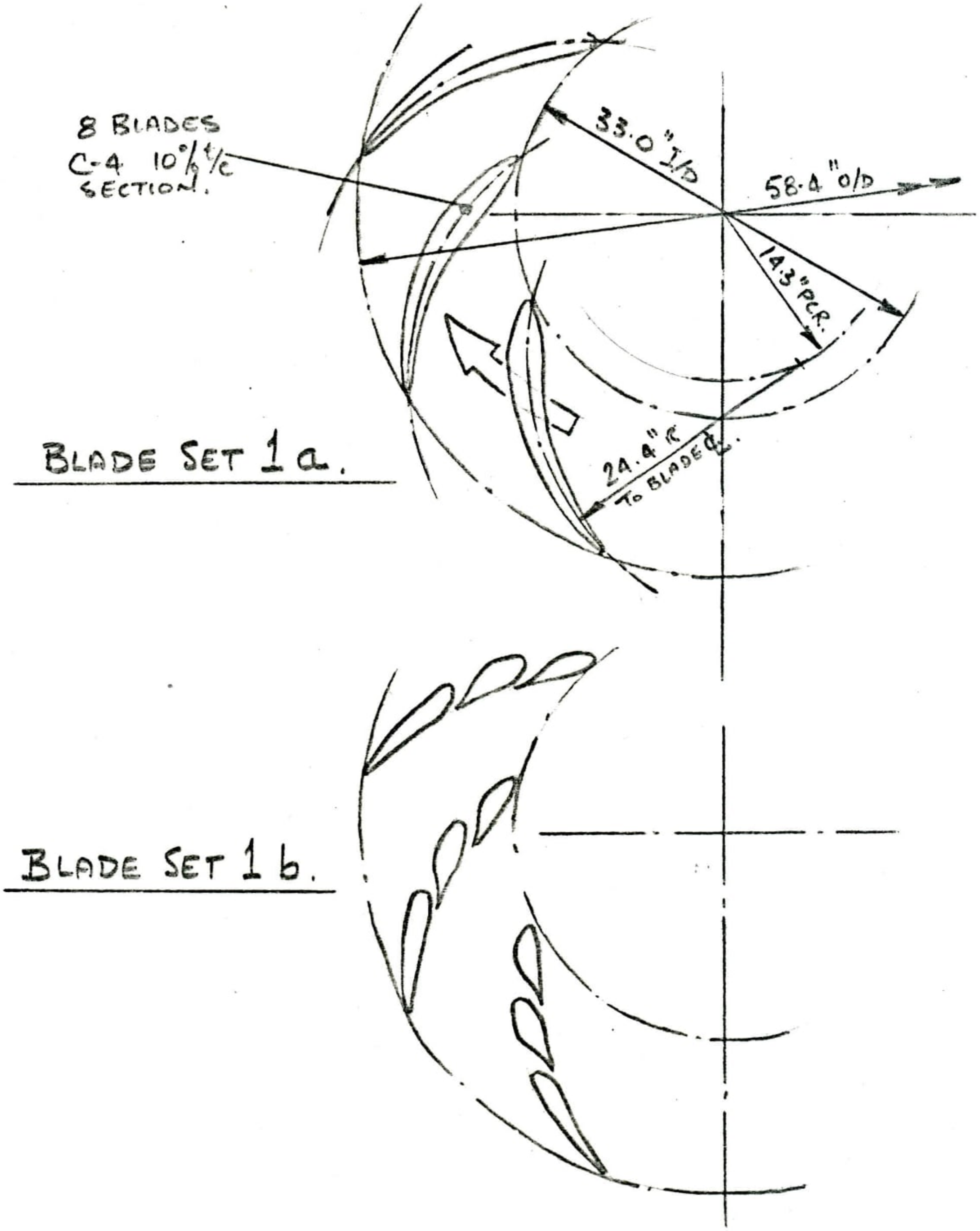
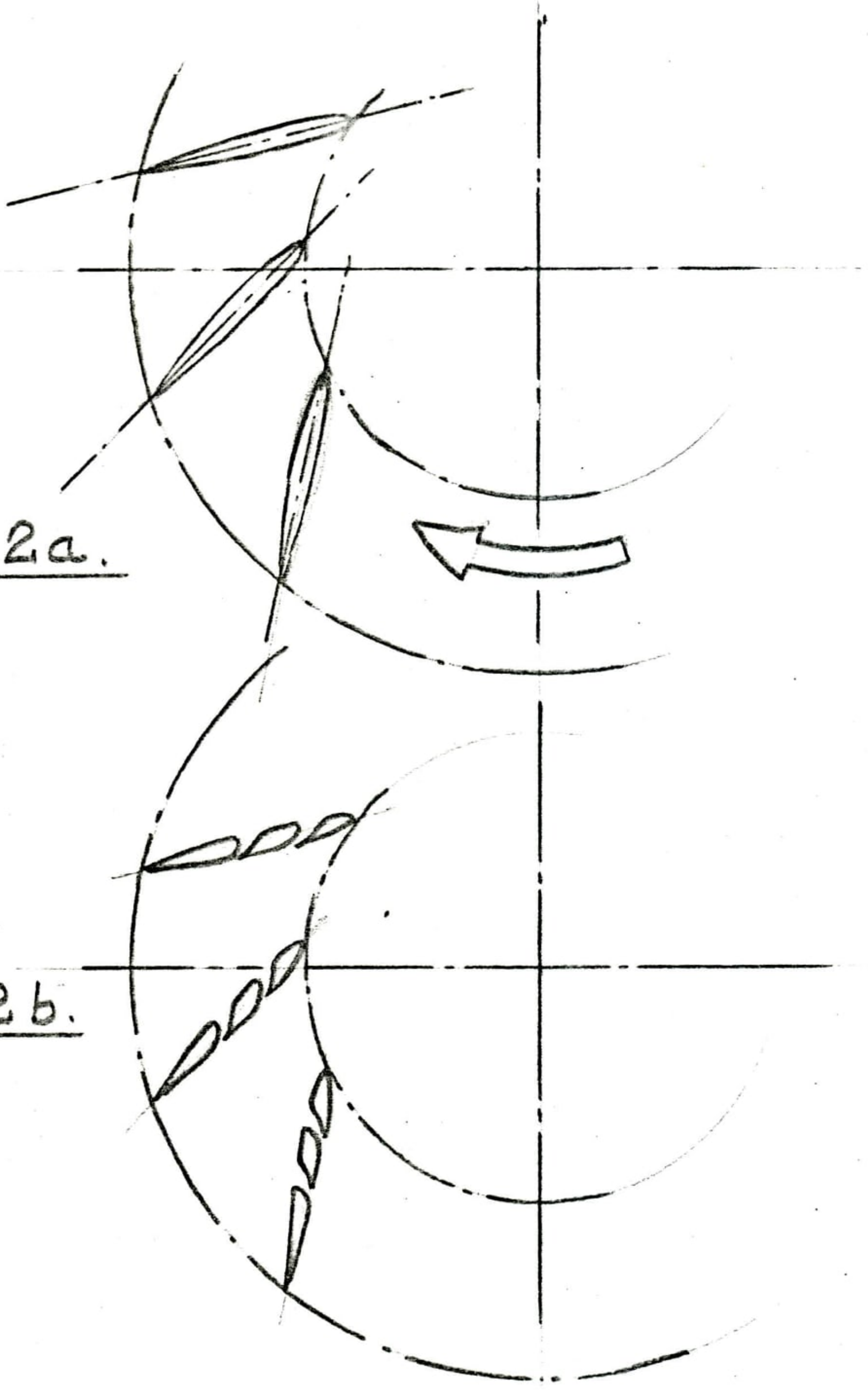


FIG 4.: DETAILS OF SET 1a & 1b BLADING.
DRWG No. C.25747.

FIG. 4.



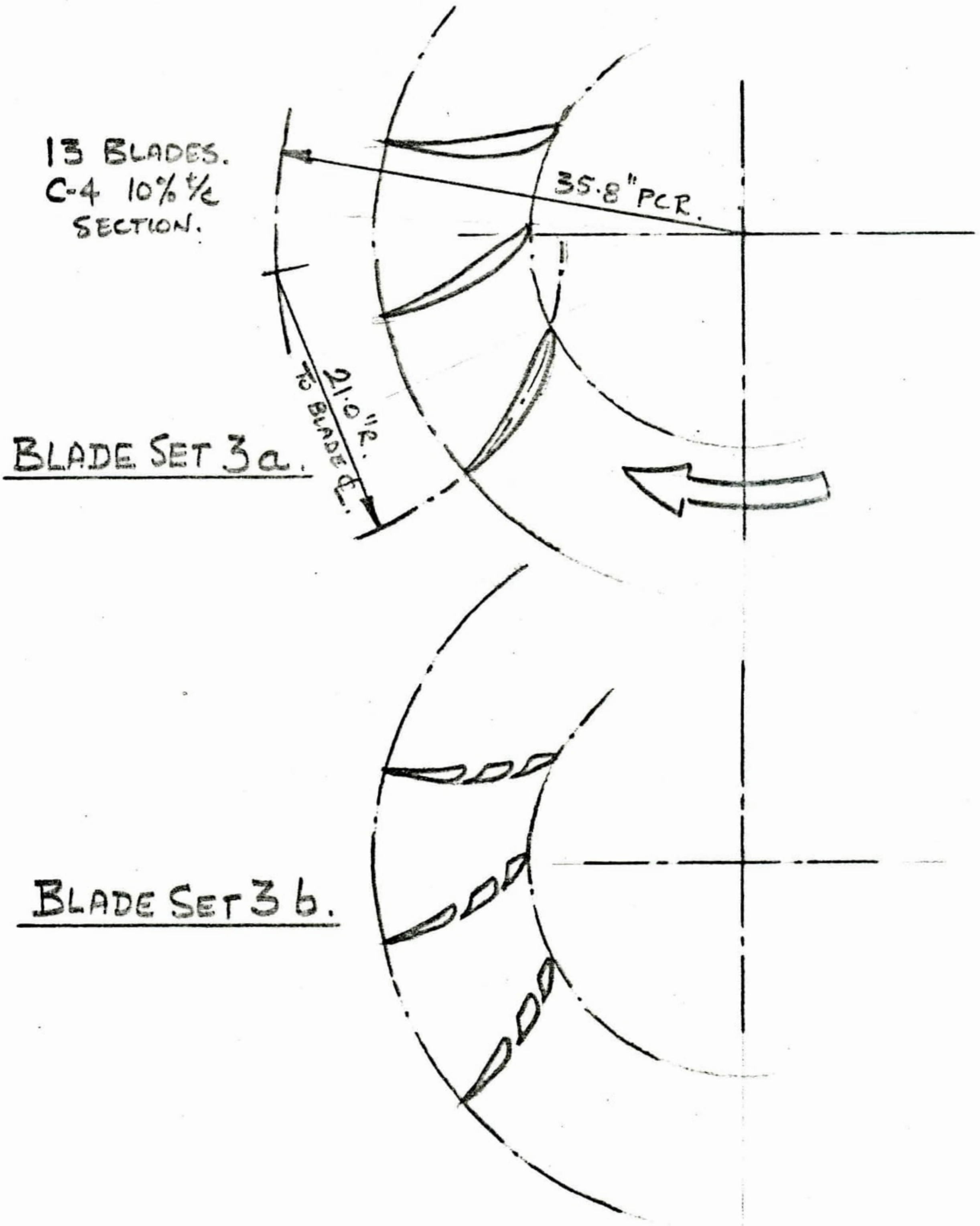
BLADE SET 2a.

BLADE SET 2b.

FIG 5. DETAILS OF SET 2a & 2b BLADING.

DRWG. Nº C.25918.

FIG. 5.



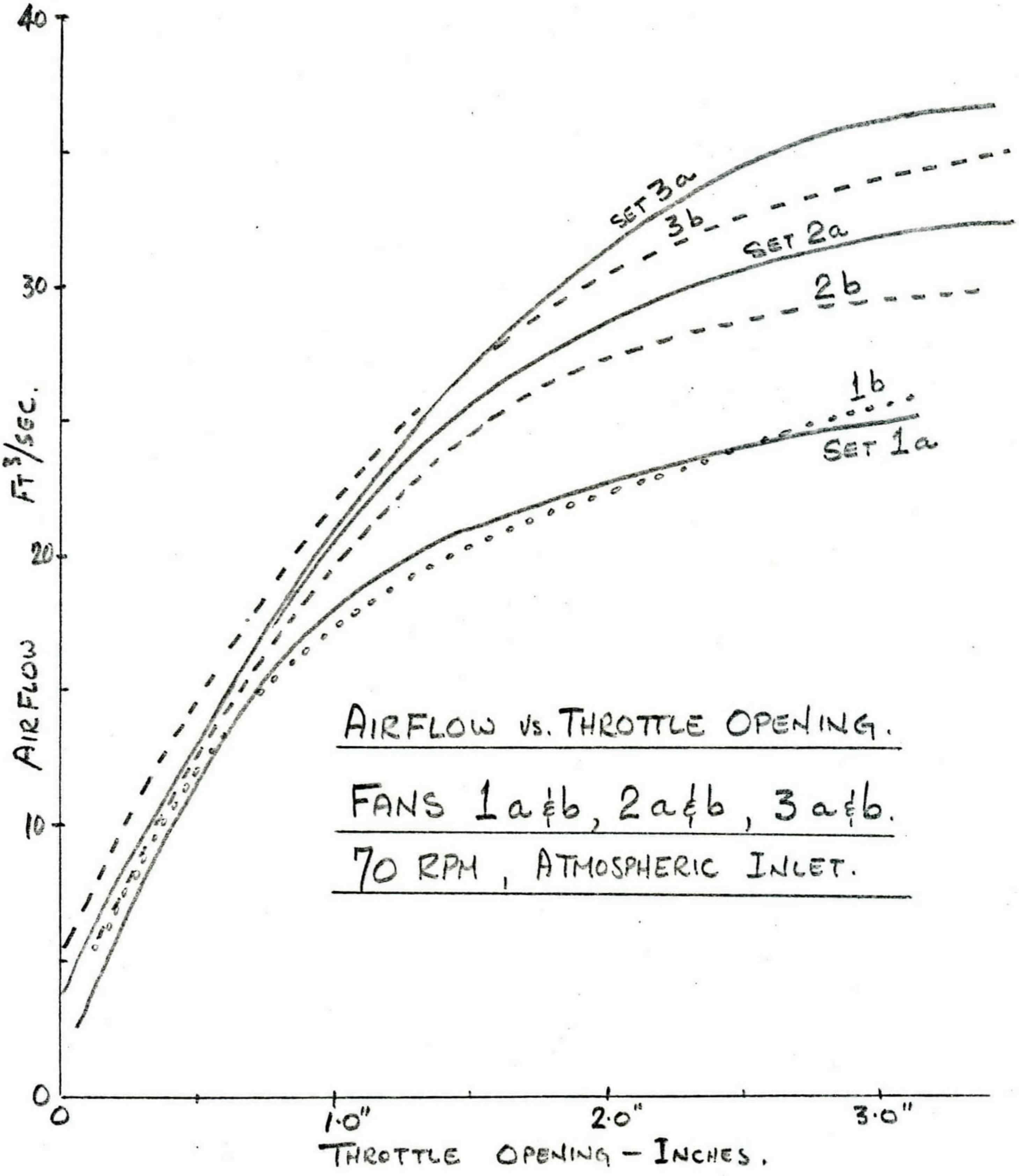
BLADE SET 3a.

BLADE SET 3b.

FIG. 6. DETAILS OF SET 3a & 3b BLADING.

DRWG. Nº C.25919

FIG. 6.

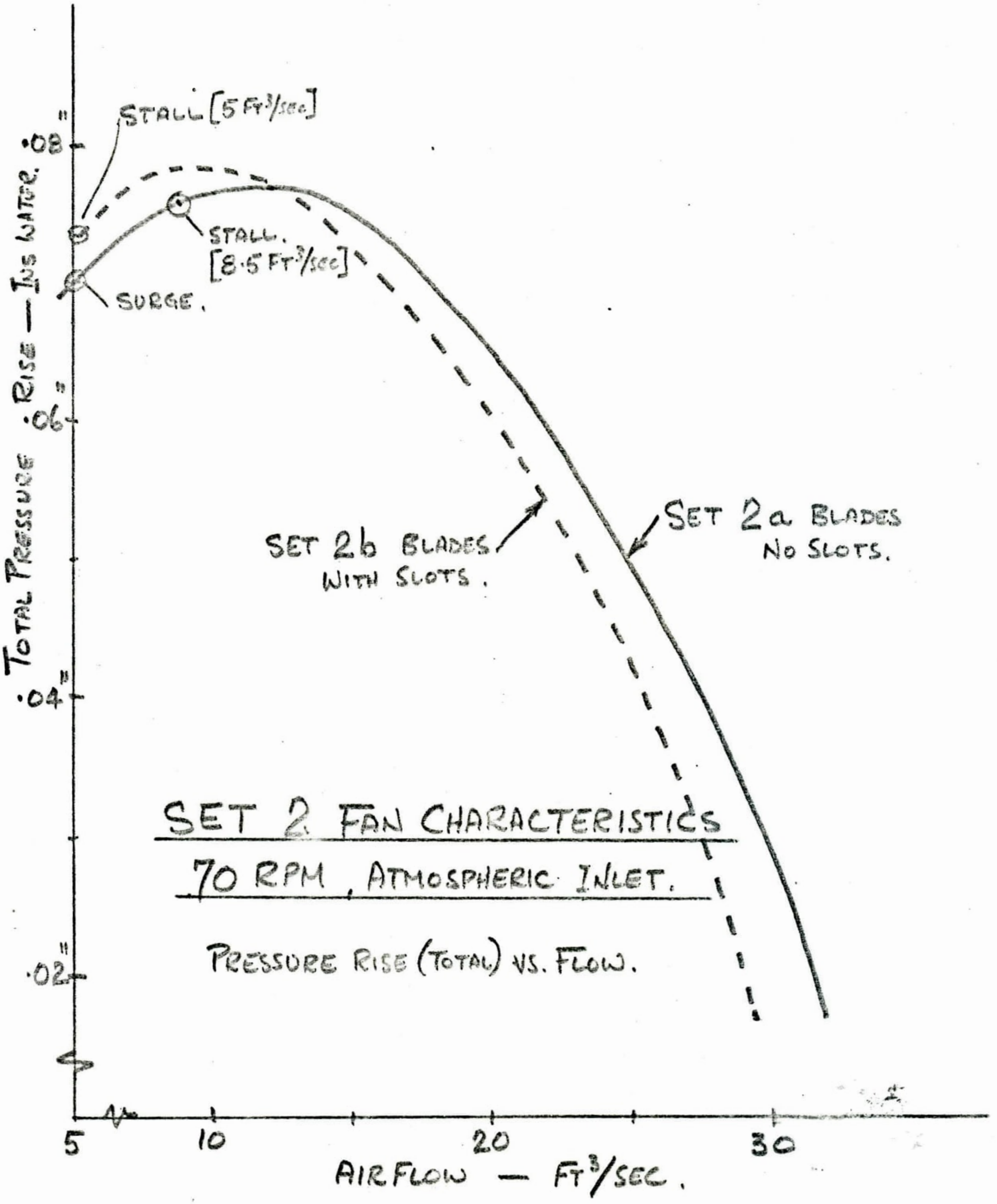


AIRFLOW vs. THROTTLE OPENING.

FANS 1a & b, 2a & b, 3 a & b.

70 RPM, ATMOSPHERIC INLET.

FIGURE. 7.



SET 2 FAN CHARACTERISTICS

70 RPM, ATMOSPHERIC INLET.

PRESSURE RISE (TOTAL) VS. FLOW.

FIG. 8.

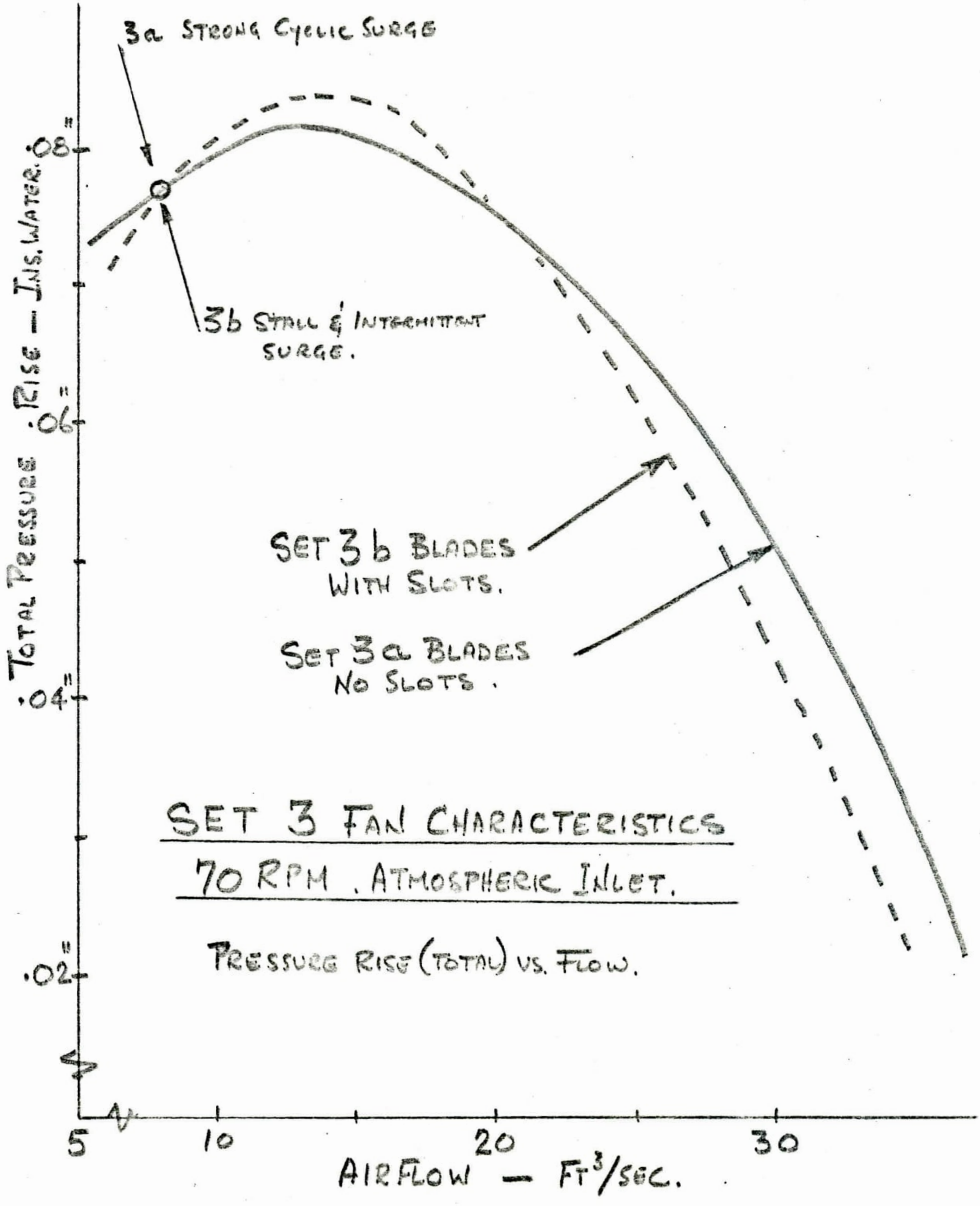
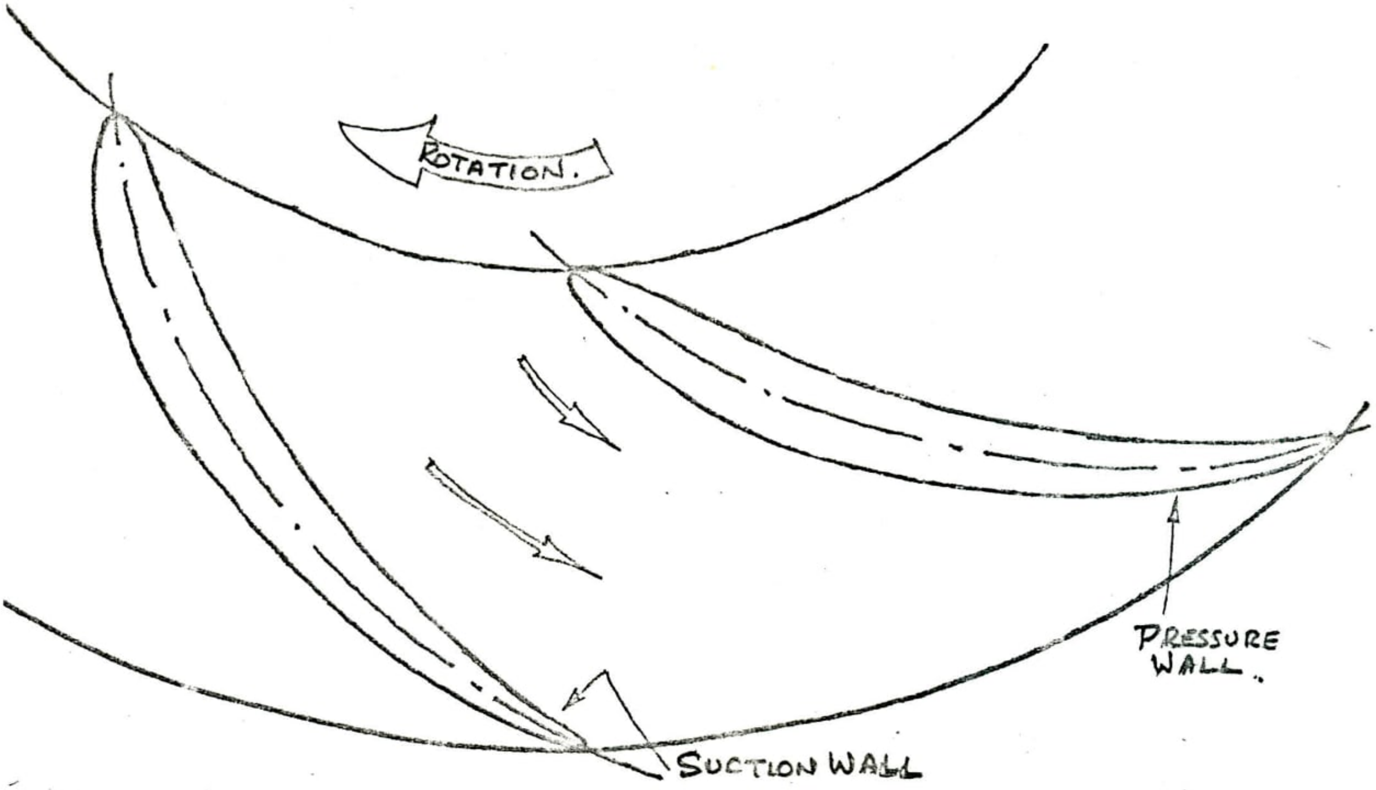
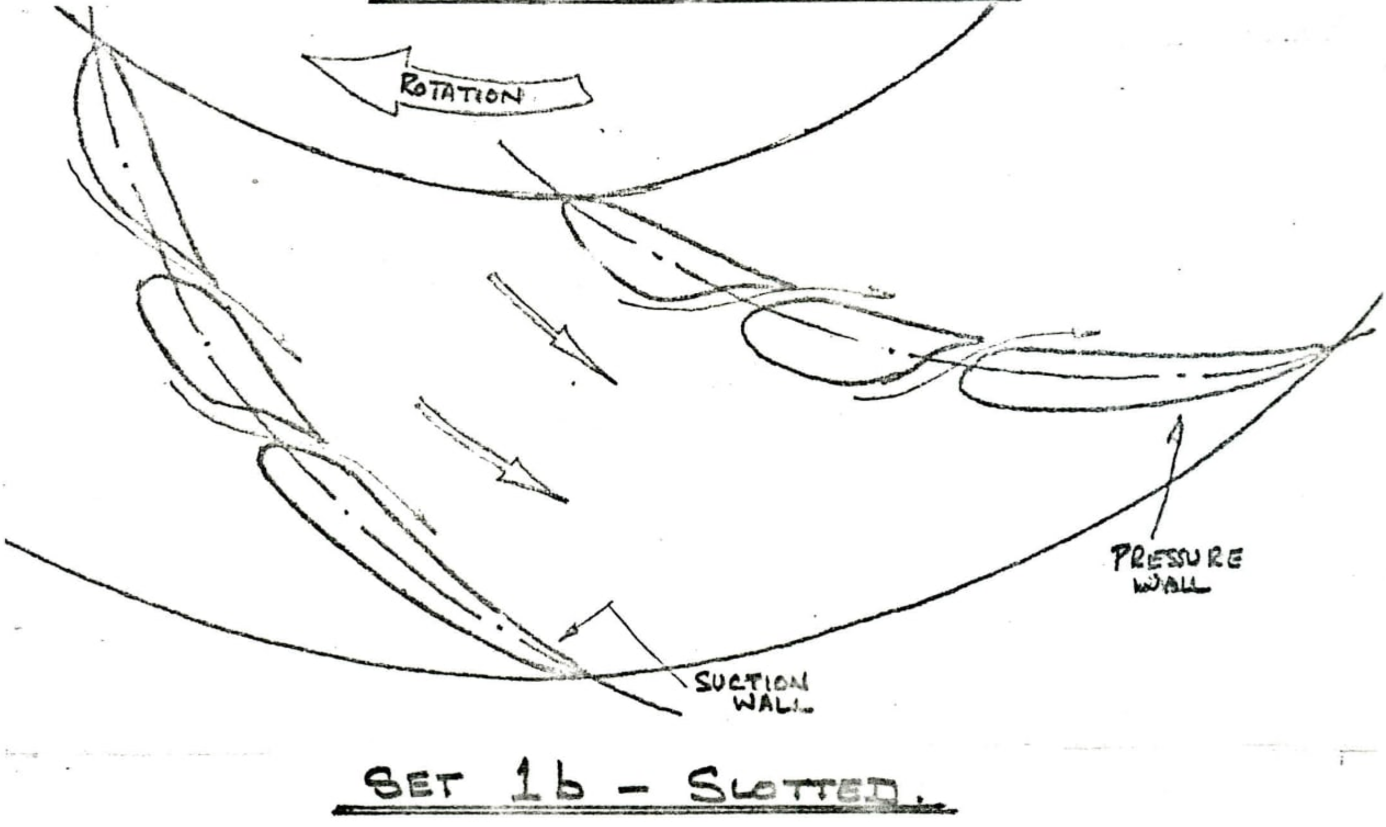

3a Strong Cyclic Surge
3b Stall & Intermittent surge.
Set 3b Blades With Slots.
Set 3a Blades No Slots.
Set 3 Fan Characteristics
70 RPM. Atmospheric Inlet.
Pressure Rise (Total) vs. Flow.
Total Pressure Rise — Ins. Water.
.08"
.06"
.04"
.02"
5
10
20
30
Airflow — Ft³/sec.

Fig. 9.



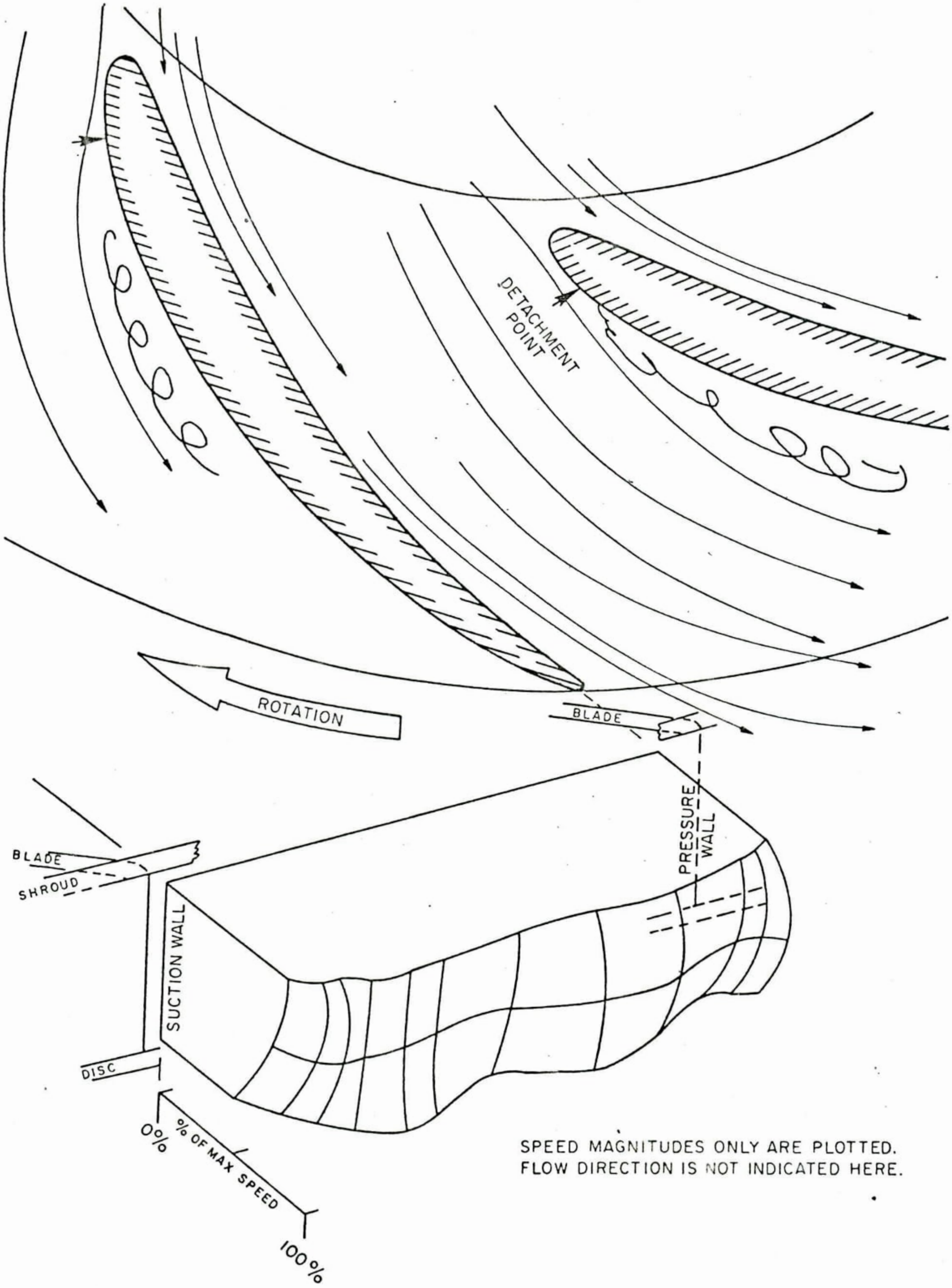
SET 1a — UNSLOTTED.



SET 1b — SLOTTED.

BLADE SET 1.

FIG. 10.



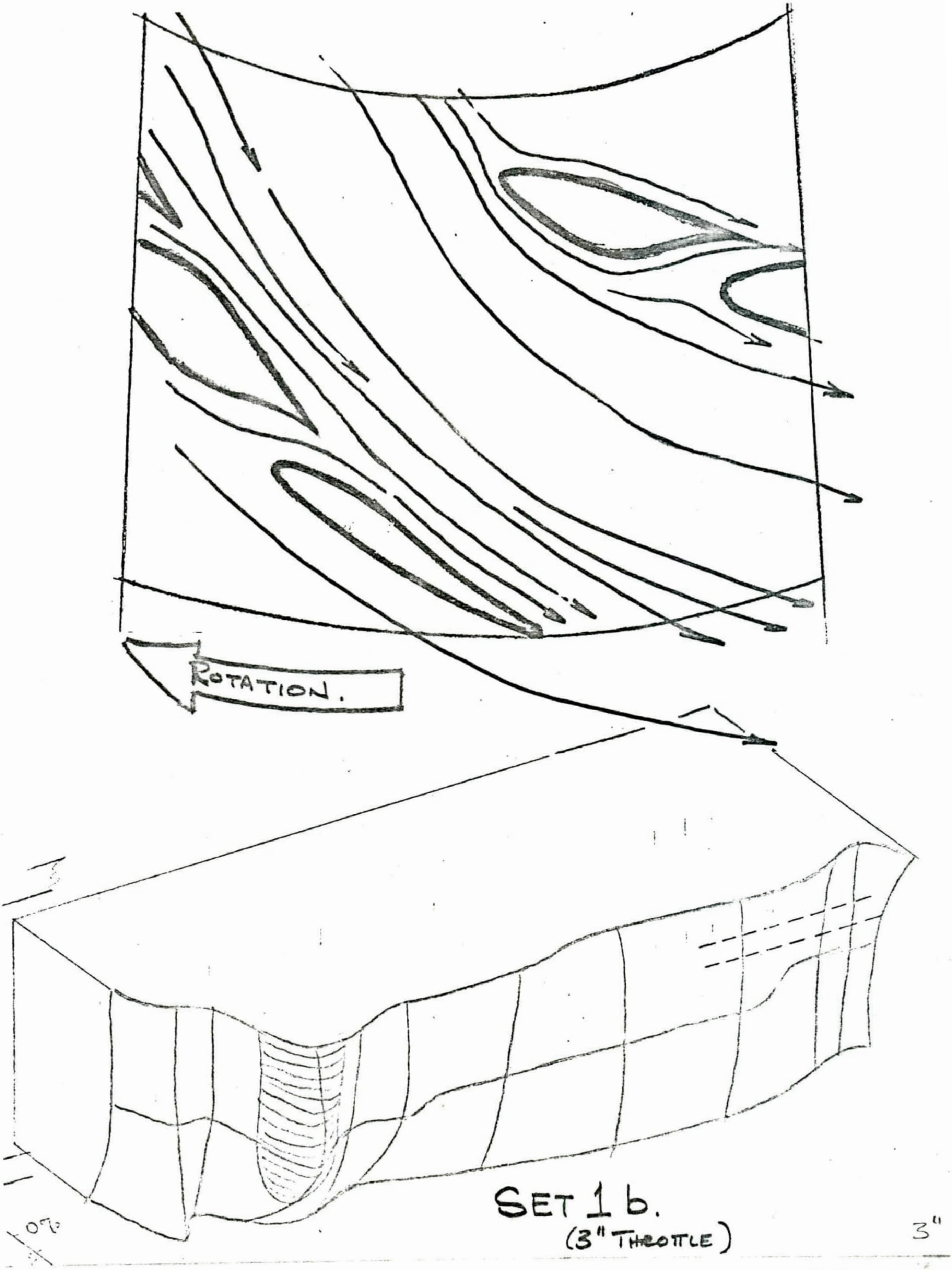
SPEED MAGNITUDES ONLY ARE PLOTTED.
FLOW DIRECTION IS NOT INDICATED HERE.

FIG.[redacted] : FLOW IN ROTOR CHANNELS

[redacted] SET 1a.

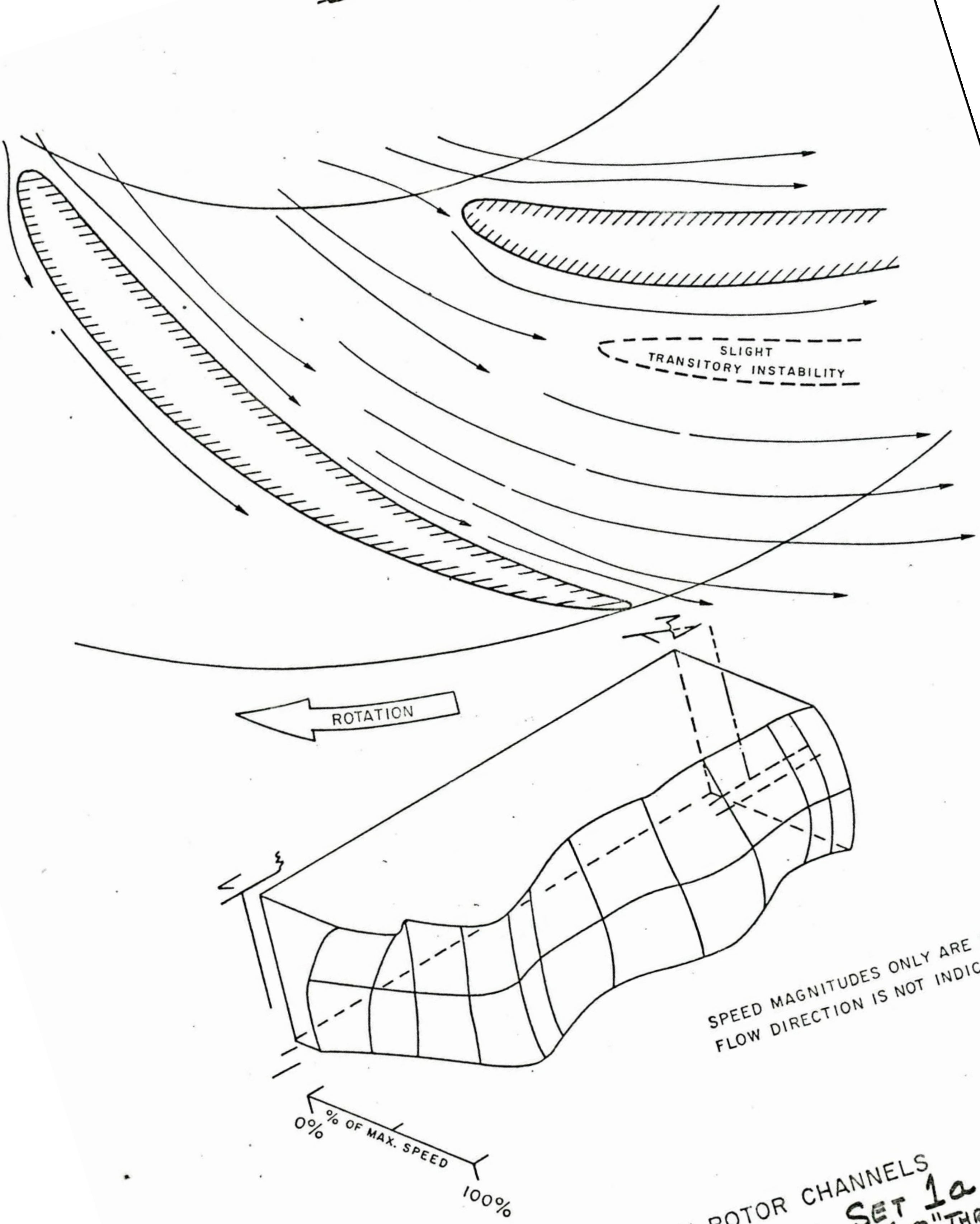
MAXIMUM FLOW POINT [redacted] (3" THROTTLE)

FIG. 11.



SET 1 b.
(3" THROTTLE)

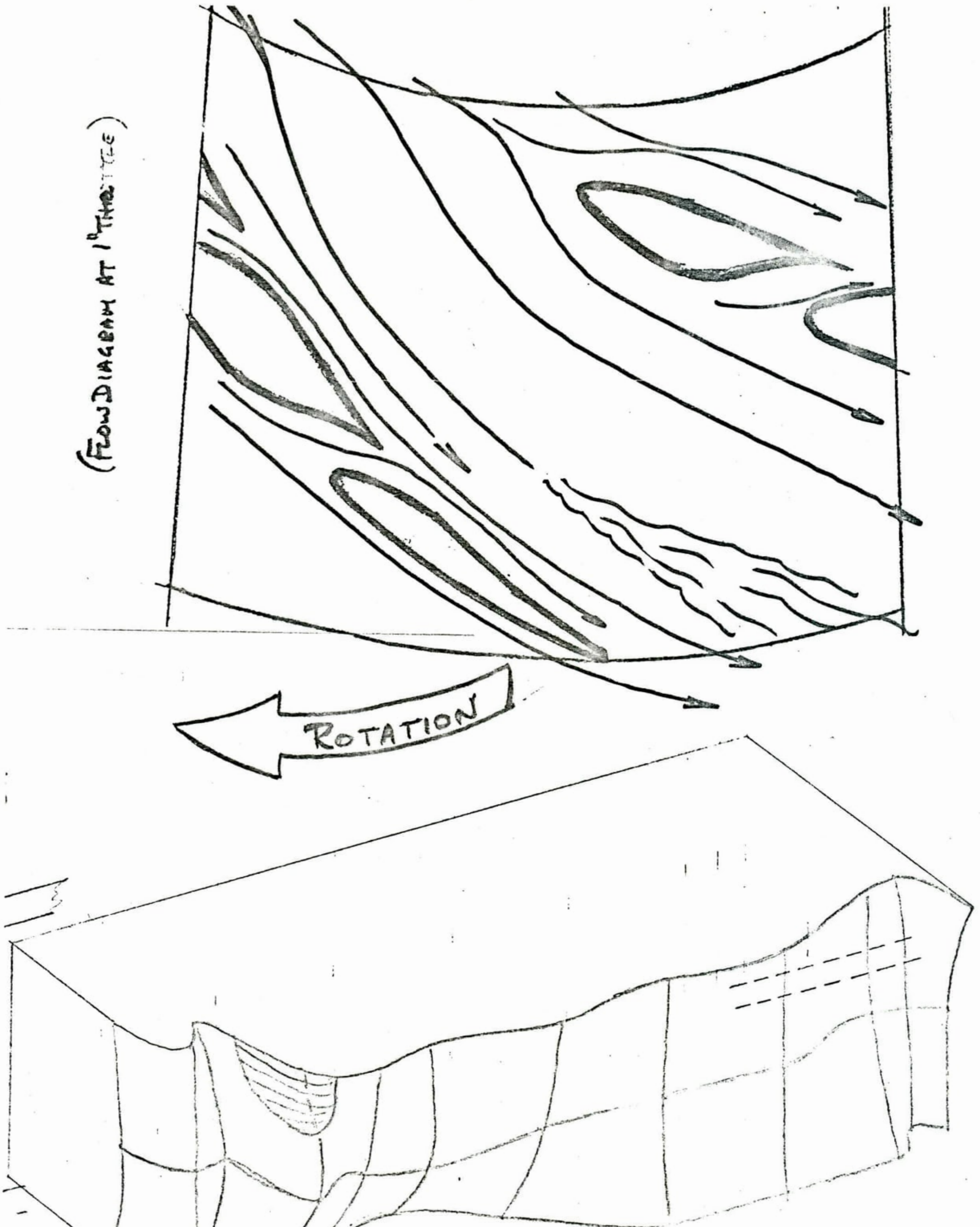
FIG. 12.



SPEED MAGNITUDES ONLY ARE PLOTTED.
FLOW DIRECTION IS NOT INDICATED HERE.

FIG. [redacted] : FLOW IN ROTOR CHANNELS
[redacted] SET 1a.
ZERO° INCIDENCE POINT [redacted](·8" THROTTLE)

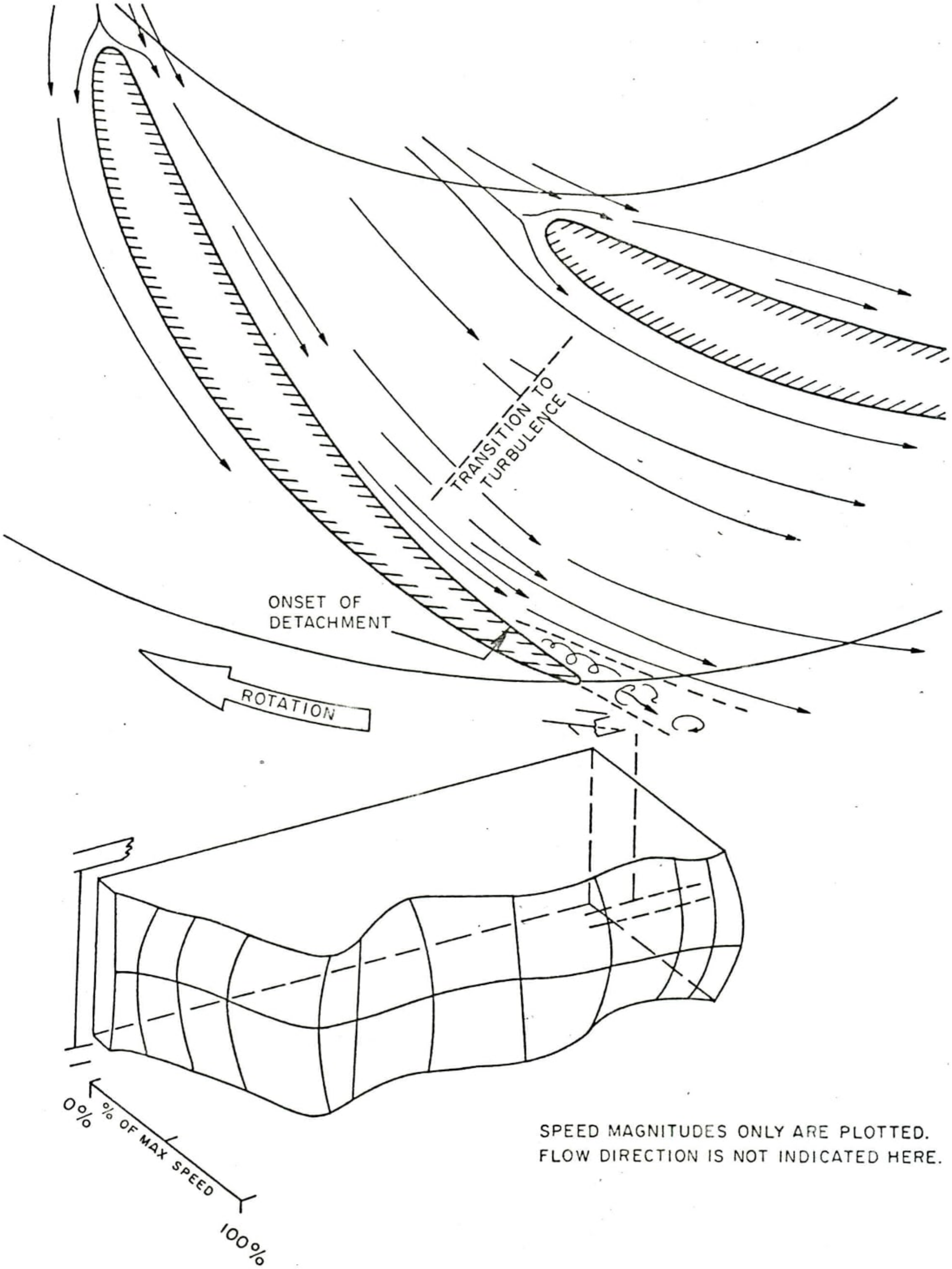
Fi



(FLOW DIAGRAM AT 1" THROTTLE)

SET 1 b. (·8" THROTTLE)

Fig 14.



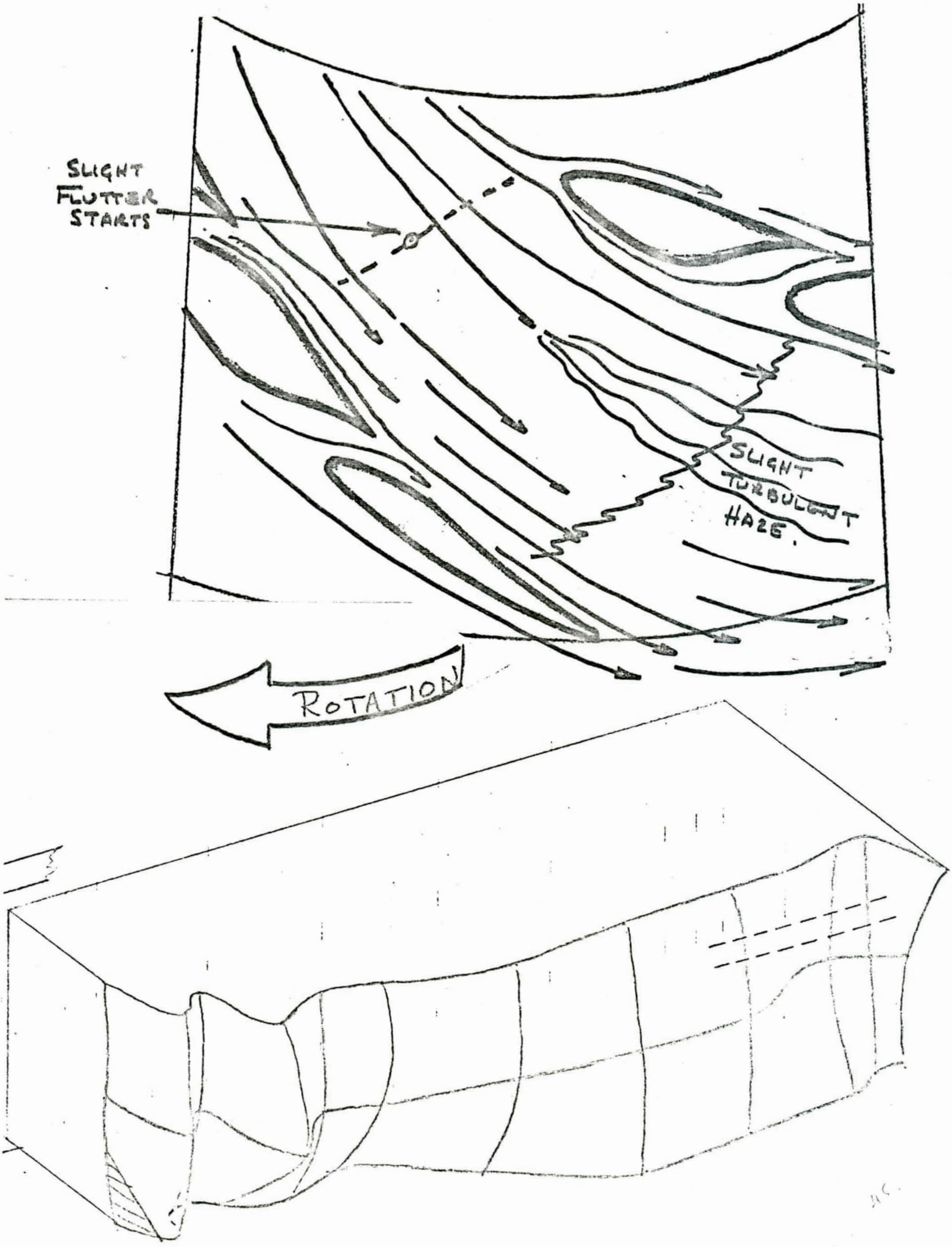
SPEED MAGNITUDES ONLY ARE PLOTTED.
FLOW DIRECTION IS NOT INDICATED HERE.

FIG. [redacted] : FLOW IN ROTOR CHANNELS

[redacted] SET 1a.

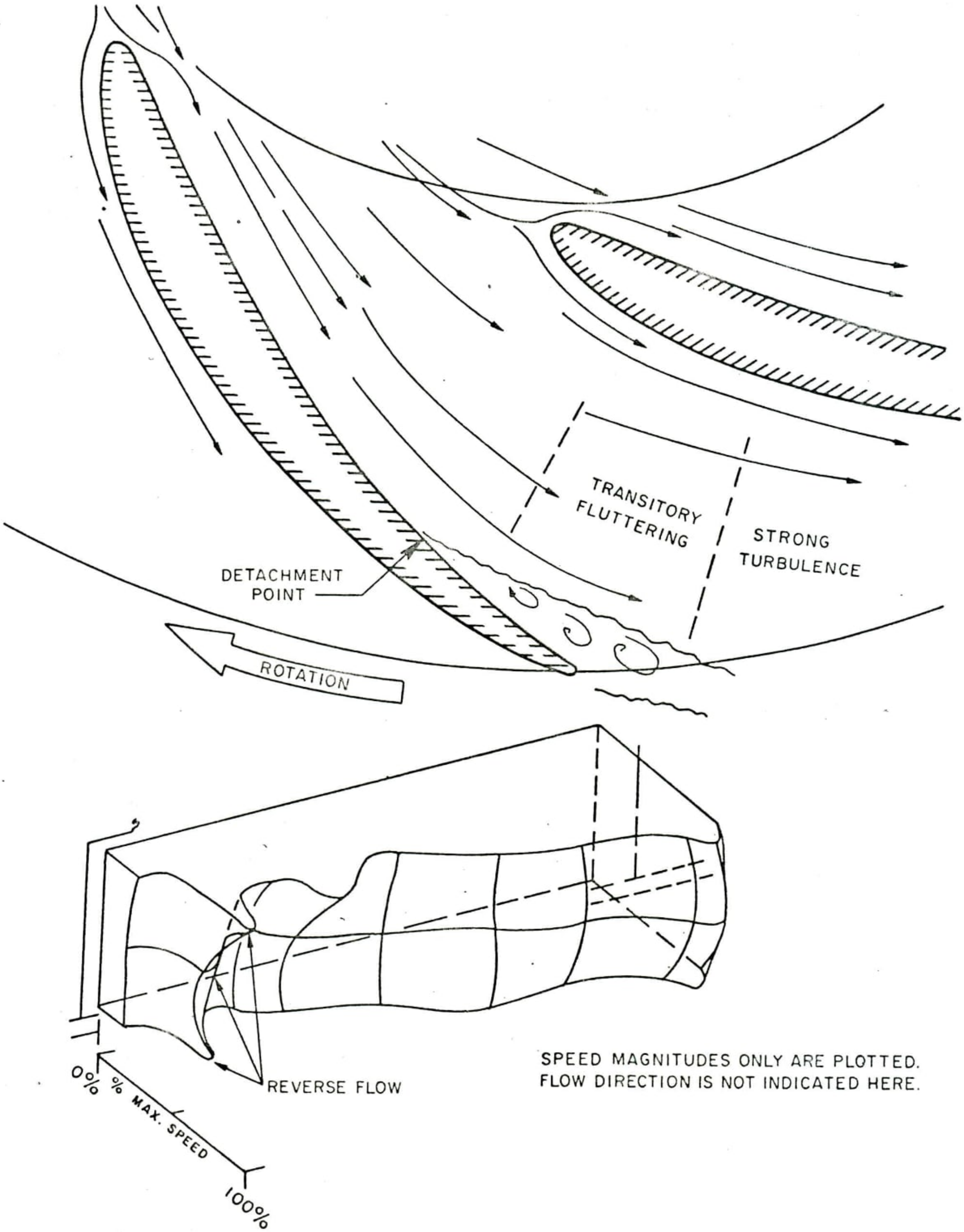
ONSET OF DETACHMENT POINT [redacted] (·45" THROTTLE)

FIG. 15.



SET 1 b. (·45" THROTTLE)

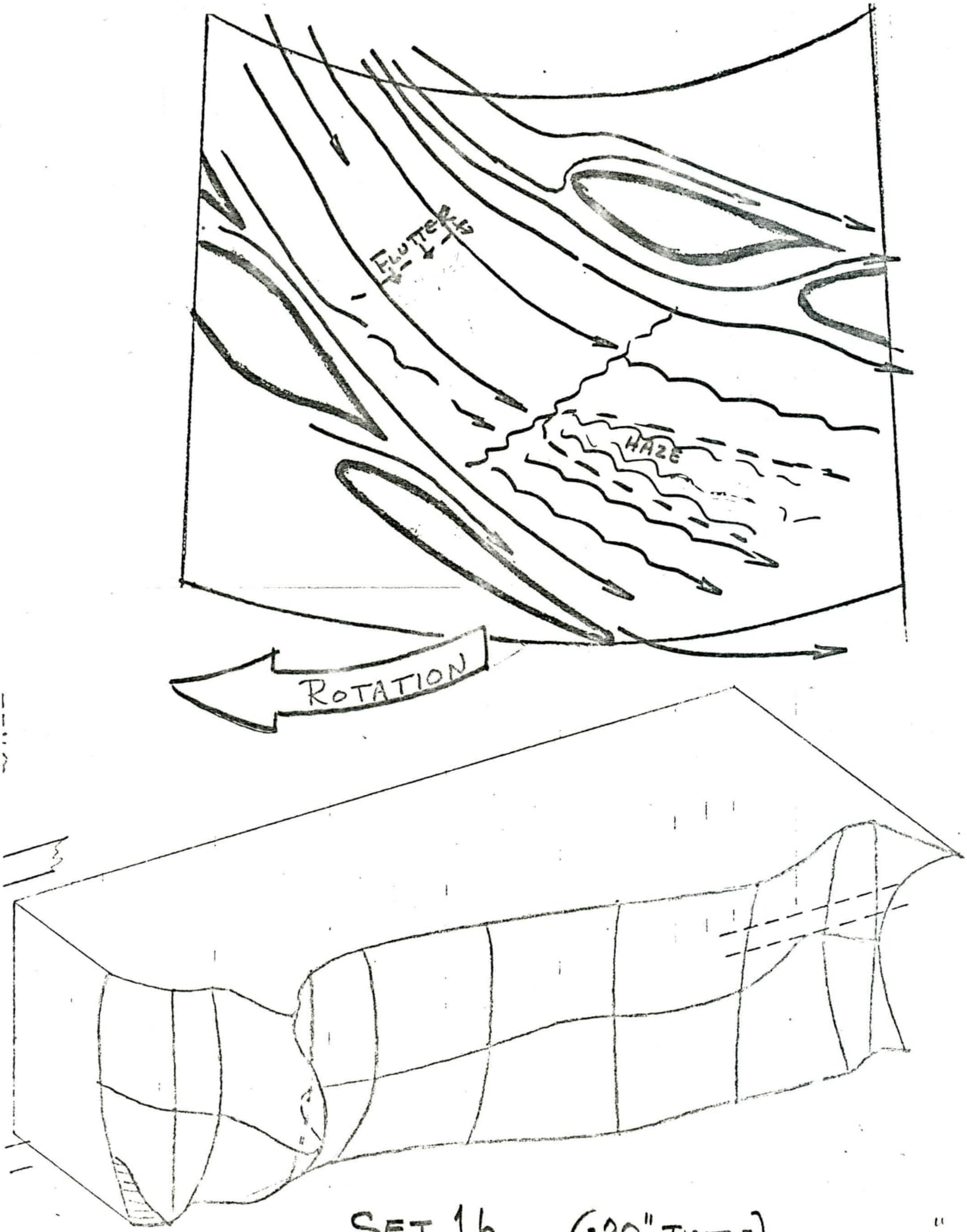
FIG. 16.



SPEED MAGNITUDES ONLY ARE PLOTTED.
FLOW DIRECTION IS NOT INDICATED HERE.

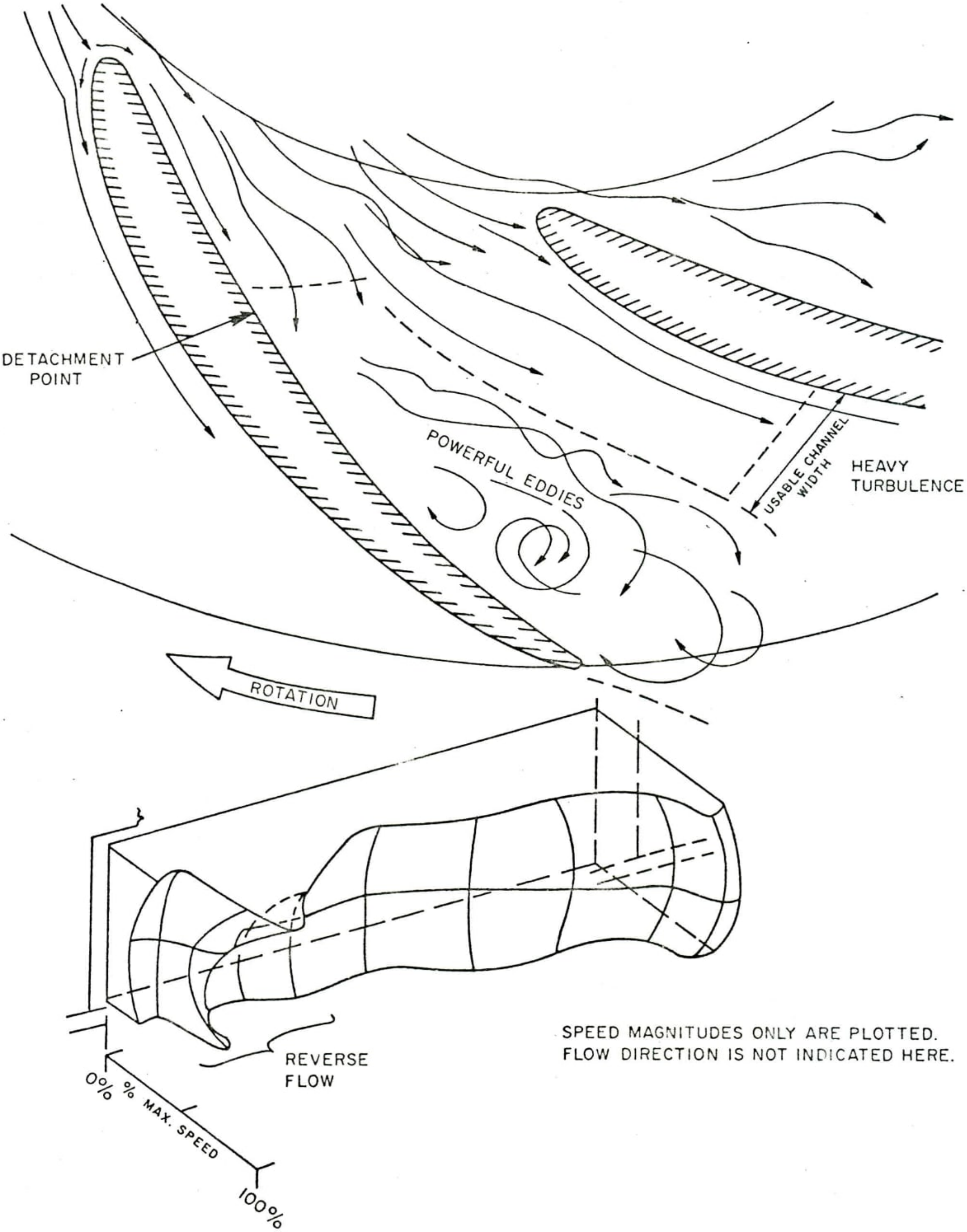
FIG. [redacted] : FLOW IN ROTOR CHANNELS
~~AEROFOIL BLADES~~ SET 1 a.
BELOW STALL POINT [redacted] (·2" THROTTLE)

FIG. 17.



SET 1b. (·20" THROTTLE)

FIG. 18.



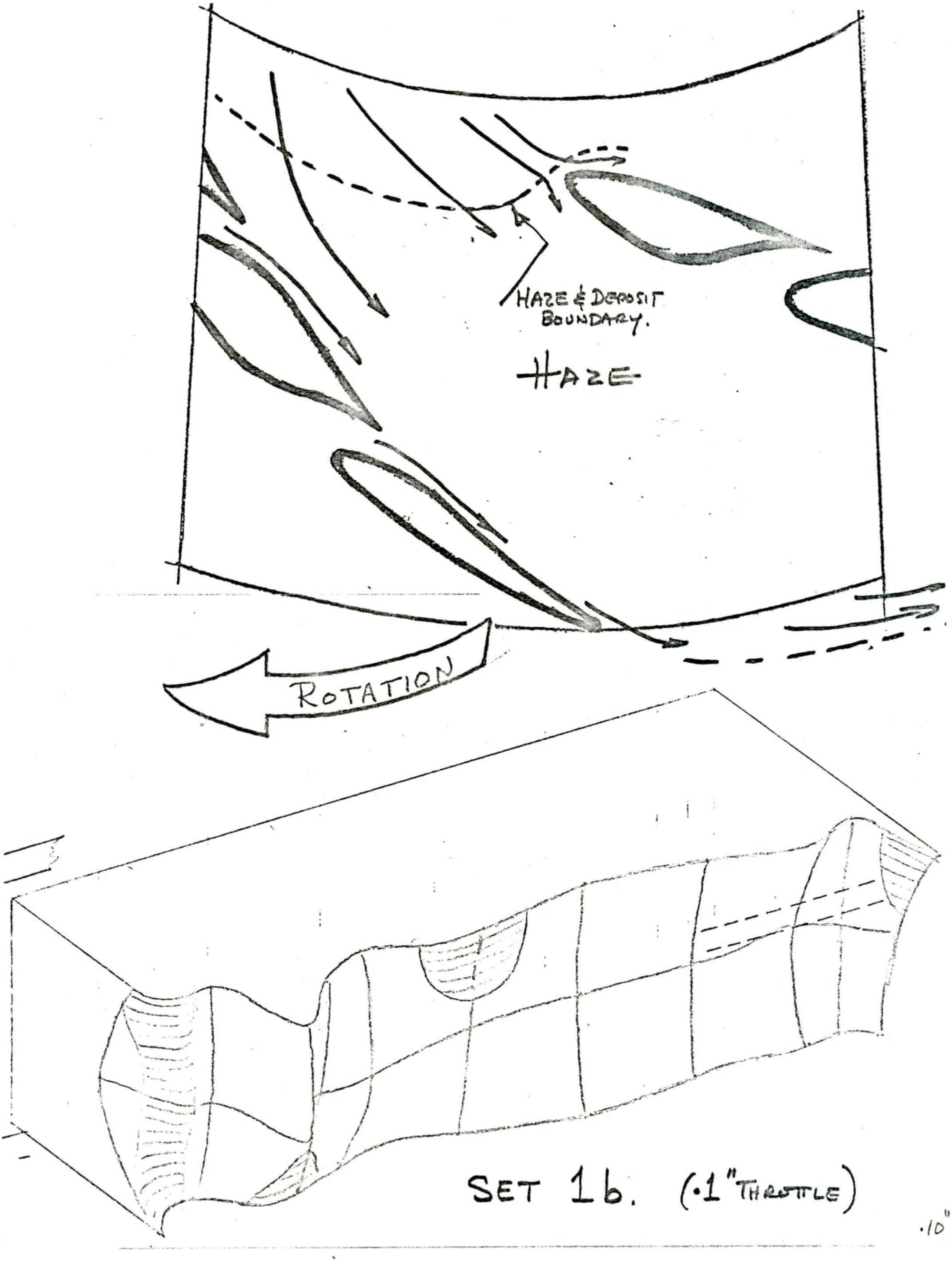
SPEED MAGNITUDES ONLY ARE PLOTTED.
FLOW DIRECTION IS NOT INDICATED HERE.

FIG. [redacted] : FLOW IN ROTOR CHANNELS

[redacted] SET 1a.

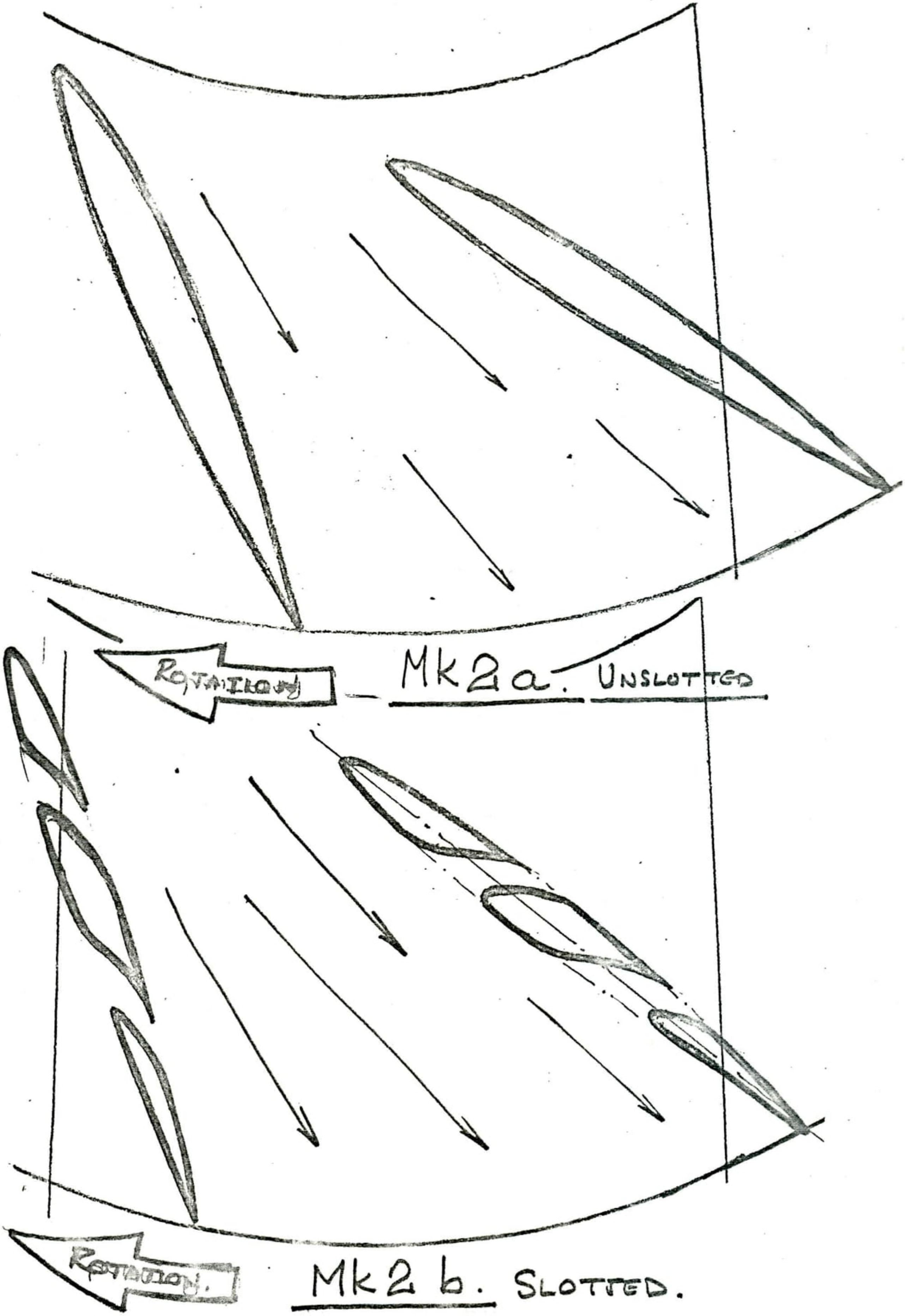
BELOW STALL POINT [redacted] (·1" THROTTLE)

FIG. 19.



SET 1b. (·1" THROTTLE)

FIG. 20.

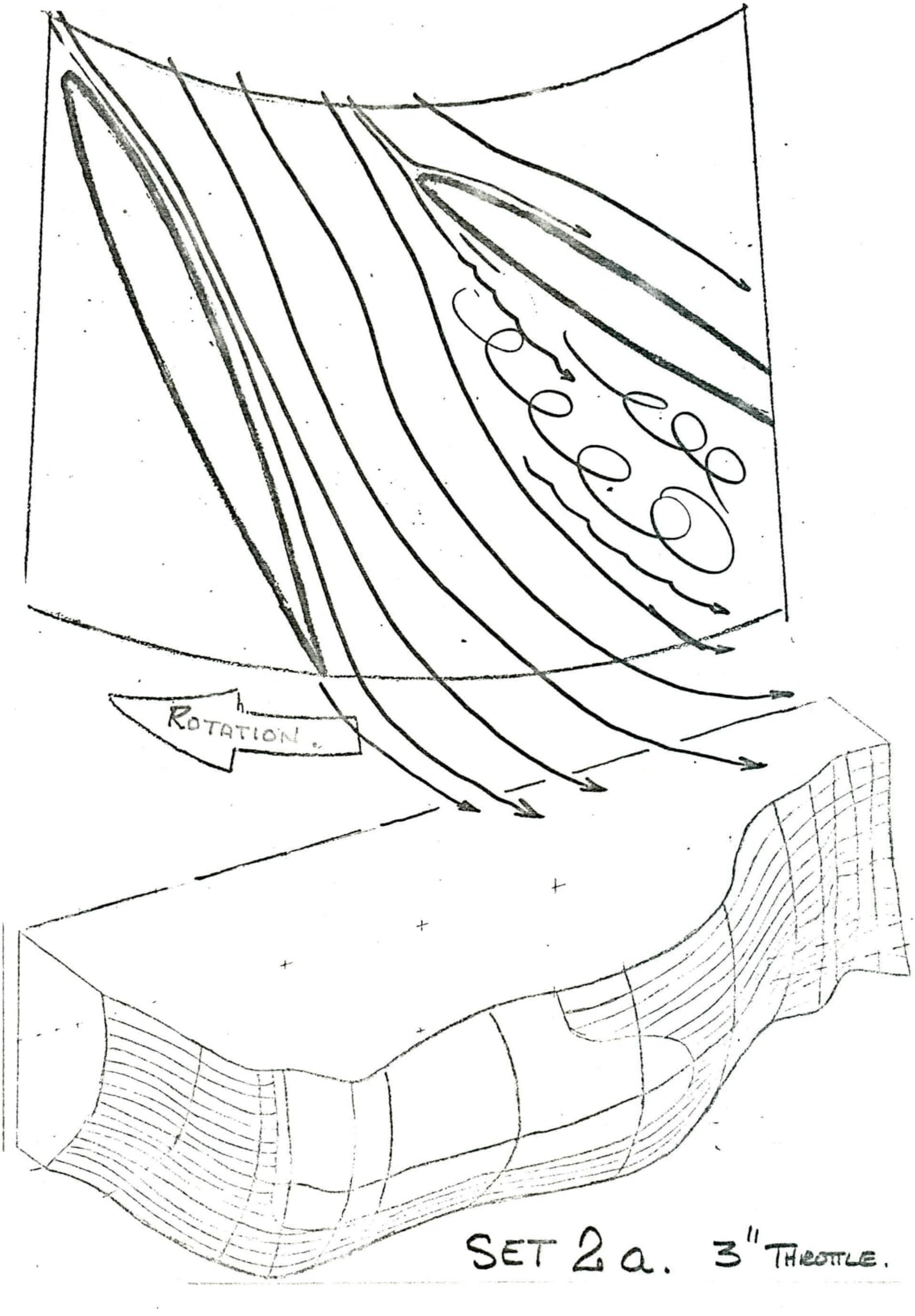


Mk 2a. Unslotted

Mk 2b. Slotted.

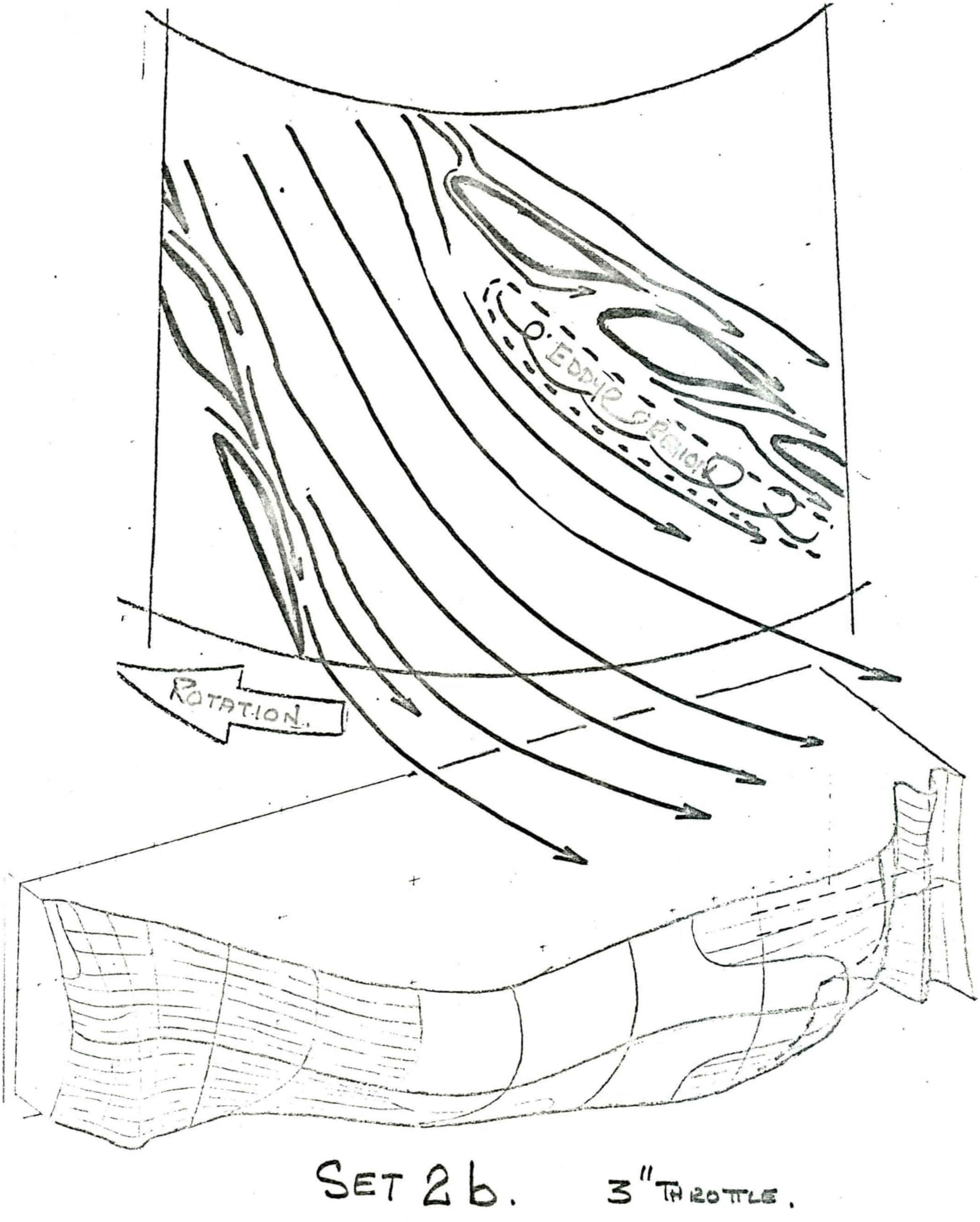
Blade Set 2

Fig. 21.



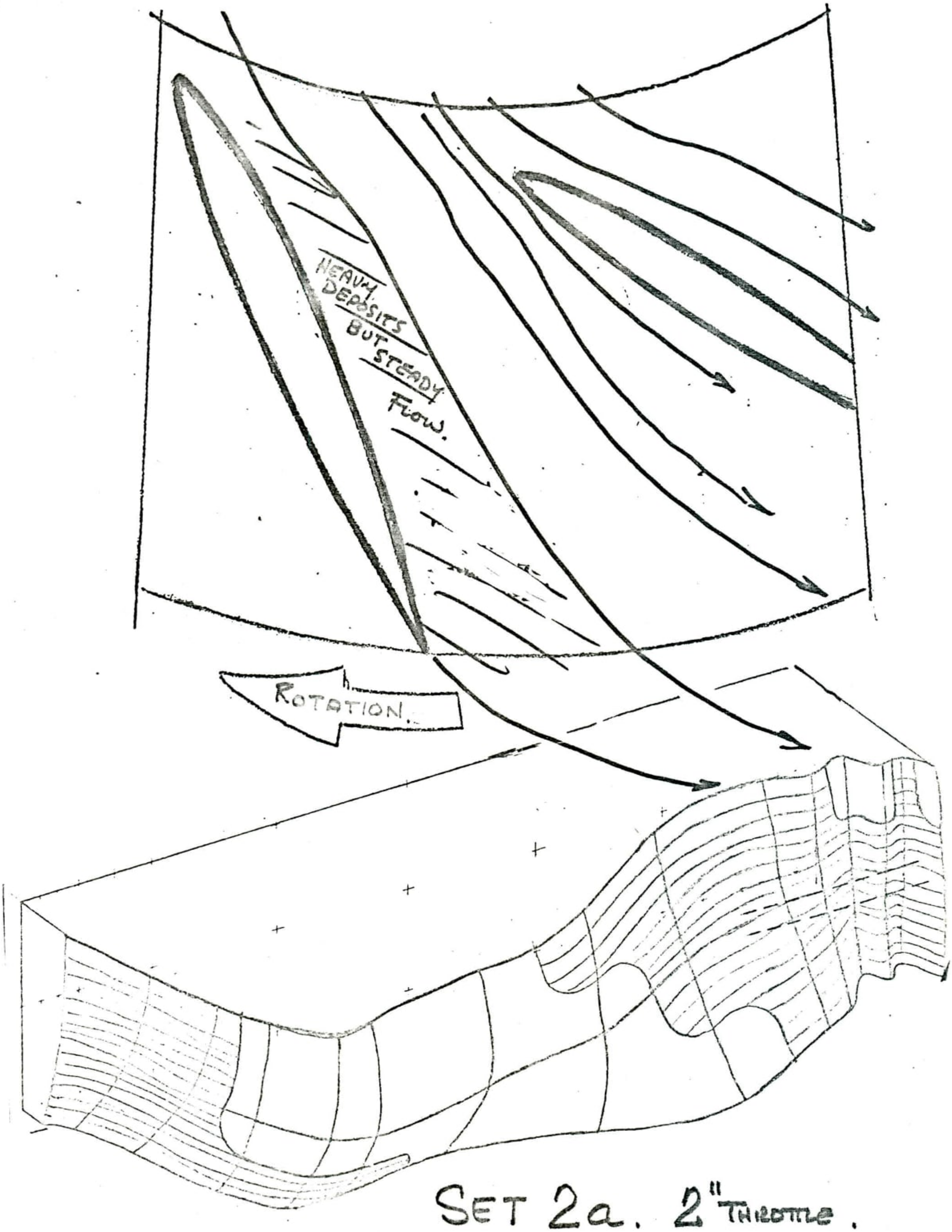
SET 2a. 3" THROTTLE.

FIG. 22.



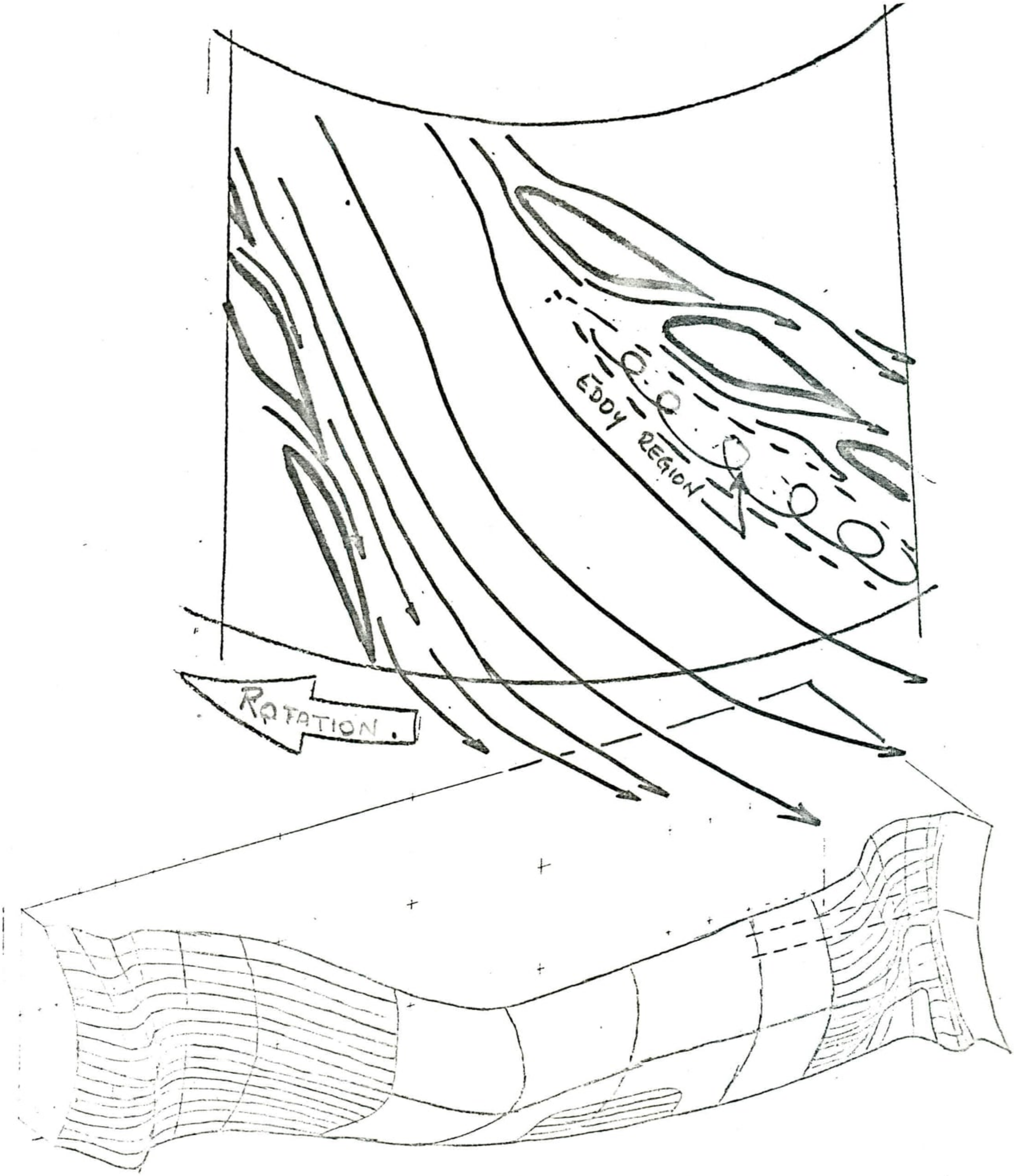
SET 2b. 3" THROTTLE.

FIG. 23.



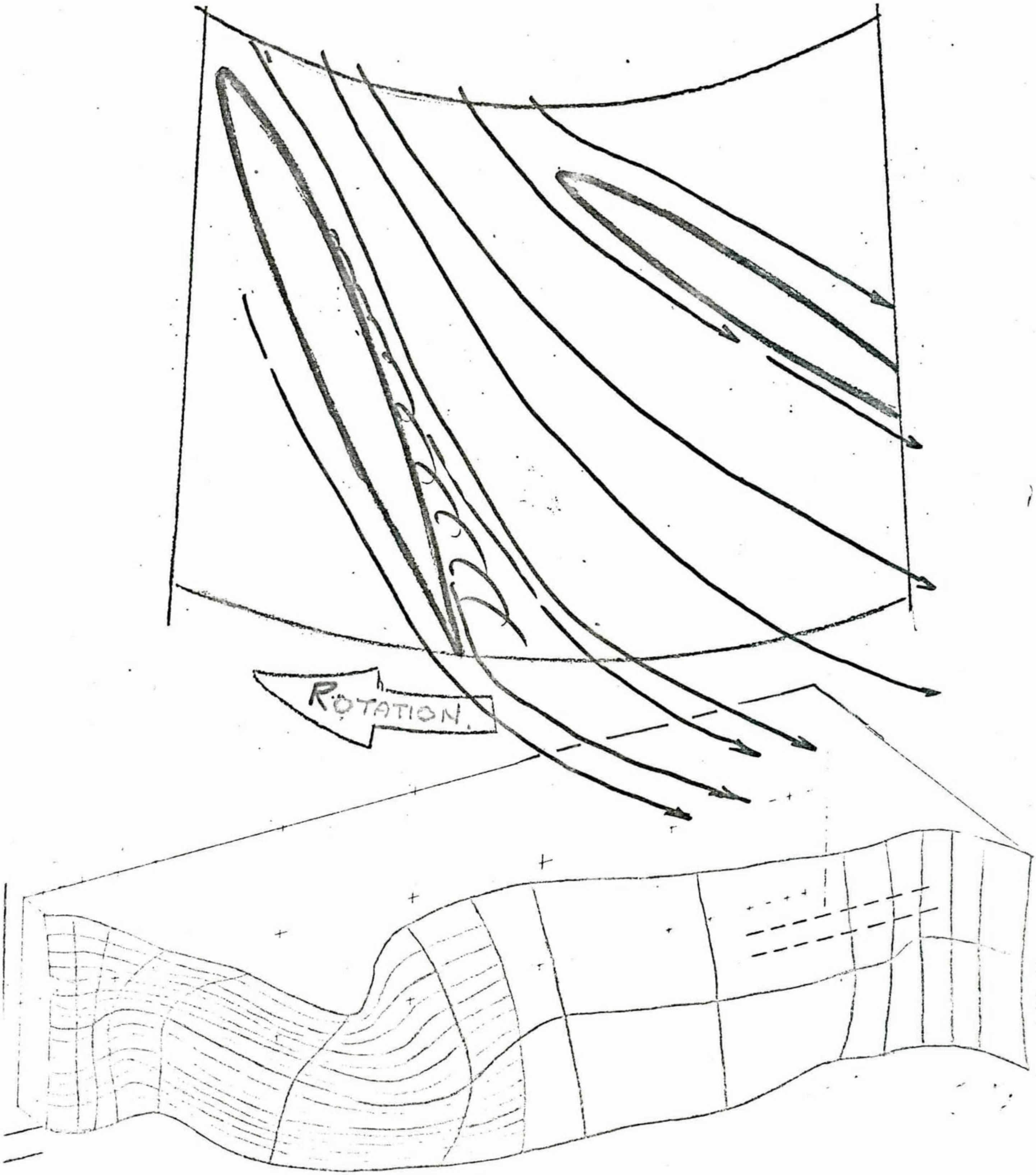
SET 2a. 2" THROTTLE.

FIG. 24.



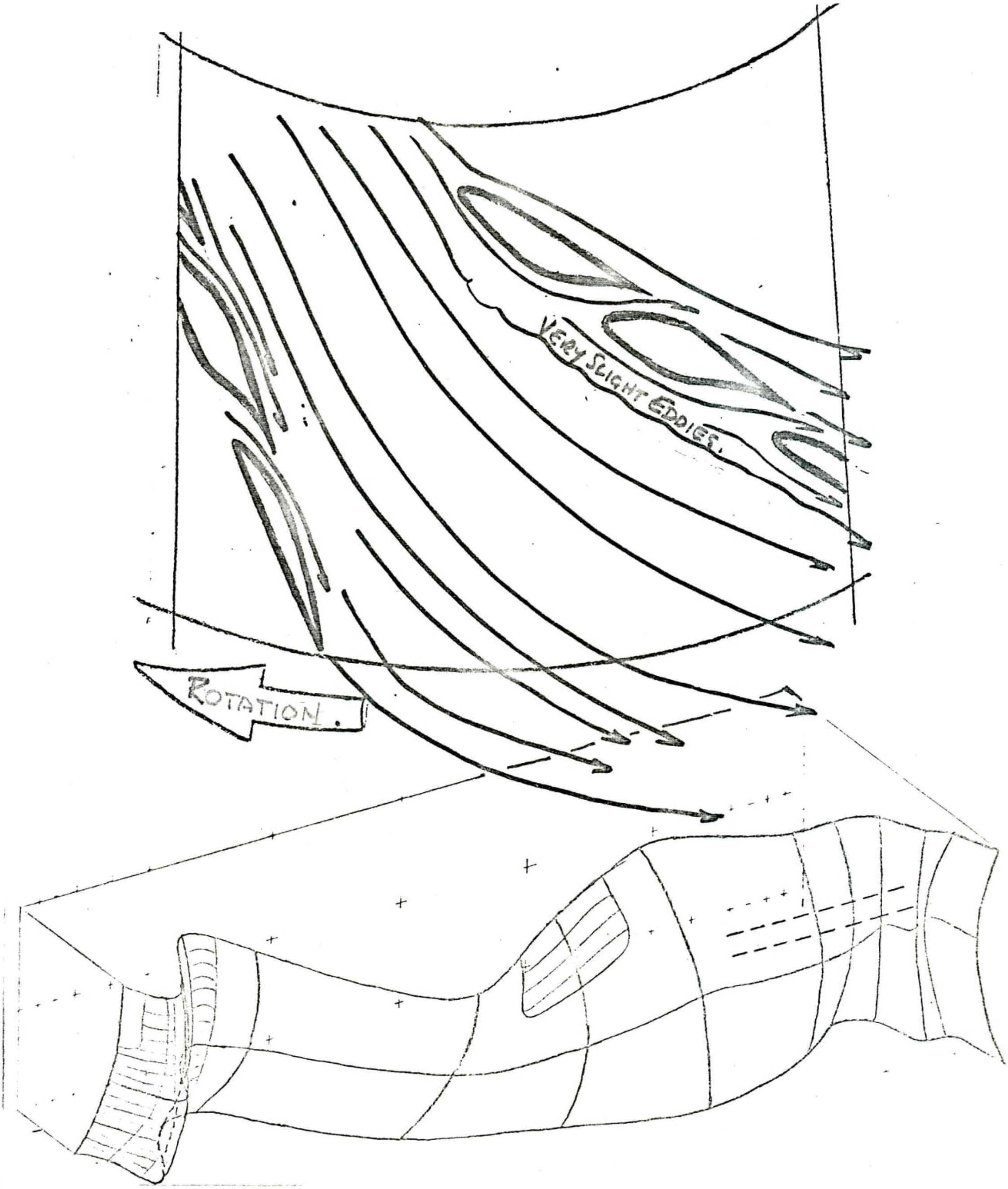
SET 2 b. 2" THROTTLE.

FIG. 25.



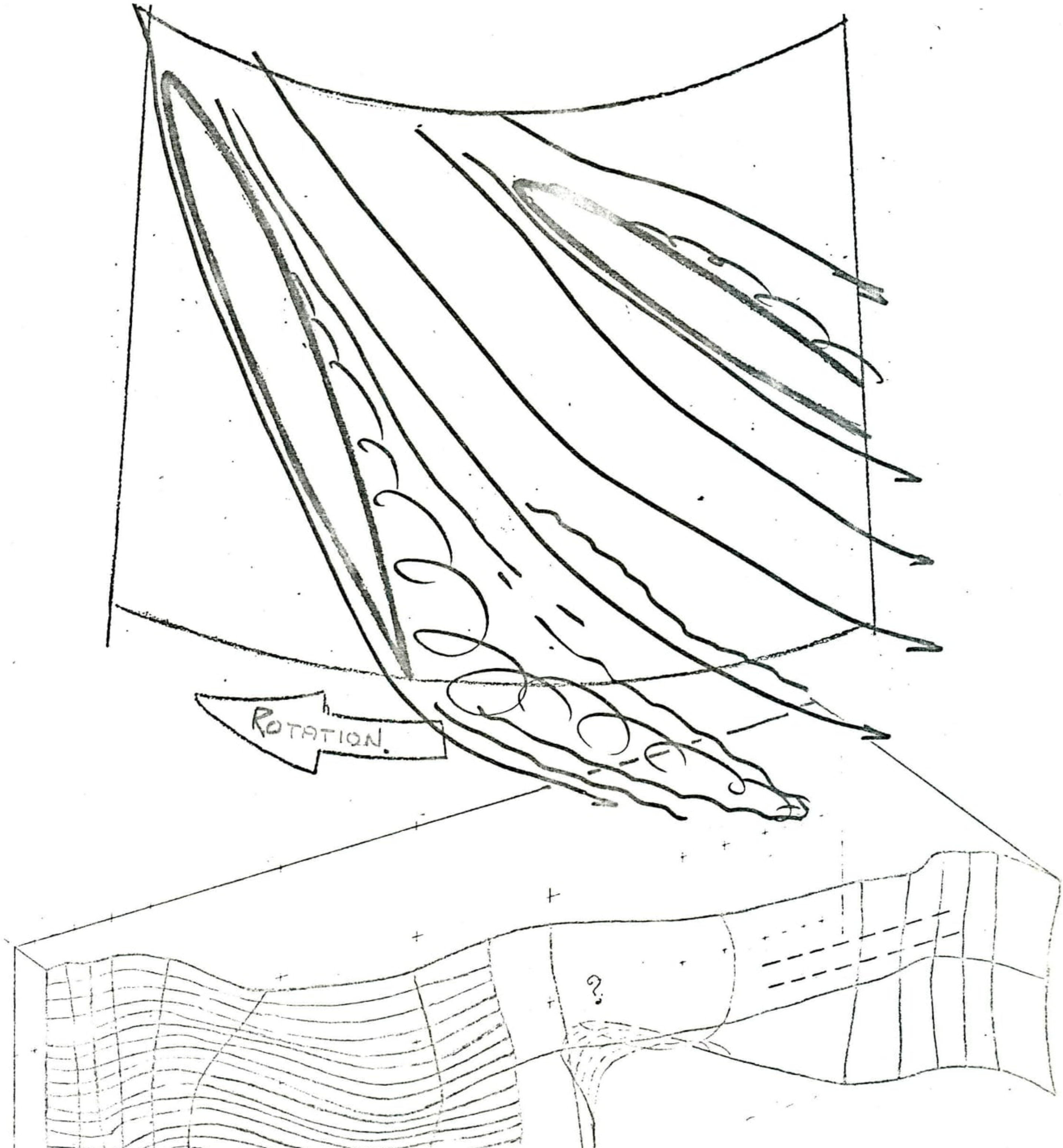
SET 2a. ·8" THROTTLE.

FIG. 26.



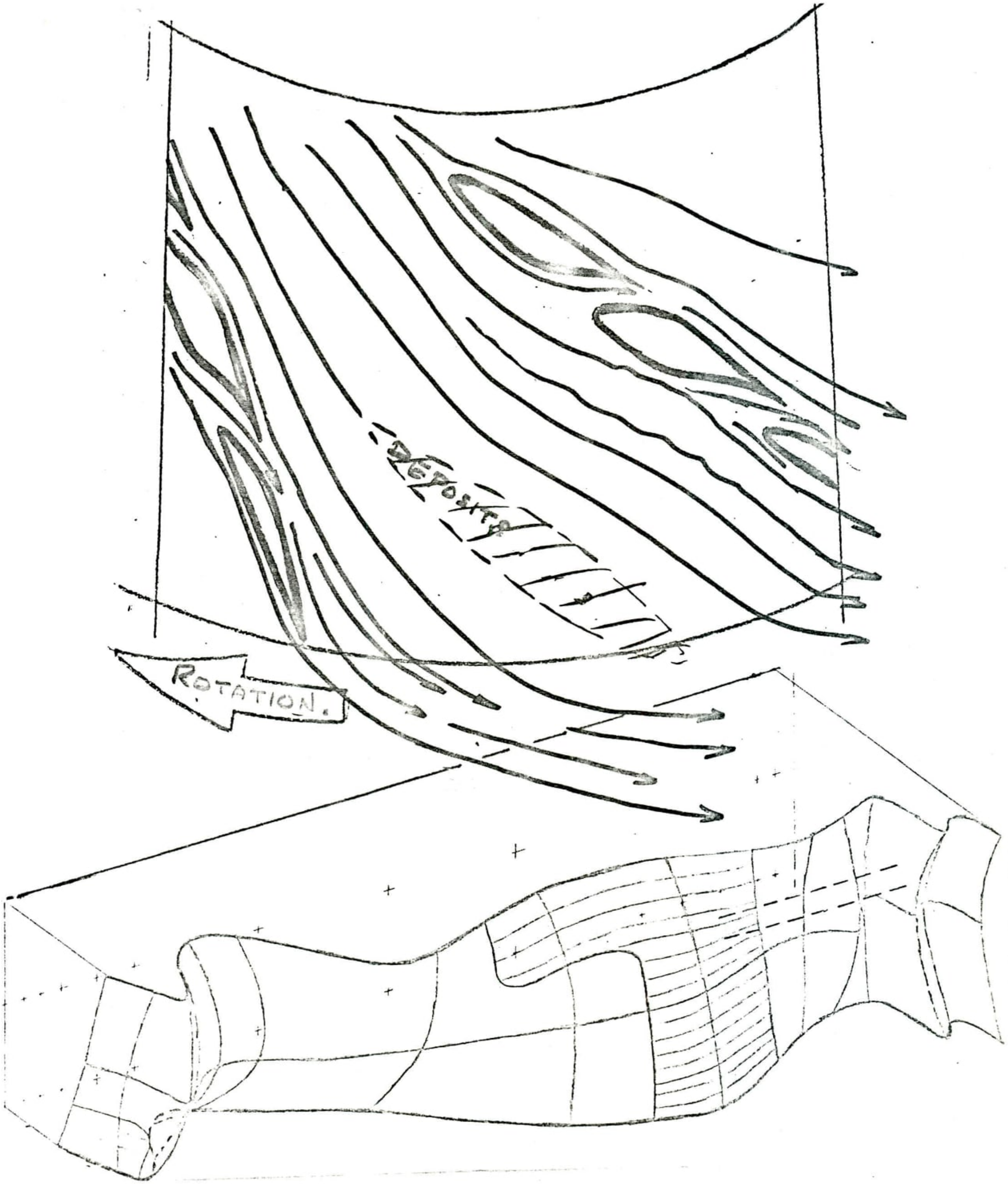
SET 2 b. ·8" THROTTLE.

FIG. 27.



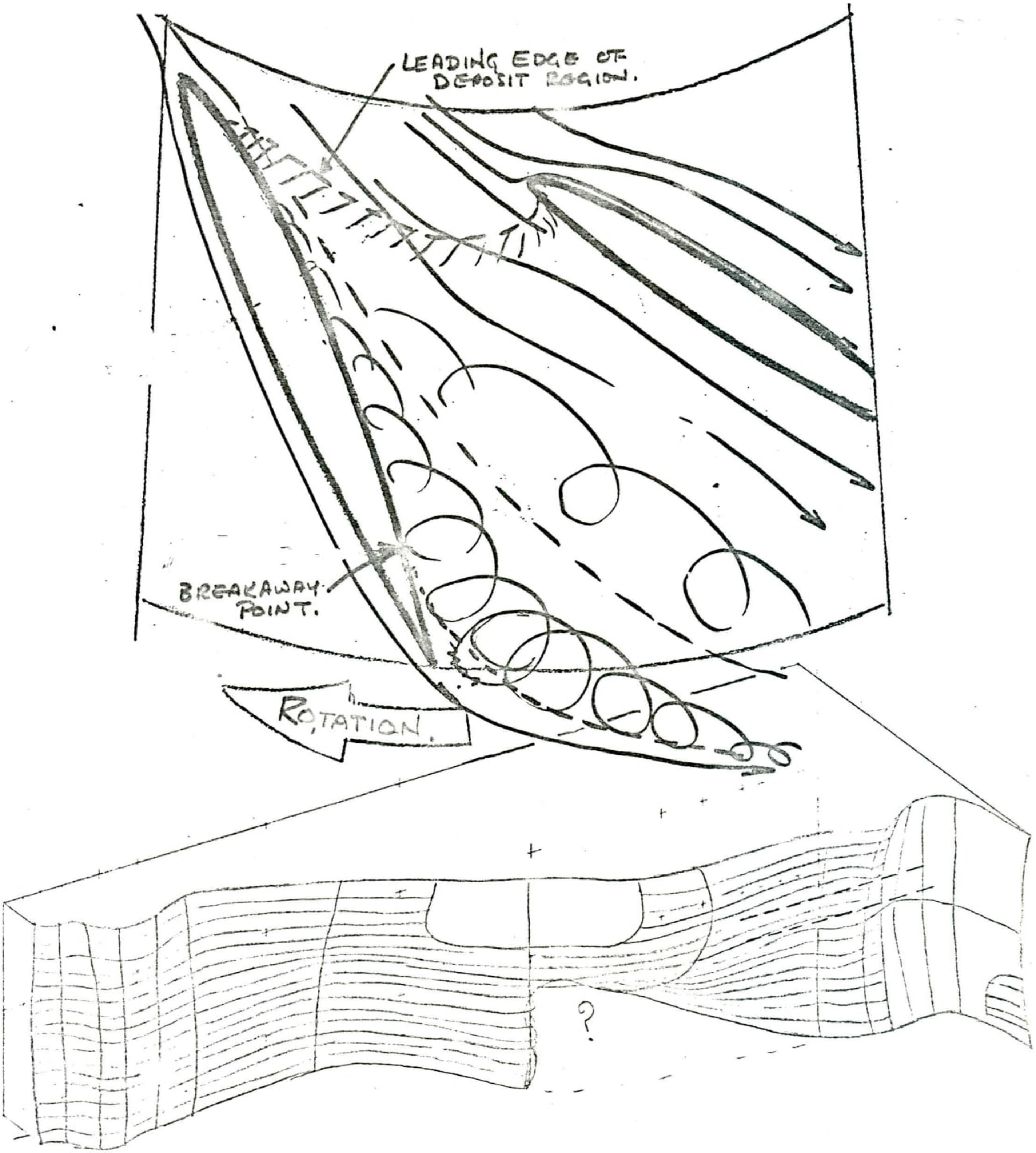
SET 2 a. ·55" THROTTLE.

FIG. 28.



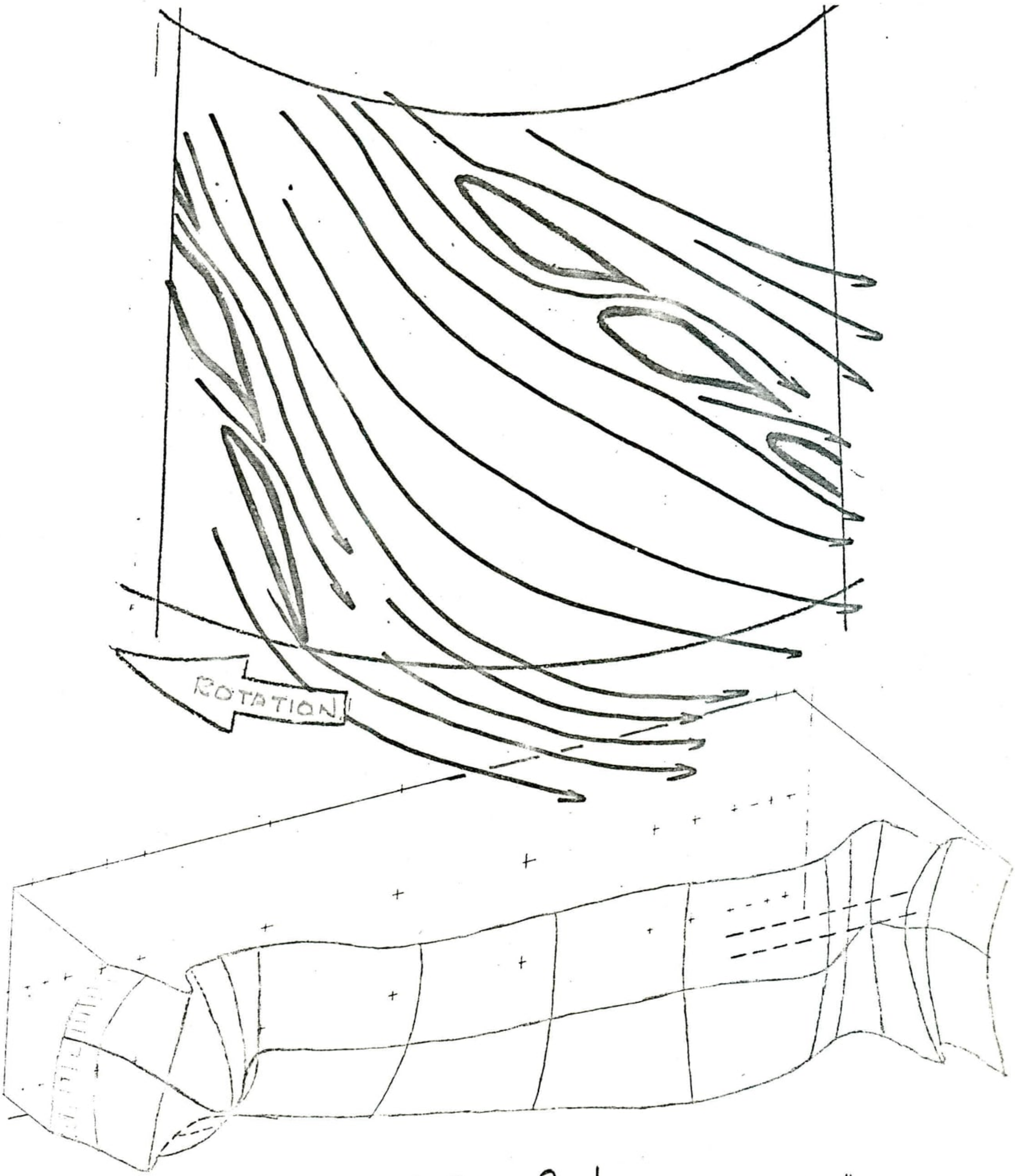
SET 2 b. ·55" THROTTLE.

FIG. 29.



SET 2 a. ·375" THROTTLE.

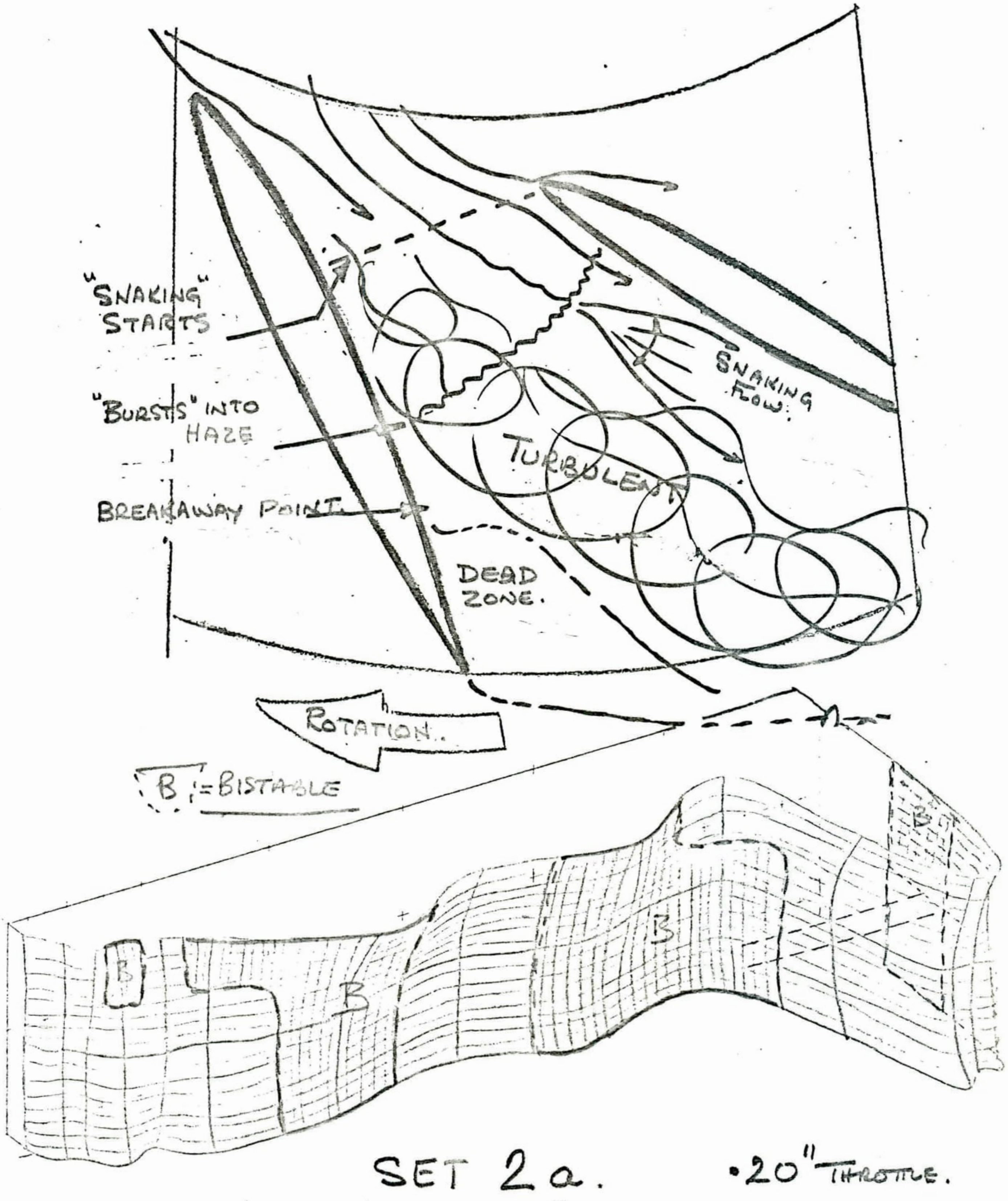
CONSIDERABLE TURBULANCE. FIG. 30.



SET 2 b. ·375" THROTTLE.

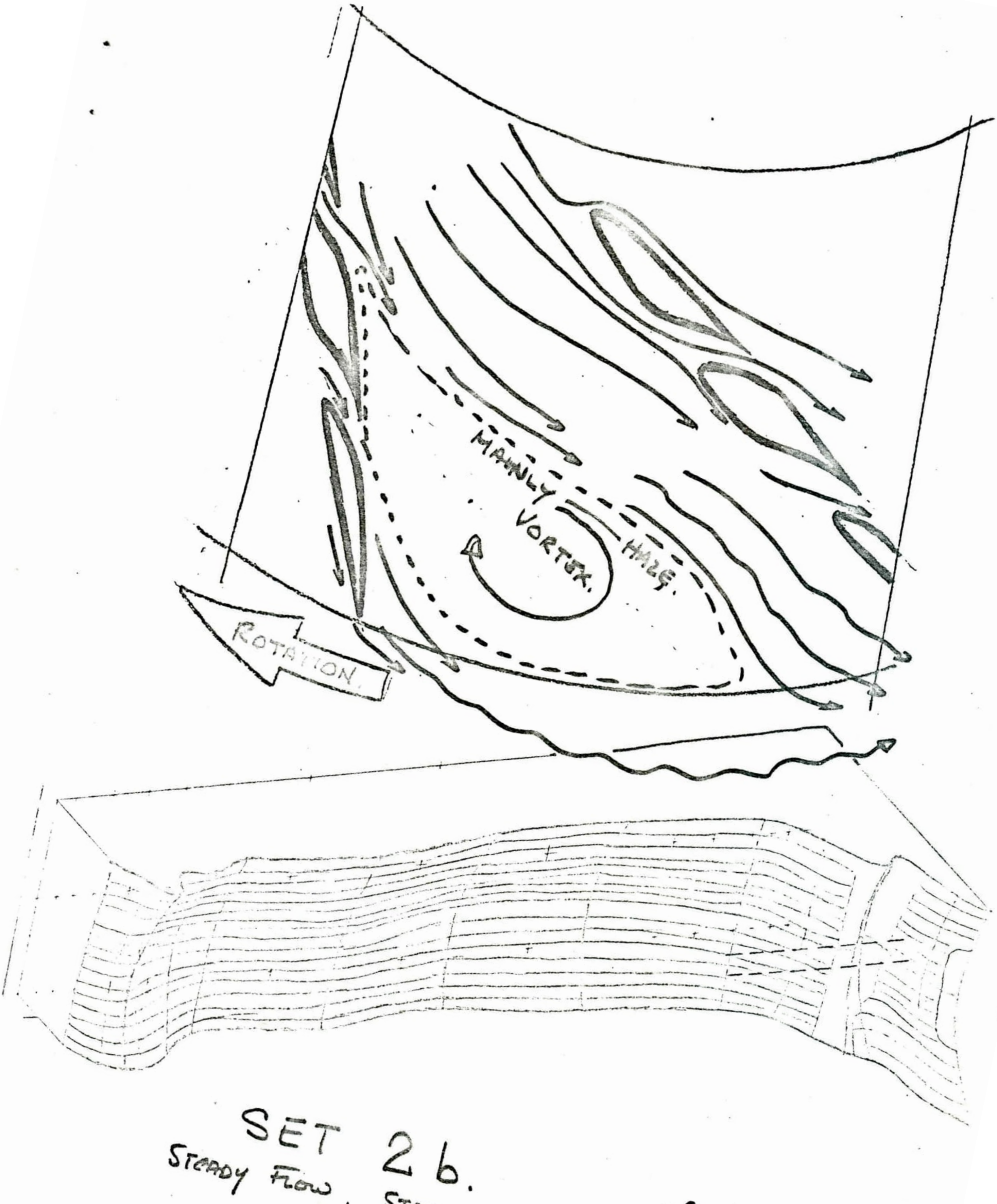
COMPLETELY SMOOTH.

FIG. 31.



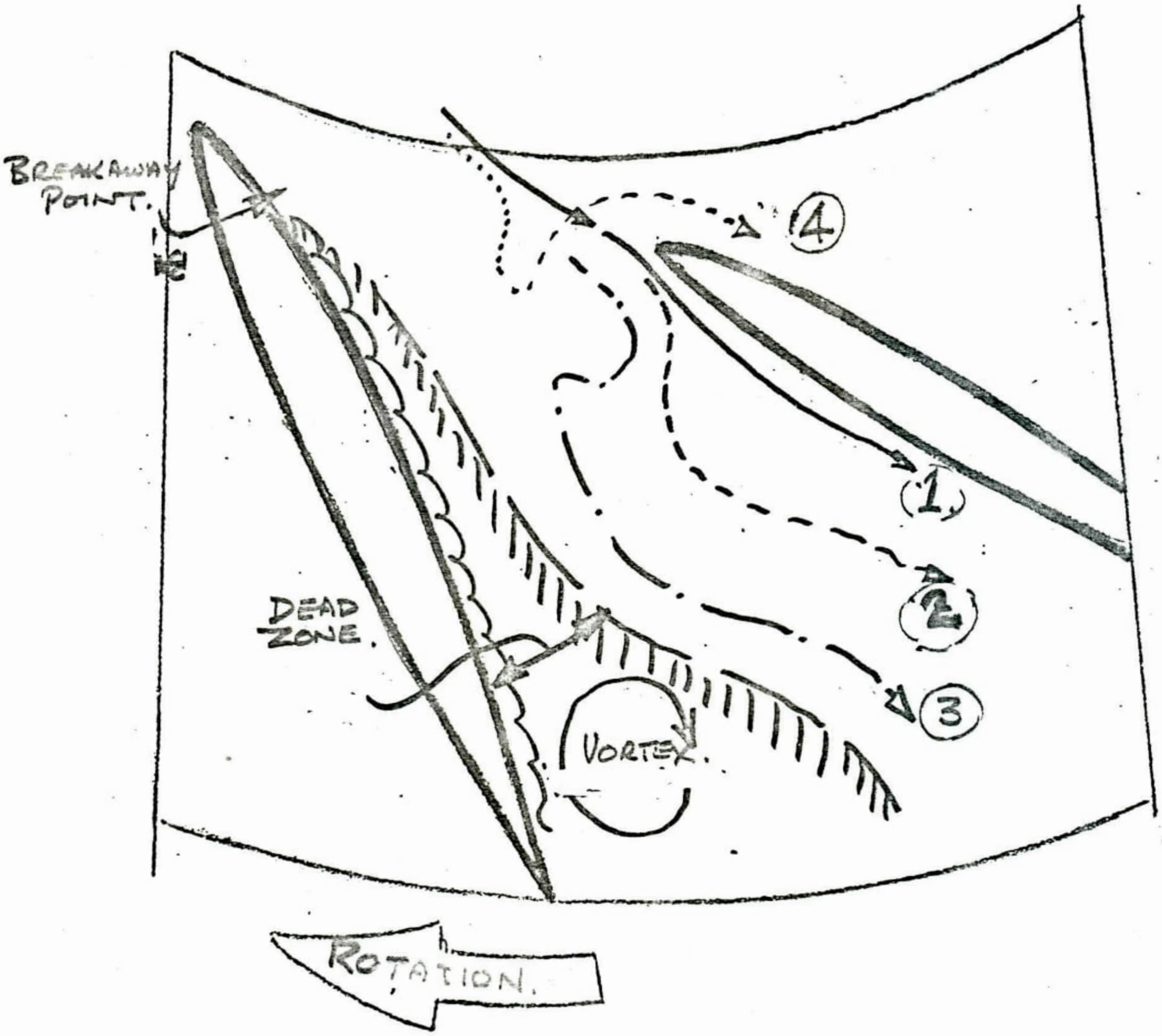
SET 2a. •20" THROTTLE.
HIGHLY UNSTABLE - STALLED.

FIG. 32.



SET 2b.
STEADY FLOW, STABLE PATTERN. ·20" THROTTLE.

FIG. 75



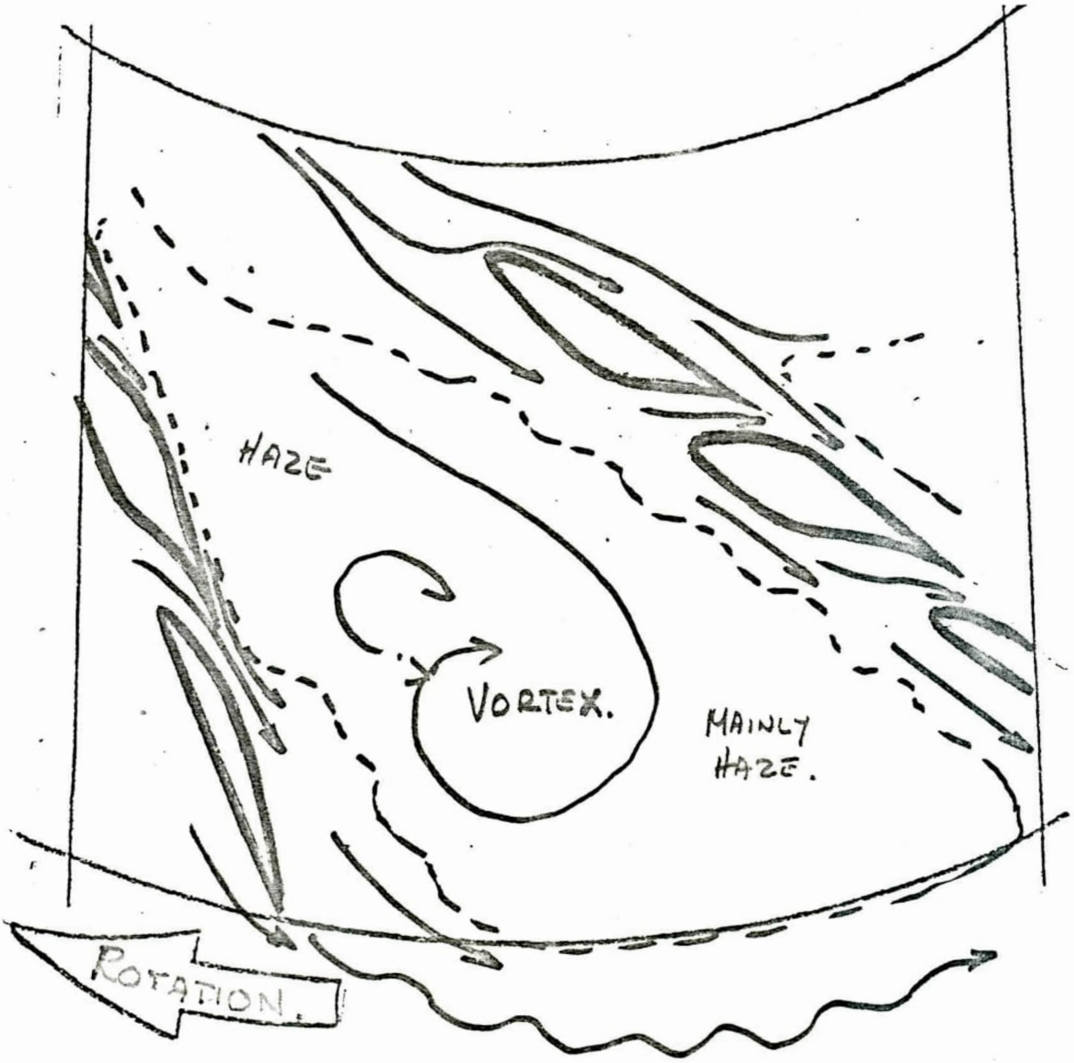
SET 2a. ·10" THROTTLE.

1, 2, 3, & 4 ARE STAGES IN SNAKING CYCLE, WITH FULLY REVERSED FLOW AT ④, WHIPPING BACK AND INTO FOLLOWING CHANNEL.

FULLY DEVELOPED SURGE.

OWING TO UNSTEADY NATURE OF FLOW, HOT-WIRE MEASUREMENT OF EXIT VELOCITY PROFILE WAS MEANINGLESS.

FIG. 34.



SET 2 b. ·10" THROTTLE.

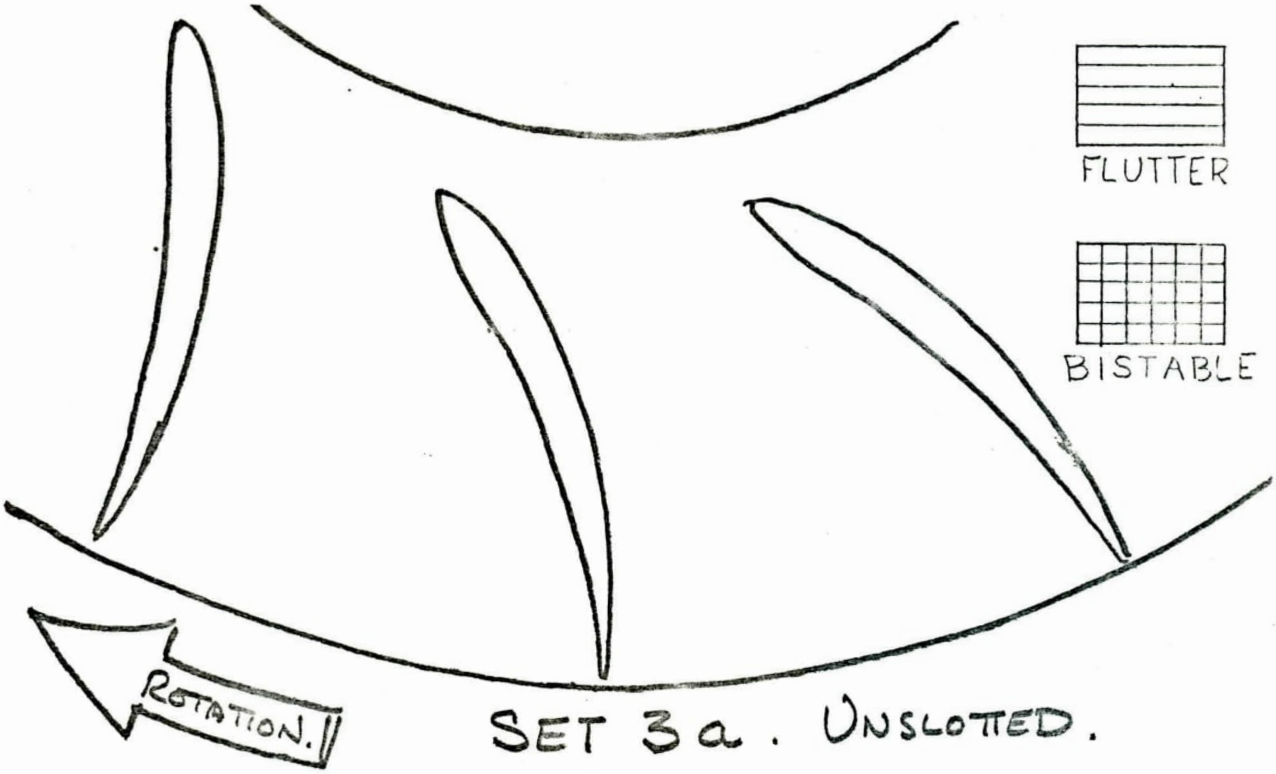
FLOW IS SMALL, AND CONCENTRATED AROUND BLADE. FLOW PATTERN IS STATIONARY AND QUITE STABLE. NO SIGN OF SURGE WHATEVER.

FIG. 35..

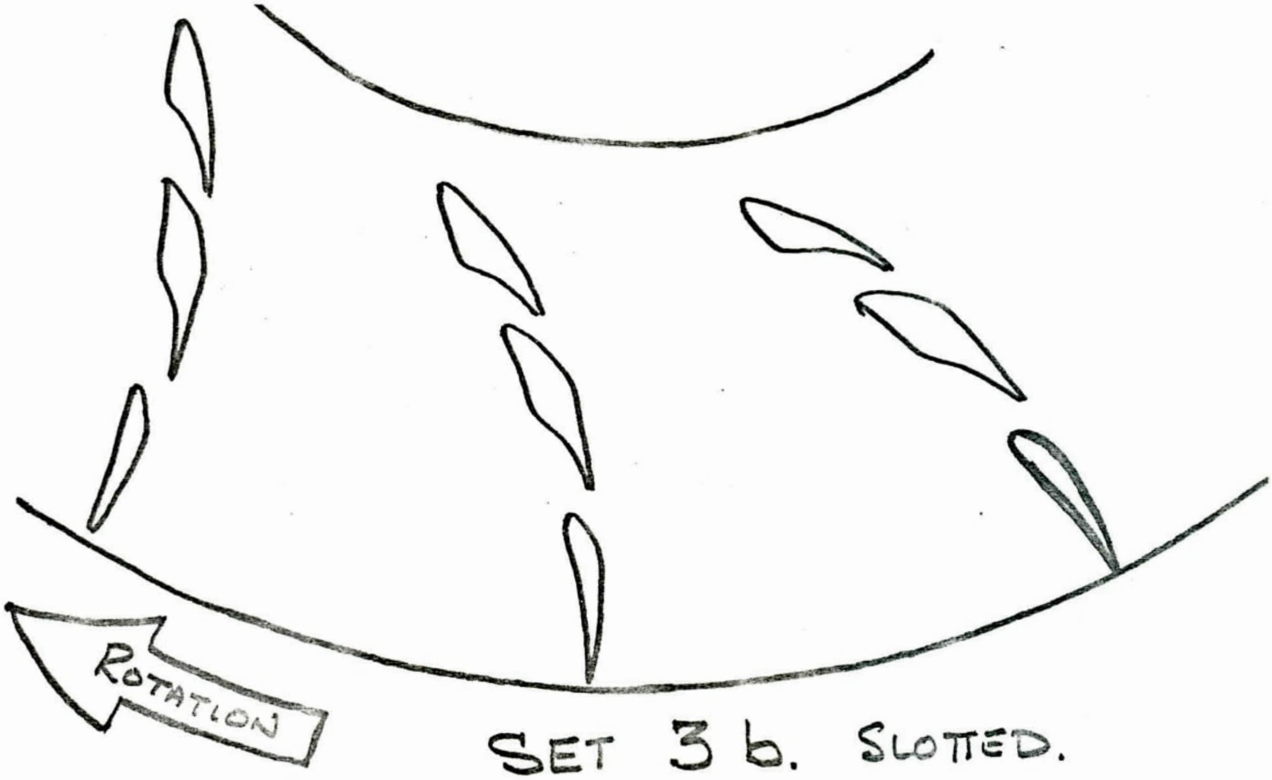
☐ STEADY

▤ FLUTTER

▦ BISTABLE



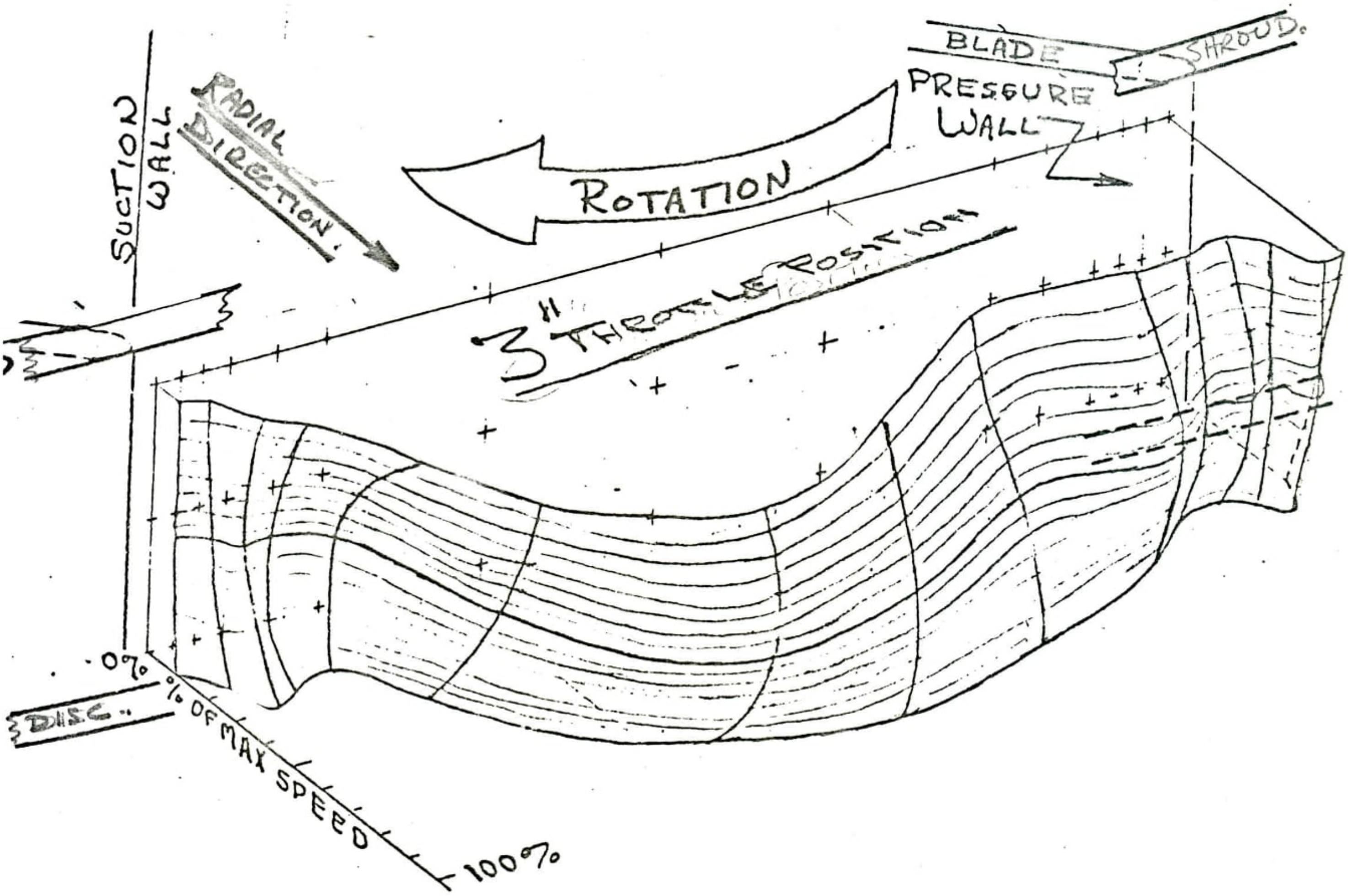
SET 3a. UNSLOTTED.



SET 3b. SLOTTED.

BLADE SET 3.

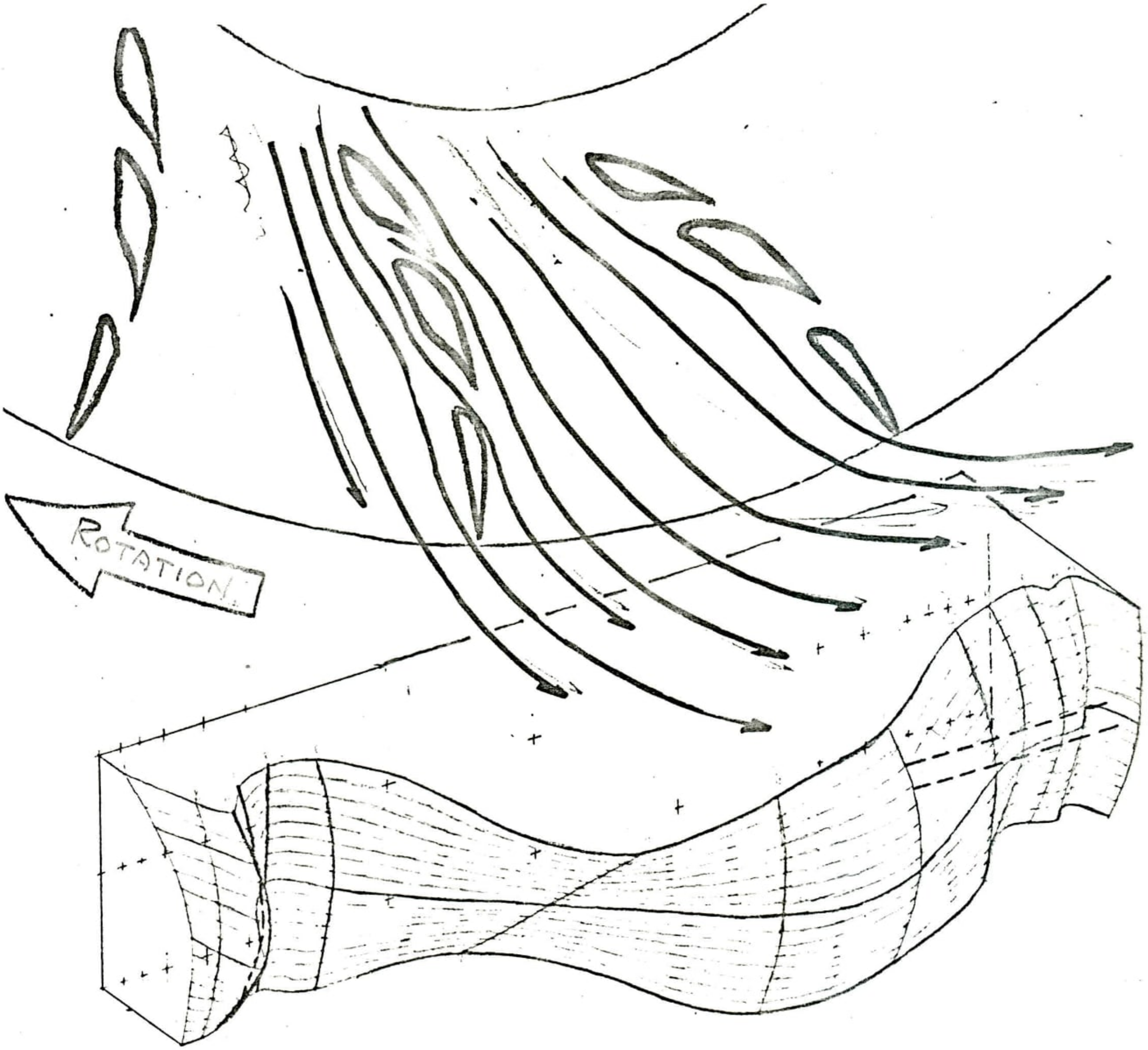
FIG. 36.



<u>NOTE.</u> OWING TO EXTERNAL CIRCUMSTANCES, ONLY A FEW KEY FLOWS COULD BE FILMED IN THE 3a SERIES. THOSE AVAILABLE ARE SHOWN AT THE APPROPRIATE PLACES.

SET 3a. 3" THROTTLE.

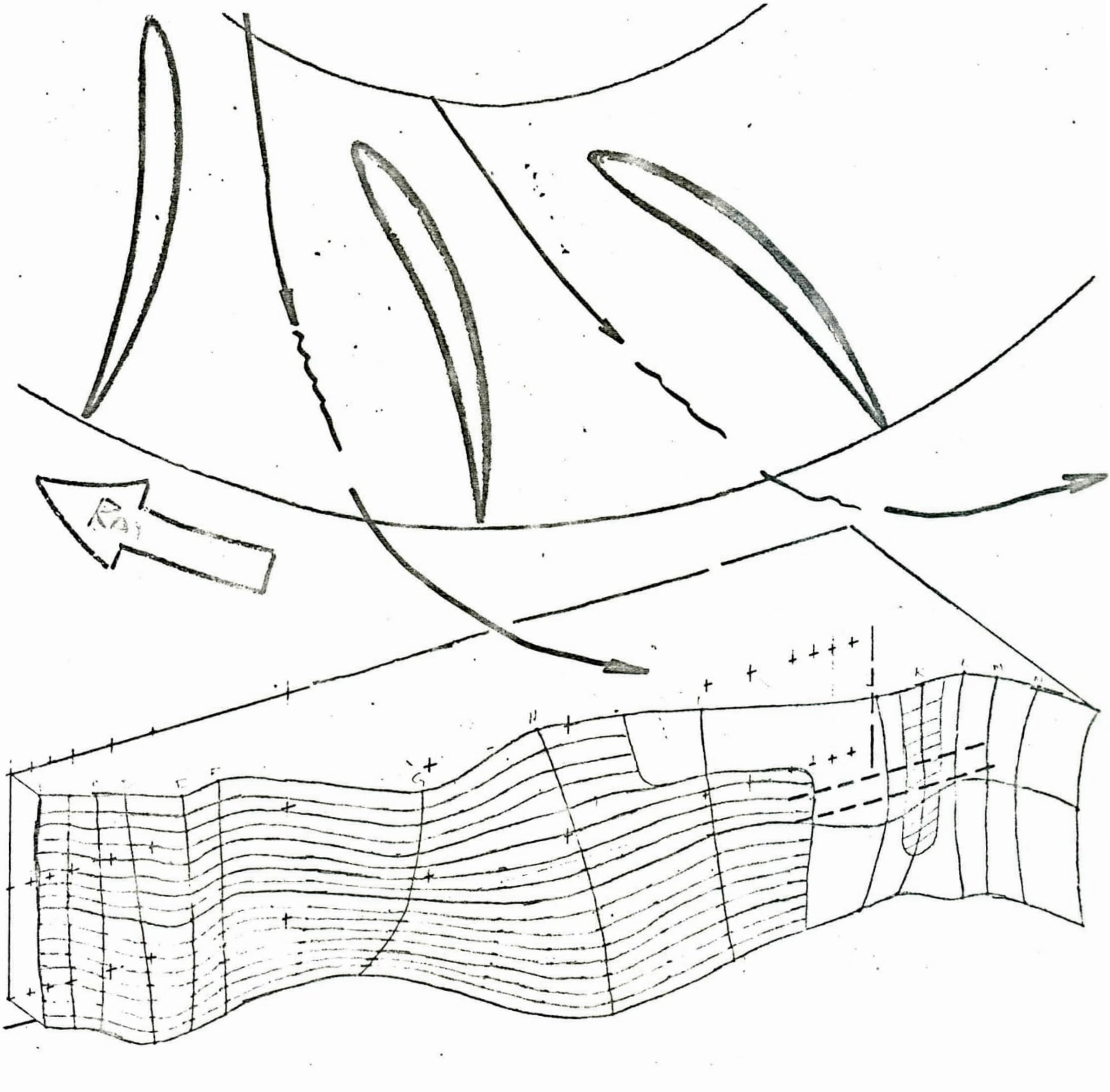
FIG. 37.



SET 3 b. 3" THROTTLE

FLOW STEADY.

FIG. 38.

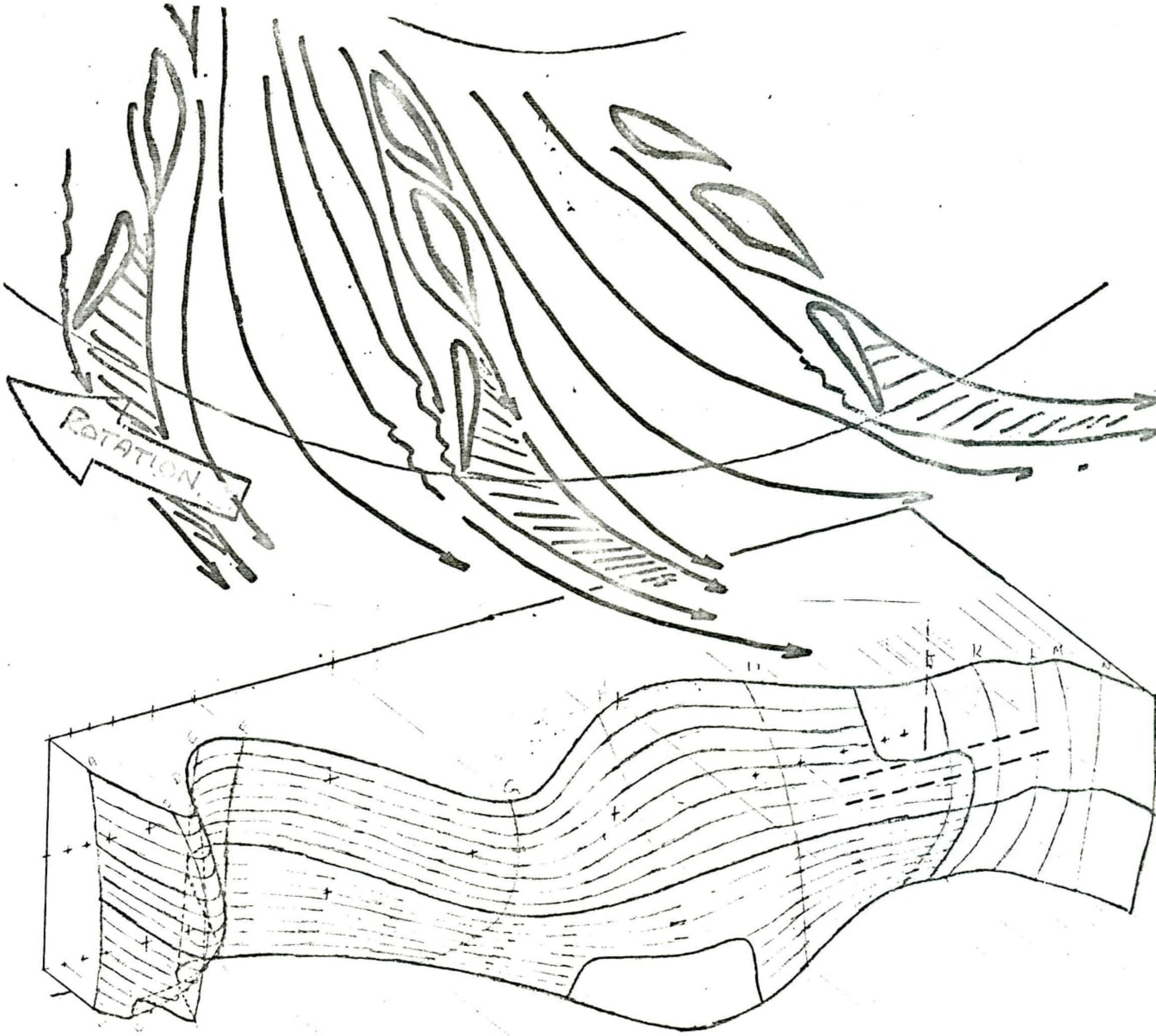


SET 3 a. •8" THROTTLE.

FLOW STEADY.

[FLOW DIAGRAM AT 1.0" THROTTLE].

FIG. 39.



SET 3 b. ·8" THROTTLE.

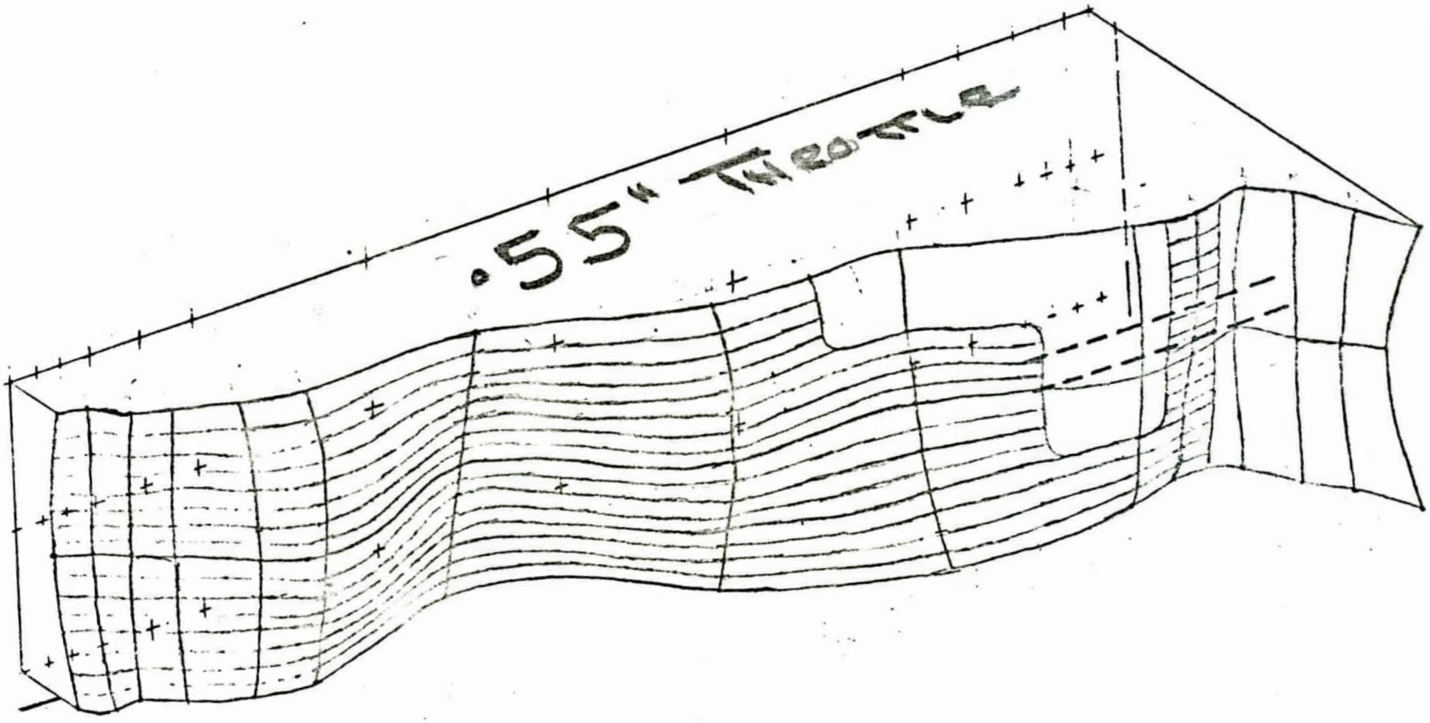
FLOW PATTERN STEADY.

STEADY FLOW →

FLUTTERING FLOW ⇝

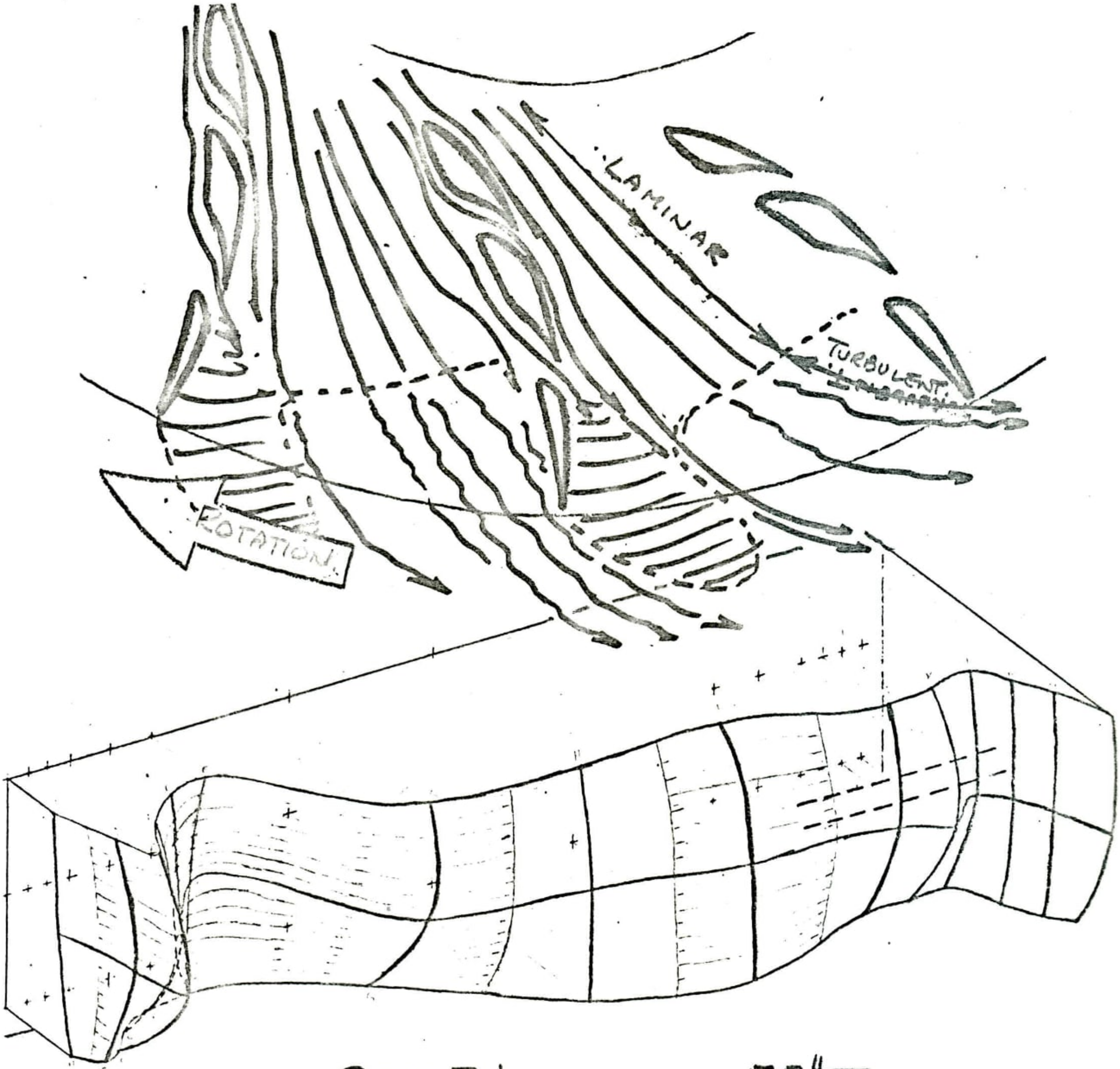
DEAD WAKE ////////

FIG. 40.



SET 3 a. ·55" THROTTLE.

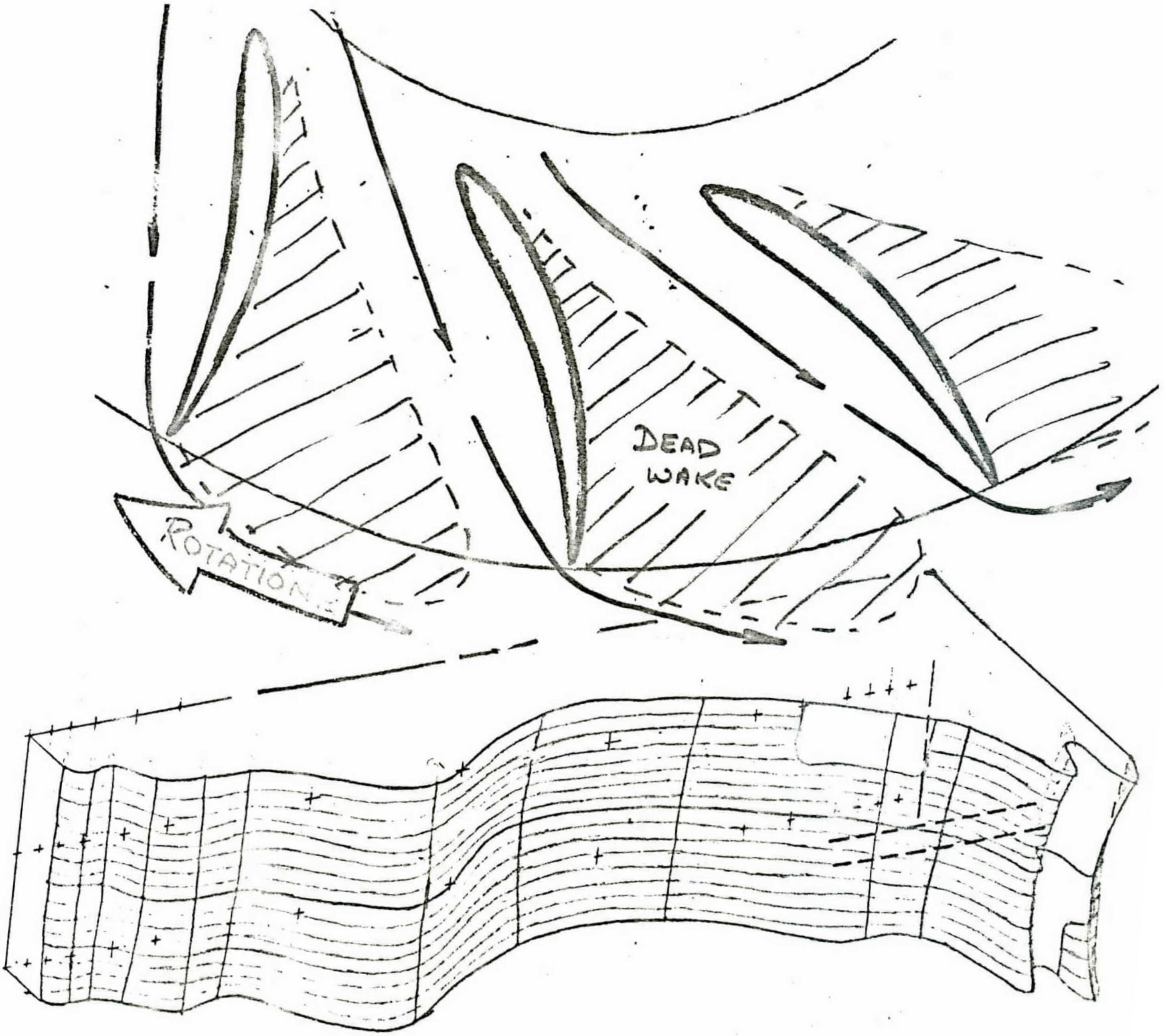
FIG. 41.



SET 3b. ·55" THROTTLE.

STABLE FLOW PATTERN.

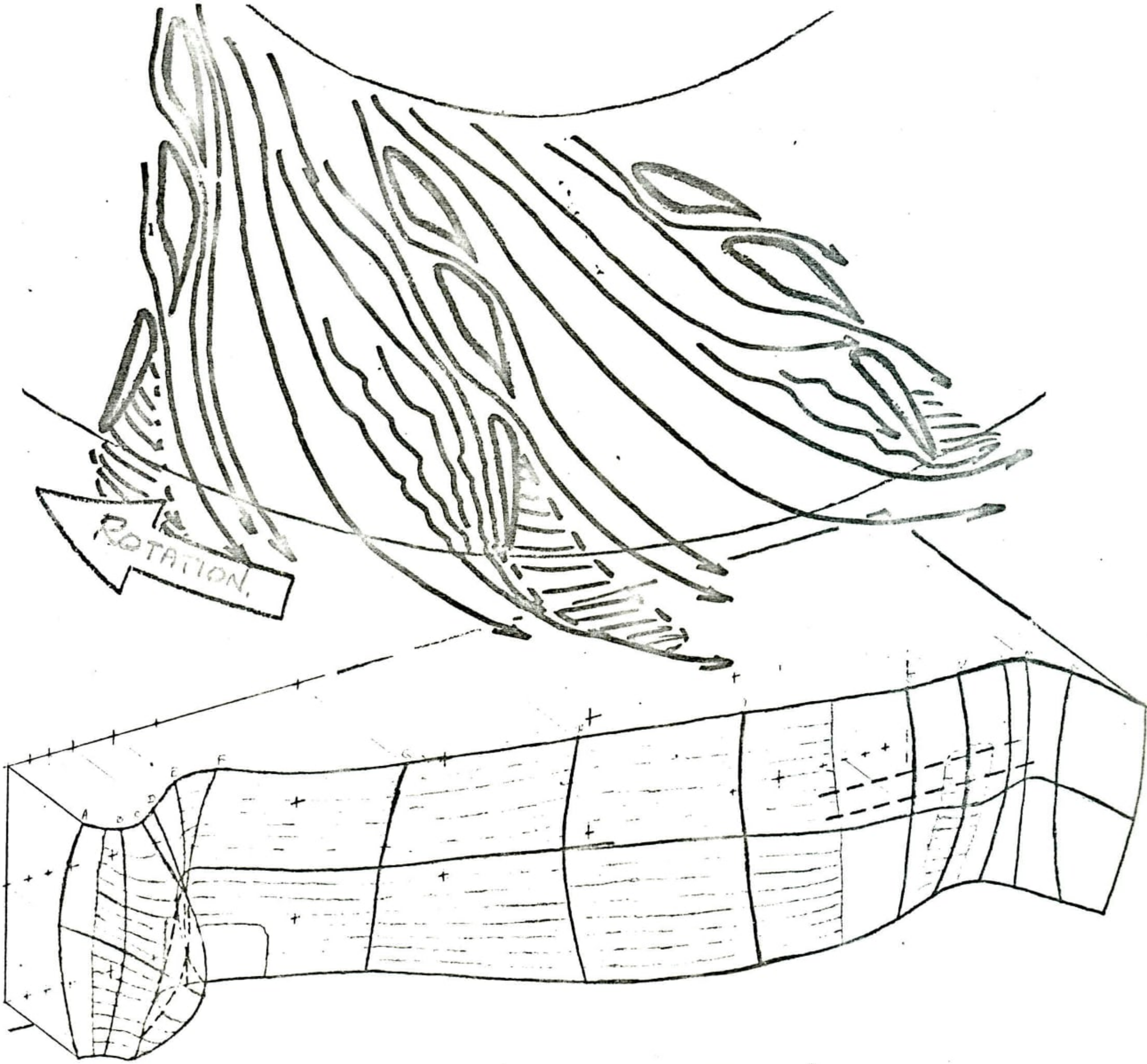
FIG. 42.



SET 3a. ·375" THROTTLE.

STABLE FLOW PATTERN.

FIG. 43.

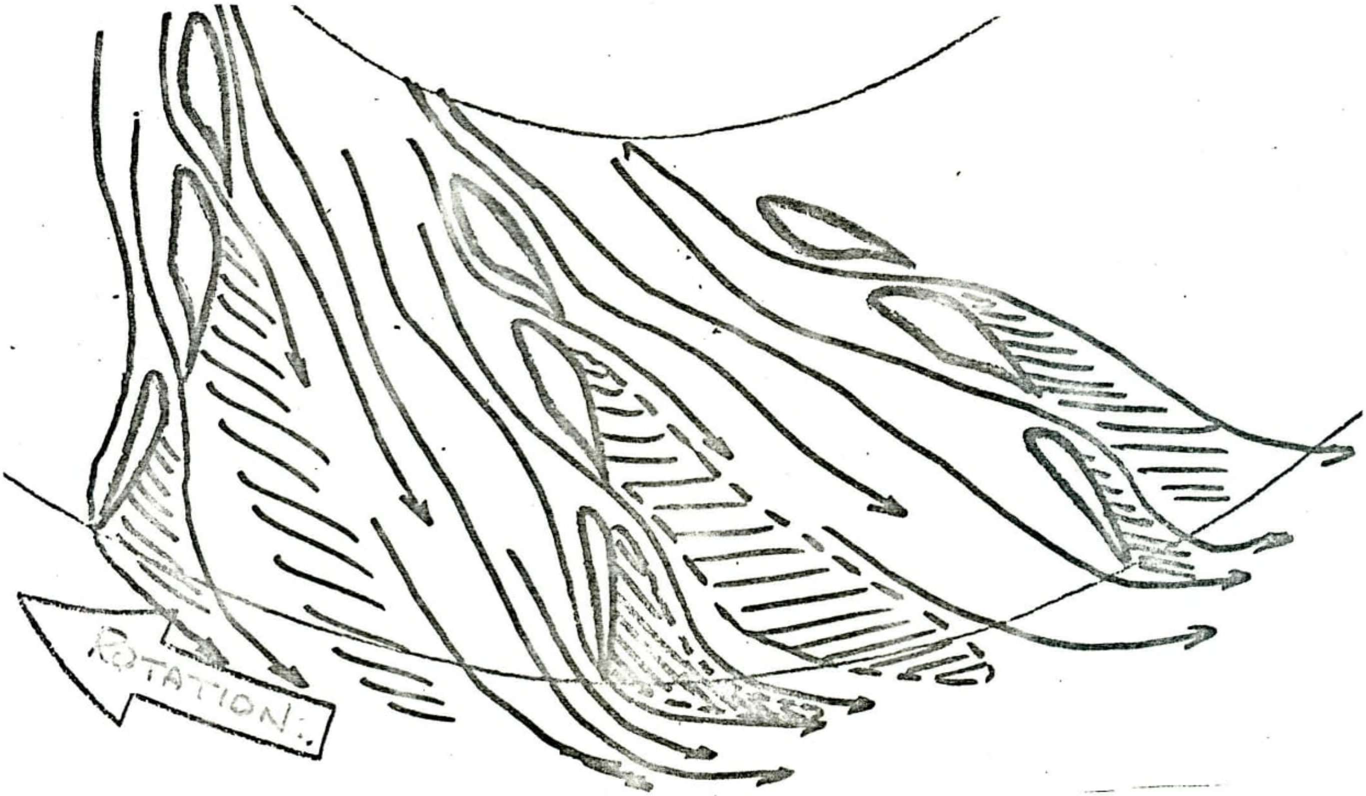


SET 3b. ·375" THROTTLE.

STABLE FLOW PATTERN.

WAKES ATTACHED TO T.E. ELEMENT OF BLADE ONLY.

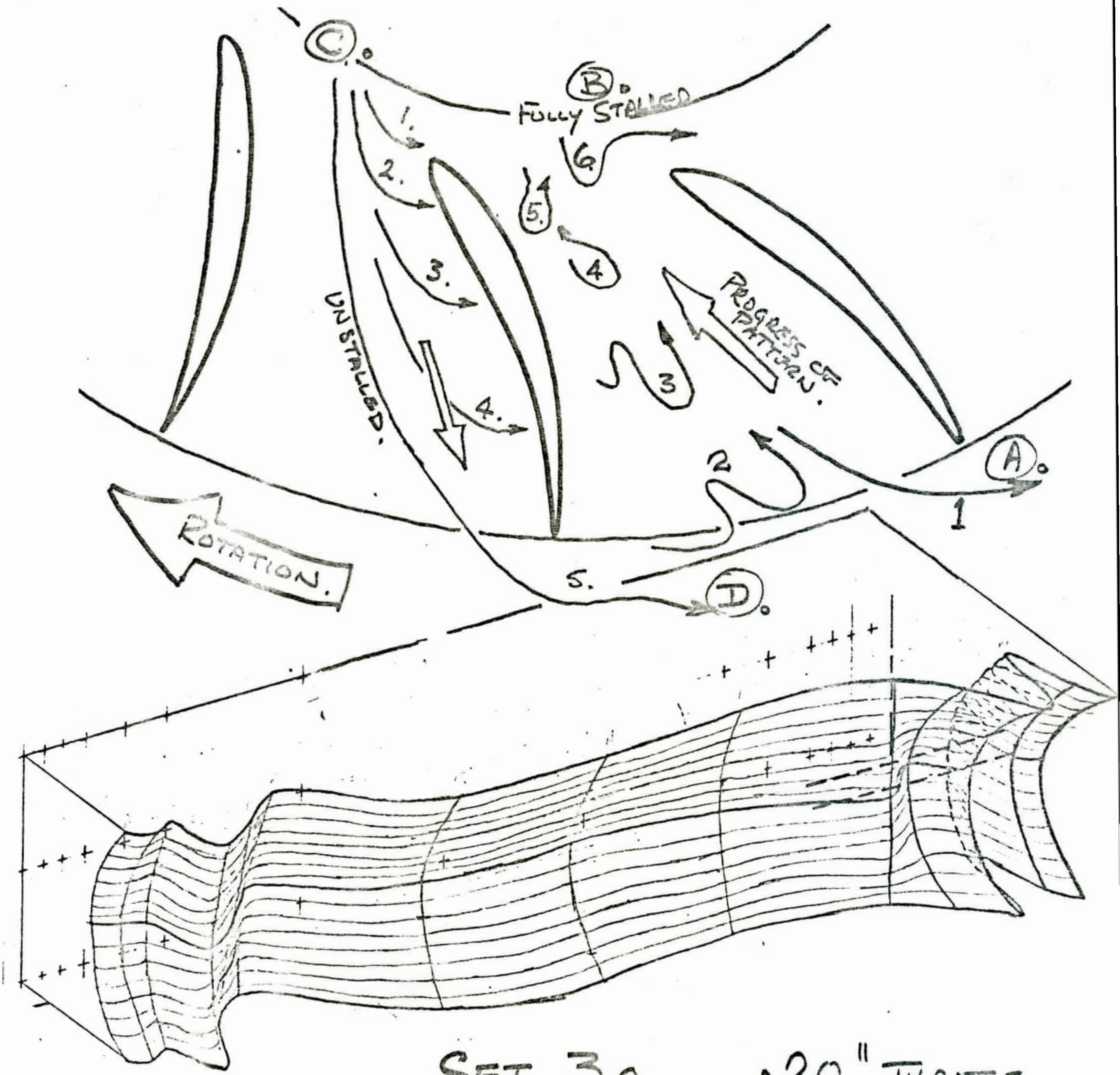
FIG. 44.



SET 3 b. ·30" THROTTLE.

FLOW PATTERN STEADY.
WAKES ATTACHED TO MIDDLE & T.E. ELEMENT
OF BLADE.

FIG. 45.



SET 3a. ·20" THROTTLE.

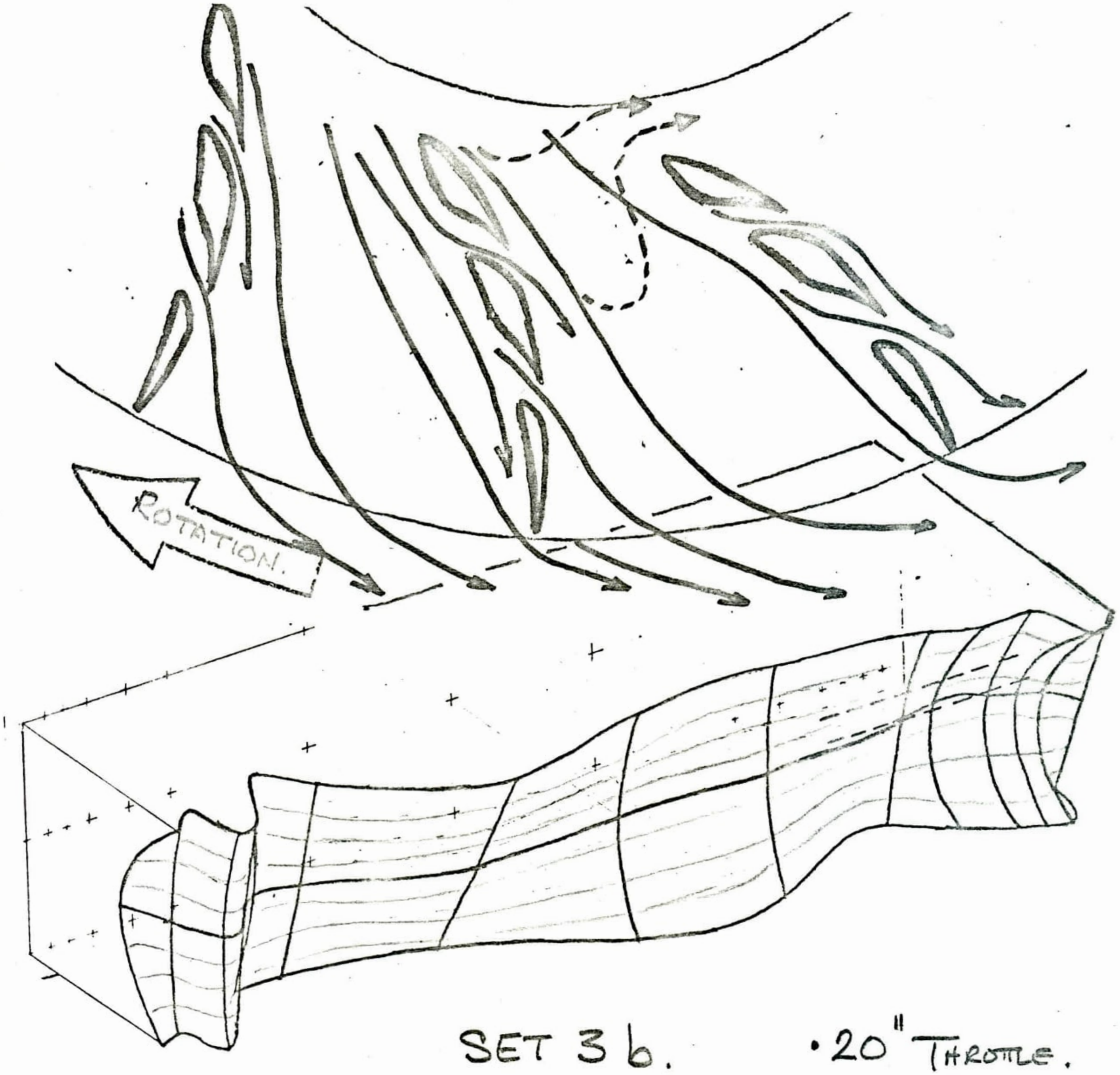
CYCLIC STALL ["SURGE"]

CONTINUOUS OSCILLATION FROM FULL FLOW Ⓐ. THROUGH STAGES 1-6 TO Ⓑ. – FULL STALL.

IMMEDIATE RETURN FROM Ⓑ=Ⓒ THROUGH STAGES 1-5 TO Ⓓ. – FULL FLOW.

THIS IS CONTINUOUS, WITH NO PAUSE AT EITHER FULL FLOW OR FULL STALL.

FIG. 46.



SET 3 b. ·20" THROTTLE.

MAINLY STEADY FLOW, BUT WITH INTERMITTENT QUASI-CYCLIC STALL. APPROX 2-3 TIME-UNITS ON STEADY FLOW, THEN WHIPS BACK TO STALLED FLOW, BUT RETURNS IMMEDIATELY TO STEADY FLOW.
THIS PROCESS IS ALMOST PERIODIC, BUT MISSES THE STALL WHIP ABOUT EACH 3rd OR 4th CYCLE.

FIG. 47.