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An experimental investigation of the switching of a bistable fluidic amplifier.

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AN EXPERIMENTAL INVESTIGATION OF THE SWITCHING OF A BISTABLE FLUIDIC AMPLIFIER

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ABSTRACT

This thesis presents an experimental study of the effects of main flow rate, control flow, setback and back pressure on the switching time of a bistable fluidic amplifier. An amplifier with a throat width of 1/4" was constructed and the switching time was measured by recording the output of hot wires placed in the control channel and output leg on an oscilloscope screen.

It was found that increasing the main flow rate decreased the switching time and the percent of the main flow which would be required to switch the amplifier.

The fact that different mechanisms for switching exist for low and high values of control flow, slow and rapid switching respectively, is discussed in detail.

A low value of control flow gave long unpredictable switching times while a high value gave a short constant switching time. The latter was the minimum switching time of the amplifier for the particular configuration of variables being used. This time was expressed as a Strouhal number, and the minimum Strouhal number range was found to lie between 40-110 for all main flow rates and setbacks examined.

An increase in the setback increased the minimum control flow required to switch. Also for slow switching, increasing the setback increased the switching time whereas during rapid switching a change in the setback did not affect the switching time.

Increasing the back pressure on the amplifier (i.e. the loading of the output ports), by reducing the output area, was found to reduce the entrained flow in the passive leg. This led to a decrease in the interaction region pressure drop, and to the minimum Strouhal number range reducing to 11-19.

Using an alternative method for imposing the back pressure on the amplifier viz., tanks at the output ports, the effect of a capacitance was added to the switching mechanism. This increased the minimum Strouhal number range to 30-75 from a range of 11-19 for a mere reduction in the outlet area of the outputs. It was found that the ratio of the minimum control flow required to switch divided by main flow rate was 0.02 compared with 0.05 for the unrestricted case.

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NOTATION

B.P.	Back pressure, i.e. the loading on the outputs of the amplifier
D_n	Main flow nozzle width
E	Entrained flow
N_{BP}	Non-dimensional back pressure (see appendix B3)
	Static Pressure Tap Locations
P_{ST}	Settling chamber
P_{sth}	Throat of Amplifier
P_{S1}	1st tap in output leg
P_{S2}	2nd tap in output leg
P_{S3}	3rd tap in output leg
P_{S4}	4th tap in output leg
P_{SB}	Back pressure tank
	(Subscripts of $_R$ and $_L$ refer to right or left legs)
QC	Control flow
QC_{min}	Minimum control flow required to switch the amplifier
QS	Main flow
R_e	Reynolds number, $\frac{U_n D_n}{\nu}$
S	Setback of attachment walls from main flow nozzle
S/D_n	Non-dimensional setback
S'	Spillover flow

ST	Strouhal Number, $\frac{QS' \times t}{D_n^2}$ (see appendix B.1)
ST_{min}	Minimum Strouhal Number capable of being produced by the amplifier
t	Switching time of the amplifier
U_n	Velocity of the Main Flow Measured at the nozzle Exit
QS'	Main Flow per Unit Depth

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CHAPTER I

INTRODUCTION

1.1 Development of the Technology of Fluidics

The tendency for a jet to attach to an adjacent surface, is the basis of operation of the bistable fluidic amplifier. This tendency was first noted by Thomas Young in 1800(1)*.Dr.Henri Coanda is reported to have noticed the effect in 1910, but it was not until the 1930's that the phenomenon was re-examined and was subsequently named the Coanda effect. An interest in using this effect for controlling fluid logic (fluidic) devices was first announced by the Harry Diamond Laboratory in 1960(2) In the past ten years there has been a growing interest in the technology of fluidics, which describes the general field of fluid devices or systems performing sensing,logic, amplification and control functions employing primarily no moving parts.

There are two categories of elements; active and passive. Comparing these with familiar electronic components the passive elements consist of resistances which are capillary tubes causing a restriction to the flow, and capacitances formed by cavities. Active elements, so named because their function results in a power amplification, are based

* Numbers in parenthesis designate references at the end of the thesis.

on the interaction between two flows, i.e., a low power control flow modulates the relatively high powered supply flow. There are, to date, primarily six such amplifiers viz.,

i) Proportional deflection of the supply jet by the momentum of the control jet.

ii) Supply jet impact amplifier.

iii) Vortex amplifier in which a vortex in the main flow is formed or destroyed by the control jet.

iv) The movement of the point of separation in flow round an elbow.

v) The turbulence amplifier in which the supply jet goes from a laminar flow to a turbulent flow by the application of the control flow.

vi) The bistable amplifier which is described in section 1.2.

A number of other methods of modulating the supply flow form the basis of operation of other fluidic devices, which normally perform special functions. A description of these can be found in Kirshner's book (1)[*] and the 1967 A.S.M.E. Fluidics Seminar (2).

1.2 The Bistable Fluidic Amplifier

The bistable amplifier is the most frequently used element in fluidic circuits thus it has received the most attention from research workers.

The bistable, or flip-flop, wall attachment amplifier can be defined as a digital component with two stable outputs and sufficient hysteresis so that it has a "memory". The output channel in which the flow occurs is changed by a control pulse. A continuous control signal is not necessary for the main jet to remain in a given output condition.

The mechanism for switching from one output to the other has been studied by the eight workers mentioned in Chapter 2. Measurements of the time taken for the jet to switch from one output port to the other have been made by Lush (3), Savkar, Hansen and Keller(4) and Muller (5). The present study aims at experimentally verifying the results available on the switching time and performing a preliminary investigation on the effects of geometry on the switching time.

Information obtained from this study would be useful in furthering the understanding of the switching mechanism, and in attempting to find the optimum design with reference to response time of a bistable amplifier. The latter point is thought to be of importance as there have already been reports of fluidic circuits being too slow for some industrial applications(15).Also, as the technology of fluidics advances, the number of components used in one application increases, and hence the overall response time increases.

CHAPTER II

LITERATURE SURVEY

The material covered in this chapter summarizes the existing literature dealing with the principle of operation, the switching mechanism and the switching time of a bistable elements.

2.1 Principle of Operation

A knowledge of how a bistable amplifier works, and the flow pattern therein, is essential for the understanding of the switching mechanism and subsequently for the determination of the importance of the factors affecting the switching time. Kirshner (1) has given the most complete description.

The characteristics of a fluid stream flowing between boundary walls and emerging in a similar medium are shown in fig (1). As the jet issues from the nozzle its particles collide with those of the surrounding fluid. By these collisions and turbulent mixing the jet entrains a portion of the surrounding fluid. The removal of fluid from the interaction region lowers the pressure in the area between the jet and the boundary walls. This low pressure zone induces a flow from the relatively high ambient pressure region beyond the opening to maintain equilibrium. Due to the random nature of turbulent mixing the counterflow on either side of the jet is never exactly equal. A smaller counterflow on the right hand side of the main jet will result in fewer particles being returned to this side of the jet. There will then be a lower local pressure existing on the right hand side of the jet. This low local pressure existing near the right wall and the higher pressure on the left wall, will force the stream towards right wall. This results in an even greater pressure differential due to an even smaller counter-flow. Thus, a self reinforcing action occurs that quickly shifts the stream completely against the right wall as shown in fig.(2). Once the stream is forced against the wall, the pressure differential holds it there as long as the main stream is flowing. The low-pressure region is called a low-pressure or separation bubble. Along the wall, downstream of the low-pressure bubble, the pressure suddenly increases greatly at the region of attachment fig. (3b). This high pressure region tends to seal off the low pressure bubble from pressures existing in the region downstream of the point of attachment. Equilibrium is established when the volume of the returned flow equals the volume of the fluid entrained from the low-pressure region, fig. (4). This equilibrium pressure is a direct function of stream velocity; increasing or decreasing the velocity of the stream changes the volume of the fluid entrained, thereby resulting in greater or lesser pressure differential across the stream. As the stream is introduced into the chamber through the nozzle, it can be caused to attach to a selected wall by a relatively slight assymetry of the walls. The typical flow through a wall interaction amplifier is shown in fig. (3). There is a central core which has not yet been affected by entrainment and which is at essentially the same pressure as the source. An outer mixing zone exists which is similar to that for submerged streams not affected by walls. There is also a separation bubble, near the wall, which consists of flow originally in the power stream. This flow has a relatively low kinetic energy and a low pressure. A vortex motion occurs in the separation bubble as the stream continually entrains fluid which is replaced by backflow from the attachment point.

Between the separation bubble and the core is the inner mixing zone, which consists of flow originally in the main stream and fluid entrained from the separation bubble.

If high pressures occuring downstream could proceed upstream through the boundary layer into the low pressure region, the stream would leave the boundary wall in a manner similar to stall on an air-plane wing. However, the local high pressure immediately downstream of the point of attachment must be exceeded before the equilibrium can be disturbed. The point of attachment, in general, moves downstream as the velocity of the stream increases.

The above is a description of the two dimensional jet flowing adjacent to a flat plate as first investigated by Bourque and Newman (6), and Sawyer (7 and 8).

Several other workers have confirmed and added to this explanation and below is a summary of their conclusions. Experimental results on the switching will be presented separately in the next section.

Muller (9) proceded to examine the effects of the length of the attachment wall and of the aspect ratio, defined as the ratio of the nozzle width to nozzle depth, on re-attachment. He set the angle of the inclined wall at the optimum value of 15 degrees. With increasing wall angle the minimum Reynolds number of the main jet necessary for jet attachment to occur increases, while a low wall angle causes instability.

A short wall, of 15 times the nozzle width was found to be preferable as this produced a higher flow and pressure gain, see Sec.B4. The reason for investigating the aspect ratio is that for constant supply pressure the Reynolds number becomes smaller as the model size is reduced, and approaches the

the critical value below which the jet no longer attaches to the wall. Miniaturization of the elements is very important for short switching times at low power consumption. It was found that the minimum Reynolds number for attachment was reduced only slightly when the aspect ratio was more than two. A further increase in the aspect ratio is no longer economical as the power consumption is proportional to the model depth.

Foster and Jones (10) added to the description by predicting the streamlines of the flow and adding the reattaching streamline fig. (5). They stated that there is no net flow across this line; all the flow above continues downstream while all the flow below is recirculated.

Lush (3) extended this flow pattern by adding a setback, defined by S as shown in fig. (6). He included a description of the flow entrained by the main jet from the separation bubble and that returned to bubble fig. (4). He also stated that when the main jet flow remains constant and the control flow = 0, then the bubble volume is also constant and the entrained flow equals the returned flow. By using a dye injected into water this condition was shown by observing that the bubble shrank to a constant size after switching had taken place.

The most effective photographs of the flow inside a bistable amplifier have been produced by Savkar, Hansen and Keller (4) who suspended aluminium particles in water for photographing the flow. As is shown in Plate 1 the aforementioned details of the flow are all clearly shown.

2.2 The Switching Mechanism

To shift the stream for one wall to another, control channels are introduced on the sides of the power stream as in fig. (6). Basically the switching mechanism can be explained thus: if fluid is allowed to enter the low-pressure region on the right at a greater rate than the main stream can entrain and remove it, the pressure will increase; as the flow continues the separation bubble will expand and the pressure differential across the jet will approach zero. The jet moves to the centre and the Coanda effect will then cause the stream to attach to the left wall.

As this switching process was studied in more detail it was realized that there are in effect four different mechanisms contributing to the switching of a wall attachment type amplifier. For ease of reference these are individually listed below with each worker's contribution to that particular mechanism.

2.2.1 Terminated Wall or Bleed-type Switching

Terminated wall or bleed type switching will be predominant in amplifiers which have short wall lengths or bleeds, see fig. (7). As explained by Kirshner (1), Foster and Jones (10), and Wilson (11) the action of control flow is to help satisfy the entrainment of the jet and hence reduce the vacuum in the low pressure region so that the bubble increases in size. This action continues until the attachment point moves to the bleed outlet, or the end of the wall, where the ambient fluid is drawn into the separation bubble causing the jet to switch.

2.2.2 Contacting-Both-Walls Switching

Foster and Jones (10) state that the second wall can have a predominant effect. If the setback of the attachment walls from the nozzle exit is low, then due to bubble expansion and the momentum of the impinging control flow the main jet is deflected far enough to allow entrainment to cause a low pressure region on the opposite wall. This may happen before the main jet loses contact with the initial wall resulting in a separation bubble on the initial wall which is being expanded by the control flow, and one on the opposite wall being contracted by entrainment. Lush (3) and Savkar, Hansen and Keller (4) showed examples of this process as shown diagramatically in fig. (8). Wilson (11) adds that this type of switching will occur when a high control flow is used and in that case the second separation bubble is formed before the effects of splitter switching come into force.

2.2.3 Splitter Switching

When a splitter, as shown in fig. (6), is used to separate the output flow then this can become a large influence on the switching process. A point can be reached at which the jet strikes the splitter at an angle as shown in fig. (9b), resulting in a low pressure region towards the tip of the splitter. This will help to lift the jet from the wall. This explanation given by Foster and Jones (10), Kirshner (1) and Wilson (11) is demonstrated by Savkar, Hansen and Keller (4), by flow vizualization as previously mentioned.

2.2.4 Critical Attachment Angle Switching

Wilson (11) and Foster and Jones (10) indicate that Bourque and Newman's (6) works on the attachment angle, see fig. (10), leads to one of the most important parameters in jet switching. This angle controls the amount of flow returned to the attachment bubble and, thus indirectly dictates the amount of control flow required to switch the main jet. Consequently any change of parameters that results in an increase of attachment angle correspondingly decreases the amount of control flow required for switching. This mechanism for switching can occur after a short burst of control flow. The bubble is left in a condition such that it's growth is self-sustaining,i.e.,the returned flow is greater than the entrained flow. This is often called rapid switching.

2.2.5 <u>The Three Usual Modes for Switching</u>

Depending upon the conditions under which the amplifier is operating three common modes of switching are:

i) Slow switching: as this requires the least control flow it was the only mode examined by Muller (5), Savkar, Hansen and Keller (4) and Lush (3). Wilson (11) summarizes their description by explaining that a low value of the control flow is used to primarily cause terminated wall or bleed switching, augmented by splitter and contacting both walls switching. During the whole process until separation occurs the angle of attachment is increasing.

ii) Rapid or Momentum Switching: this was only described by Wilson (11) who states that if a control pulse of sufficient strength is supplied the jet will be deflected so that it will contact the opposite wall. The critical attachment angle will be exceeded, hence the switching process may continue even if the control flow is shut off.

iii) Load switching: is explained by Foster and Jones (3) as a separation of the jet beyond the reattachment point. With increasing back pressure on the active leg the separation point approaches, and eventually reaches the position of reattachment which causes the separation bubble to be vented and hence switching occurs.

2.3 The Switching Time

Switching time is defined, by Savkar, Hansen and Keller (4), as the time elapsed between the initiation of the control pulse and the attainment of a steady state flow signal as measured by a flow sensor in the output channel. Their definition is incomplete as the location of the flow sensors to detect the main and control flows must be accurately described. Savkar, Hansen and Keller (4) used water flowing through a large scale model and a thermistor placed in the output leg to measure the switchtime. They showed that switching time decreased with increasing control pulse length and that there was a minimum control pulse which would initiate switching. By performing a similar experiment Muller (5) measured the time for the main jet to be released from the active wall. He combined this time with the time taken for the maximum pressure of the main flow to be detected at the receiver in the previously passive leg, to give the switching time. From these experiments he concluded that the switching time decreased with increasing control flow and that a minimum switching time existed for the particular fixed geometry of his amplifier.

Lush (3) used a large scale model with constant parameters and air as the fluid. In order to measure the time for the main jet to move from one output leg to the other he placed pressure transducers in the output legs, on the point of the splitter and at various points along the attachment walls. The initiation of the control pulse was measured from a pressure transducer placed in the control line. By recording these readings on an ultra-violet recorder he was able to determine the same quantities as the above two workers.

It is meaningless to compare the results of these three experimenters with each other as in each case the geometries differed considerably. Where possible an attempt has been made to correlate their results with those of the present investigation in the discussion of results.

2.4 Effects of Three of the Parameters on the Switching Mechanism

2.4.1 Setback

The generally recognized fact that reducing the setback has the effect of decreasing the minimum control flow required to switch a bistable amplifier has been experimentally proved by Savkar et al (4), Foster and Jones (10) and Moses and McCree (12). Kirshner (1) explains this as the effect of reducing the setback gives rise to a smaller separation bubble and a movement upstream of the reattachment region. The latter result has the effect of increasing the flow returned to the separation bubble and hence less control flow will be required to fill the now smaller separation bubble. Foster and Jones (10) showed that when the setback was increased beyond a value equal to the throat width of the main jet, then the control flow required to switch will begin to gradually reduce. This is due to the ease of dettachment of a jet from a distant wall, but this would lead to instability in a fluidic device.

2.4.2 Main Flow Rate

Foster and Jones (10) examined the effects of varying the main flow rate. Their general conclusion was that increasing the Reynolds number increased the vacuum in the bubble and therefore decreased the relative flow required to switch. Muller (5) using an amplifier with much lower setbacks found that as the Reynolds number increased the relative flow required to switch increased. He gave no explanation of this but the difference in results probably occurs due to a difference in geometry and hence flow pattern inside the amplifier.

2.4.3 Back Pressure

The only persons to have studied this, Foster and Jones (10), concluded that the relative flow required to switch decreased with increasing back pressure. Their explanation of this is similar to Lush's (3) for load switching as given in section 2.2.5 (iii).

2.5 The Effects of the Three Parameters on the General Operation

It is generally recognized by most of the aforementioned workers that changing the setback by a small amount, when the setback to nozzle width ratio is low, has a negligable affect on both the pressure and flow recoveries.

There exists a minimum main nozzle Reynolds number below which the amplifier will not operate, i.e., attachment will not occur.

The effect of increasing the back pressure is to reduce the entrained flow in the passive leg. A further increase in back pressure will reduce the entrained flow to zero and then result in spillover of the main jet into the passive leg. It is obviously undesirable to increase the back pressure much further as the resulting spillover into the passive leg will reduce the hysterisis effect upon which the bistable is based.

CHAPTER III

EXPERIMENTAL EQUIPMENT

The apparatus is shown in schematic diagram in Fig. 11 and an overall view is given in Plate 2. The following sections are all discussed with reference to these two illustrations.

3.1 Air Supply and Main Flow Measurements

The main flow air through the appratus was supplied through a one inch pipeline from the building service, which was capable of providing 15 s.c.f.m. at 80 p.s.i $\pm$ 5 p.s.i. It was first passed through a 982 x C Trerice pressure reducer which had an output range of 10-50 p.s.i. and then through a similar reducer with a range of 0 - 20 p.s.i. Pressure gauges were situated downstream of the reducers to record the pressure entering the second reducer and to ensure that the output of the second reducer was free from any pressure variation. A typical output pressure from the reducers was 5 p.s.i. with no measurable fluctuation.

The main flow rate could be varied by means of gate valve No. 1 and measured by the venturi flowmeter which was calibrated in situ with a Blackwell 415 gas meter.

3.2 Settling Chamber and Bellmouth

In order to stabilize the flow, the settling chamber was designed to have a maximum air velocity of 50 ft./min. This resulted in a chamber 12" in diameter. At the inlet end of the chamber a 3" diameter baffle was placed to spread the fluid evenly over the area of the tank. The chamber was made 26" long so that the two wire mesh screens could be placed 6" and 10" downstream of the baffle to dampen some of the turbulence out of the flow. To further assist in obtaining laminar flow in the nozzle of the amplifier the 6" diameter outlet of the tank was reduced down to 1 1/2" diameter aluminium pipe by a plexiglass bellmouth.

A statis pressure tap was located at the top of the settling chamber.

3.3 The Bistable Amplifier and its Instrumentation

The flow channels of the amplifier were formed by bolting 1" thick pieces of plexiglass to a 1/2" thick plexiglass base plate. With a nozzle width of 1/4" the aspect ratio of the amplifier is 4:1. This figure was chosen from the discussion given by Foster and Jones (10) on the effects of aspect ratio on a jet wall. They concluded that with an aspect ratio of 4:1 or above, the effects on the internal flow of the boundary layer forming on the top and bottom plates of the flow channel can be ignored.

The dimensions of the segments of the amplifier are given in Plate 3 and a view of the assembled pieces covered by the 3/8" thick plexiglass top is given in Plate 4.

The angle of inclination of the attachment wall, 12^{o}, and the location of the splitter, 5 to 6 nozzle widths downstream of the nozzle exit, were taken from information given by Sarpkaya (13). He studied the effects of these two parameters on the gain of a bistable amplifier and concluded that the values given above were the optimum.

The walls of all the channels were machined to a smooth finish to prevent any disturbance of the flow. Also any interfaces were machined smooth and smeared with silicone grease to prevent leakage.

The square inlet to the nozzle was bored out with a conical tool to provide a 1 1/2" diameter inlet which could be coupled to the aluminium flange from the plexiglass bellmouth. This provided a smooth transition from the circular aluminium tube to the square channel of the amplifier inlet.

To assemble the amplifier the segments were bolted loosely to the base plate with bolts passing through oversized holes in the segments. By placing gauge blocks of the correct thickness in each of the channels, and pushing the segments against these blocks before tightening the segments, constant channel widths were assured.

The dimensions of the amplifiers were chosen by scaling up approximately by a factor of ten a Bowles Engineering Corporation Flip Flop B-207-A. The main jet nozzle width of this is 0.023" with a control channel width of 0.015". The maximum flow recommended for normal operation is 0.4 s.c.f.m. which produces a Reynolds number at the throat of 19,000. For the amplifier used in this investigation a throat width of 0.25" was chosen with a Reynolds number range of 12,500 to 30,000. The control channel width was 0.125".

The setbacks used were 0, 15,30 and 45 thousandths of an inch which would provide machineable dimensions when scaled down by a factor of ten. These values also served to extend the setback range examined by Foster and Jones (10). The oversized bolt holes mentioned above allowed sufficient movement of the segments to acheive this setback range.

The outlets from the legs of the amplifier were 1 1/2" long by 1" diameter aluminium flanges bolted onto the output ports as shown in Plate 4.

The inputs for control flow were flanges, of the same dimensions as above, bolted to the lower side of the 1/2" thick plexiglass base. During all the experiments one control channel was permanently blocked while the other was fed a pulsed flow of air to acheive switching. The pulsing of control flow, obtained from a compressed air bottle and pressure reducer, was acheived by means of a rotating disc with a slot cut in it. The disc was driven by a Dodge S.C.R. 3/4 H.P. motor, the speed of which was varied by a Dodge S.C.R. speed controller. In order to reduce the speed still further a Dyna minidrive speed reducer was used. The pressure reducer on the outlet of the compressed air bottle was used to vary the volume of control flow entering the control channel. The disc intercepted the control line, either closing the control line completely by forming a seal between the atmosphere and the control channel with the solid part of the disc, or allowing a control flow to pass through the slot in the disc into the control channel. In all the experiments the speed of the disc was set to produce a control pulse which would last during the whole switching process.

A Disa type 55A53 miniature hot wire probe was mounted 2 3/4 nozzle widths away from the nozzle exit in the control channel to record the initiation of the control pulse. It was calibrated against a wet test flowmeter and a Brooks 0-3 s.c.f.m. rotameter to measure the control flow. A similar hot wire was placed 42 nozzle widths from the nozzle exit in one of the output legs to record effects of flow in this leg. Both wires were connected in series to the probe terminal of a Disa type 55D50 Anemometer. A constant current generator in the instrument heats the wires at the probe tips. A flow of air passing over the wire will cool it resulting in a change in electrical resistance. The probes actually constitute one arm of a Wheatstone bridge.

The voltage across the probes is measured on the bridge and given out at the output terminal of the Anemometer. The difference in time between the first resistance changing, due to control flow and the second, due to output flow was measured by displaying the output from the anemometer on an oscilloscope screen. The trace on the oscilloscope screen was triggered by an electrical pulse, given out just before the slot in the disc opened the control channel to the compressed air source. This was acheived by positioning two wires close to the circumference of the rotating disc. A bolt was screwed into the circumference of the disc so that as it passed the two wires it would momentarily complete the triggering circuit. There is no concern over the time responses of the apparatus used as both wires are in series in the same arm of the Wheatstone bridge. Plate 3 shows two bleed channels located at the end of the attachment walls. It was found that a large amount of air was exiting from these bleeds due to the fact that they had been located too far upstream. It was decided to block these bleeds off and to examine the switching of an unvented bistable amplifier.

As shown in Fig.29 static pressure taps were located throughout the apparatus in order to study the flow.

To examine the effects of back pressure a 12" by 7" diameter tank was connected to each output leg. At the exit of these tanks a 2 3/4" diameter rubber hose was connected. These could be clamped down in order to reduce the output area and hence increase the loading on the amplifier. Three static pressure taps were spaced equally around the circumference of the drum to give a true measure of total pressure unaffected by the direction of the flow inside the tanks.

All the static pressure taps were connected to a bank of manometers which could be inclined from 19° to 90° from the horizontal.

CHAPTER IV

EXPERIMENTAL PROCEDURE

4.1 Calibration

The venturi flow meter was calibrated by connecting a Blackwell 415 gas meter in the line between the venturi and the settling chamber. The relationship between main flow rate and the manometer reading from the venturi is shown in Fig. (12). A calculation was performed as recommended in Ref. (14) and there was a good agreement with Fig. (12).

The control flow was calibrated by connecting a rotameter in the control line, which was at no point left open to atmosphere during the calibration. A graph was plotted, Fig. (13), of the output of the anemometer, as read on the oscilloscope screen, against the various levels of control flow read from the rotameter. To complete the lower portion of the curve a wet-test gas meter was used for a higher accuracy.

4.2 Setting the Geometry of the Amplifier.

The plexiglass segments which formed the channels of the amplifier were assembled on the base plate. A $\frac{1}{4}''$ thick gauge block was placed between the walls forming the nozzle. Two $\frac{1}{8}''$ thick gauge blocks were placed in the control channels. The segments forming the nozzle and the wall pieces were then all pressed firmly against the gauge blocks and were clamped in place. This produced a model with a setback of zero. For the other values shims of either 15,30 or 45 thousandths of an inch thickness were placed on either side of the $\frac{1}{4}$" gauge block at the nozzle exit. The wall pieces were then set back a known distance, i.e.,0,15,30 or 45 thousandths of an inch from the line of the nozzle wall.

The wall pieces had been accurately machined to be inclined at 12^{o} from the control channel walls. Gauge blocks $\frac{3}{8}$" thick were placed in each of the output legs to ensure that the channels were of a constant width before the remaining walls pieces were tightened.

4.3 Experiments Performed

Readings taken which departed from normal experimental procedures are described below. A full list of all the experiments performed is given in Appendix C.

In order to measure the pressures in each leg while active both control channels were closed to atmosphere. Readings were then taken of the static pressures at ten locations, P_{ST}, P_{STH}, P_{S1}, P_{S2}, P_{S3}, and P_{S4} for an active left leg and then an active right leg.

The minimum control flow required to switch was measured by slowly increasing the flow rate of the pulsed control flow. At a certain value of control flow the amplifier switched.

This procedure was repeated several times to ensure that the minimum control flow necessary for switching had been found. Using this value, a photograph, Fig. (14a), was taken of the switching pattern as displayed on the oscilloscope screen. This was accomplished by opening the camera shutter before the initiation of the control pulse and closing it after switching was completed. Tri-x film was used with the aperture set at f 5.6.

The upper curve in Fig. (14a) shows the hot wire in the control channel being affected by the control flow alone. The hot wire in the left output channel was, at this time, measuring the constant main flow passing by it and was unaffected by the addition of the relatively small control flow. The control flow was then recorded as the distance between the two parallel lines, Fig.(14b), is proportional to the control flow as shown in Fig. (13). This was measured by projecting the negative onto a screen and measuring the distance as shown on the enlarged image, the enlargement factor being known.

The switching time produced by this control flow was measured from the lower curve. Again, by projecting, the distance is measured from the initiation of the control pulse to the point of switching. With the sweep rate of the oscilloscope known then the switching time was calculated.

Figs. (14b) - (14d) explain this switching pattern. Fig. (14c) shows the pattern produced during switching by the hot wire in the left leg. Initially there is entrained fluid in the left leg which is represented by the horizontal portion of the trace. During switching this entrained fluid is reduced and then has its direction reversed by the main flow which is beginning to flow down the left leg. The dip in Fig. (14c) represents initially a reduction in the output from the anemometer and then an increase due to the main flow having an increased cooling effect on the hot wire. The latter signal meant that the amplifier had switched.

For each value of control flow used three negatives were taken of the switching pattern to give more confidence in the results.

To illustrate the switching pattern produced by rapid switching Fig. (14e) is included.

The result on the main flow rate of increasing the back pressure was determined by reducing the area of the outlets of the back pressure tanks. This experiment was then repeated measuring the values of static pressure as tabulated in Appendix C, Series No. 21 - 27 to determine the effect of back pressure on the internal pressures.

The values of switching time were initially recorded with the back pressure on the amplifier being measured by the static pressure at P_{S4}. For the reason given in section 5.9, the back pressure was then recorded by measuring the static pressure in the back pressure tanks. As the velocity of the air in these tanks was low, this gave the value of total pressure at the outlets.

CHAPTER V

RESULTS AND DISCUSSION OF RESULTS

5.1 Pressures in Legs When Active

The values of the total pressures calculated from the recorded static pressures were plotted, as shown in Fig. 15, to determine whether there was an equal resistance to the flow by each output leg. A maximum difference in pressures occurs in the 6.4 s.c.f.m. flow rate. At this flow the difference in pressure produced by the flow in the left and right legs at static pressure tap number two was 5% of the total pressure at that point. This and the other small differences between the left and right channel values are due to the fact that the area of each of the outputs legs is slightly different.

It was considered that this difference in the resistance to the flow of each leg was not large enough to affect the switching properties of the amplifier.

5.2 Effect of Setback and Main Flow Rate on the Minimum Control Flow Required to Switch

In Fig. 16 the curves for constant setback demonstrate the effect of the main flow rate on the minimum control flow required to switch the amplifier. At the low main flow rate the minimum control flow required for switching is higher than at the higher main flow rate. The switching mechanism is slow switching, as described in section 2.2.5. Therefore any change in the conditions around the separation bubble will have a noticeable affect on the control flow required to expand the bubble to cause switching. As the main flow rate increases the fluid entrained from the outer edge of the bubble increases. In order to return to a steady state condition the returned flow to the bubble at the point of reattachment must increase. This can only be accomplished by an increase in the angle which the reattaching streamline makes with the wall. With the separation bubble in this condition a relatively lower control flow is required to commence switching as the reattachment angle of the streamline will soon reach the value at which dettachment of the jet occurs.

As the setback increases the control flow required to switch the amplifier increases for any given flow rate. This is due to the fact that with increasing setback the size of the separation bubble also increases. Hence more control flow is required to expand the bubble for the mechanism of slow switching to occur.

Foster and Jones (10) using an apparatus with a larger setback found that a higher value of control flow was required to switch the amplifier, as shown in Fig. 16. They also found a reduction in relative control flow required to switch with an increase in the main flow rate.

Using values of QC min/QS from Fig. 16 for the same Reynolds number at which Foster and Jones operated their amplifier $Re = 2 \times 10^4$, Fig. 17 was plotted. It shows that with a reduction in setback the minimum control flow required to switch reduces.

5.3 Effect of Control Flow on Strouhal Number

The various values of control flow produce the different switching times as shown in Appendix A table (3). The time is expressed as the non-dimensional Strouhal Number and plotted against the control flow in cubic feetper minute of air as shown in Fig. 18.

The lowest control flow QC min, at which the amplifier will just switch gives a wide range of switching times. With this value of control flow slow switching occurs. This mode of switching results in an unsteady flow condition and therefore the wide variation in switching times measured with this value of control flow can be expected.

As the control flow is increased the switching time is seen to decrease. The added momentum of the jet assists in moving the jet across the interaction region, as well as resulting in an increased initial deflection of the main jet caused by the control jet impinging on it. In this case the separation bubble is larger but the flow returned to the bubble from the point of reattachment is larger. Therefore with this increased control flow a shorter time will elapse before the jet dettaches from the wall and the amplifier switches.

With a further increase in control flow the switching time is seen to reach a constant value. This is explained by the fact that rapid switching is occurring in which the important factor affecting the switching time is the ratio of the momentum of the main jet to that of the control jet. At very high values of control flow the main jet is blown from the active leg to the passive leg. When the main stream velocity is 100 ft/sec the distance it has to travel, after switching, along the passive leg before it will have any effect on the hot-wire in the output leg is approximately ten inches. This would take 10 milliseconds to occur and therefore a shorter switching time cannot be produced with this apparatus at the main stream velocity mentioned. As is shown in Table 4 increasing the main flow rate reduces the minimum switching time.

The switching time produced by any value of control flow between approximately 0.6 and 0.8 s.c.f.m. results due to a combination of the above two mechanisms. It would be unadvisable to operate an element at this condition as with a small change in control flow the switching time will change drastically.

If an accurately defined value of control flow is available and the switching time of the amplifier is of no consequence then the most economical value to use will be QC min, i.e. approximately 3.5% of QS. If, however, the switching time is to be a minimum then the smallest value of control flow which will produce this is approximately 6% of QS.

Lush obtained the results as shown in Fig. 19 using a bistable amplifier with a much larger setback and a Reynolds number of operation of 9×10^4. The values for the control flow are drastically different to those of the present investigation which is probably due to a large difference in control channel width, and other geometrical variations. Figure 19 does, however, present an indication of the shape of the control flow v switching time curve which agrees with that of the present investigation.

5.4 <u>Effect of Main Flow Rate on Switching Time</u>

For a setback of zero the control flow v switching time curves for four different main flow rates are shown in Fig. 20. The switching time is seen to decrease with increasing main flow. This is due to the fact that a disturbance propogates more quickly with a higher main flow rate as explained in Appendix B, section B1. The influence of the Coanda effect from the unattached wall, after the jet has been initially inclined, will also be stronger with a higher main flow rate. This is because the fluid is entrained away from the low pressure region at a faster rate, thus in a shorter time a force sufficient to move the jet away from the attached wall will be produced. These results prove that switching with a high control flow is not purely a momentum effect, otherwise the minimum switching time would increase with the increasing ratio of momentum of main jet to momentum control jet.

5.5 Effect of Setback on Switching Time

For a low value of control flow the switching time decreases with decreasing setback for a given control flow as shown in Fig. 21. This is because an amplifier with a small setback requires less control flow for switching as explained in section 5.2.

When switching with a high value of control flow then rapid switching is occurs and the size of the separation bubble is relatively unimportant. It would therefore be reasonable to expect that changing the setback by a small quantity would have a negligable effect on the switching time. This is shown to be true in Fig. 21 for the setbacks of 0.15 and 45 thousandths of an inch. The value for S = 30 is 18 milliseconds which is thought to be outside of the limits of experimental error. A small increase in the switching time would be expected due to the lessening of the Coanda effect from the unattached wall.

5.6 Presentation of Effects of Setback and Main Flow Rate on Switching Time

First the rapid switching mode of operation will be discussed.

For Fig. 22 the setback is constant and the main flow rate is varied. The Strouhal number has been used to denote the switching time and this will bring the flow to a similar time independent situation as explained in Appendix B. This gives the Strouhal number range for rapid switching as 60 - 110. There is no general trend for the minimum Strouhal number with main flow rate variation showing that a truly similar situation exists in each case. This is a very convenient way to present the switching time, as the value for the minimum switching time can be calculated by interpolation when the main flow rate is known and the minimum Strouhal number will always be in the range of 60 - 110.

With a geometrical change, in this case the setback, the examination of Fig. 22 - Fig. 25 shows that the minimum Strouhal number lies in the range of 40 - 110. The regions of rapid switching are summarized in Fig. 26. The reason for this constant range is that an important geometrical variable as far as rapid switching is concerned, has not been changed. This was explained in section 5.5 by the fact that the size of the separation bubble is not important in this case.

There is very good agreement between the Strouhal number ranges for the setbacks of 0.15 and 30 thou. but, for the case of S = 45 thou. the minimum Strouhal number is 20 lower than those for the other setbacks. This represents a switching time of approximately 3 milliseconds at a main flow rate of 10 $ft.^3$/min. which is within the limits of experimental accuracy.

A given ratio of QC/QC min. will produce switching times in the same Strouhal number range for any setback or main flow rate, because a similar flow situation exists in each case. Hence the use of QC/QC min. as the ordinate in Fig. 22 - Fig. 26.

From Fig. 26 it can be seen that a change in setback affects the commencement of rapid switching. With an increase in setback, rapid switching occurs at a lower ratio of QC/QC min. For slow switching, which is the region governed by the horizontal portion of Fig. 22 - Fig. 25 a large range of Strouhal Numbers occurs. As explained in Section 5.3 this occurs due to an unsteady flow situation existing during slow switching.

5.7 Effect of Back Pressure on Main Flow Rate

This test was conducted to determine whether varying the back pressure on the bistable amplifier would alter the main flow rate issuing from the nozzle. The back pressure was increased from zero to the point at which instability occured, i.e. the amplifier started to switch due to the mechanism of load switching. From Fig. 27 it can be seen that the pressure drop across the venturi varied at a maximum of 0.8% from the mean of 12.6" H_2O.

From this it can be concluded that main flow rate was constant with varying back pressure.

5.8 Effect of Back Pressure Upon Internal Flow Condition

A plot of the static and total pressures from the first tap in the output leg, P_{S1}, through the apparatus to the tap in the back pressure tank is given in Fig. 28 for six different values of back pressure. The location of the static pressure tap is given in Fig. 29. The total pressure reduces in value from P_{S1} to P_{SB} due to pipe friction in the channels. An increase in the total pressure, P_{SB} , into which the fluid was ejected resulted in an increase in total pressure at each of the pressure taps. These results are only presented for one main flow rate, as the effect of increasing the main flow is to raise both the values of static pressure and the dynamic head due to the flow, and to increase the friction pressure loss.

The most important effect of changing the back pressure is seen to occur by plotting the values of total pressure at the throat, P_{STH}, and the first pressure tap location, P_{S1}.

Plots of the total pressure in the settling chamber, at the throat and at the first pressure tap are shown for three different main flow rates in Fig. 30 - Fig. 32. Whether there was entrainment from the atmosphere into the passive leg or spillover denoted by an E or S at the particular value of back pressure.

For a given main flow rate an increase in back pressure causes a decrease in the interaction region pressure drop. Also the flow entrained in the passive leg is decreased until it eventually reaches zero. A further increase in the back pressure results in spillover of the main jet into the passive leg. A free jet with a high static pressure will tend to spread more than one with a lower static pressure relative to the supply jet pressure. Therefore increasing the static pressure of the jet in the amplifier by restricting the area of the outputs will result in the particles on the outer side of the jet exiting from the nozzle ultimately to proceed down the passive leg. The reason for this decrease in pressure drop is explained by considering the effect of the entrained flow on the main jet. Fig. 33 shows the velocity components for the main jet and the entrained jet. The resultant component of velocity of the entrained fluid reduces the main jet velocity. By increasing the back pressure the entrained fluid is decreased and the reduction of the main jet velocity decreases. This results in a lower pressure drop across the interaction region.

It should be noted that the values of total pressure as calculated for the first pressure tap are incorrect. Due to the fact that the value of"entrained" or "spillover" flow could not be measured then the values of the dynamic head will be incorrect. They were calculated assuming the same flow passed across the first pressure tap as passed through the nozzle. For a low back pressure the total pressure shown is too small as entrained flow increased the main flow in the output leg, while for a high back pressure "spillover" flow will reduce the value of total pressure shown.

In order to estimate this error a smoke trace was introduced into each leg separately. In the passive leg the smoke could be observed to progress steadily along the channel while in the active leg the smoke trace was carried at an extremely fast rate. This showed that there was a large difference in the velocities of the flow in either leg and hence in the flow rates. It is thought that this error does not seriously affect Fig.30- Fig. 32 or the above reasoning.

5.9 Effects of Back Pressure on Switching

A back pressure was produced on the bistable amplifier by loading as described in Section 4.3. Results of a study on the switching for a constant main flow rate and setback are shown in table 8 and Fig. 34. Five different values of back pressure are shown. The value of the back pressure was recorded by measuring the static pressure at pressure tap number 4.

As can be seen from Fig. 34 with increasing back pressure the minimum control flow required to switch at first increases but then begins to reduce and approaches the value for the unloaded case. Also the minimum Strouhal number first increases and then reduces to a value equal to half that for the unrestricted output.

The reason for the changes in QC min and ST min can be explained by considering the effect of the inertia of the fluid in the output legs. In an amplifier with unrestricted outputs both the main flow in the active leg and entrained flow in the passive leg will have to be completely reversed before switching can be completed. After spillover has occurred then only the fluid in the active leg will have to be reversed, and switching can be completed in a shorter time as shown in Fig. 34 for the high back pressure tests. The increase in ST min and QC min occurs because restricting the outputs initially increases the resistance to the change in flow direction without the above effect being strong enough to overcome this resistance.

The above method of measuring the back pressure on the apparatus was thought to be insufficient. The value of the total pressure at pressure tap number 4 would be needed to compare the effects of back pressure on an amplifier with a different output leg geometry. This could have been done by placing a calibrated hot wire slightly downstream of the 4th pressure tap to measure the velocity there but no provision had been made for this in the apparatus.

The back pressure tanks described in section 3.3 were fitted to enable the total pressure at the output of each leg to be measured.

Initially a study was performed to examine the variation of Strouhal number with control flow for various values of back pressure. The results for the four main flow rates used are shown in Fig. 35 - Fig. 38. The minimum Strouhal number, produced in rapid switching, did not follow the same trend as in Fig. 34, when back pressure was produced by simply reducing the area of the outputs.

The minimum Strouhal Number range was found to be 30 - 75. For any given main flow rate increasing the back pressure did not have the effect of decreasing the minimum Strouhal number. The unrestricted outputs case discussed in Section 5.6 gave a minimum Strouhal number range of 40 - 110, while back pressuring by reducing the area of the outputs gave a minimum Strouhal number range of 11 - 19, as shown in Fig. 34.

Addition of the back pressure tanks resulted in only a slight decrease in the minimum Strouhal number range while merely reducing the area of the outputs greatly reduced the switching time. With the addition of the back pressure tanks a capacitance, formed by the volume of the tank, and a resistance resulting from the restriction at the output of the tank are added. When switching occurs the direction of inertia of the flow in the active leg has to be completely reversed through the effect of the capacitance and resistance. In fluidic circuiting a capacitance is produced by introducing a cavity into the circuit, which results in a time delay in the propogation of a signal through the circuit. A similar time delay results in the motion of the fluid from the active leg to the passive leg in the bistable amplifier. The result of this is to lengthen the time for rapid switching, giving an increase in the minimum Strouhal number range of about 60 above the range produced for rapid switching under back pressure with no capacitance effects.

The addition of the back pressure tanks did not produce a meaningful method of measuring the minimum Strouhal number. It would be better to measure the back pressure with the aid of a hot wire and static pressure reading as mentioned before.

The back pressure tanks were useful in determining the change in the minimum control required to switch, QC min, with increasing back pressure. In Fig. 39 QC min/QS has been plotted for constant values of N_{BP} which is a measure of the back pressure applied to the amplifier. An explanation of N_{BP} is given in Appendix B section 3.

As can be seen QC min/QS for an identical geometry as that for the above tests but with unrestricted outputs is less than QC min/WS for the first value of back pressure. This is due to the fact that adding the tanks resulted in an increase in the attachment wall length. When finding QC min slow switching occurs due to end of wall switching and hence the attachment wall length will be critical, and increasing the wall length increases QC min.

With increasing back pressure QC min/QS is seen to reduce below half the value for the unrestricted case. This is because of the changing inertias of the fluid in the legs as explained in the third paragraph of this section.

CHAPTER VI

CONCLUSIONS

6.1 Switching Properties

For a given setback the switching time decreases with increasing main flow rate. The ratio of the minimum control flow required to switch the amplifier to main flow rate, or the percent of the main flow which would be required to switch the amplifier, increases with decreasing main flow rate.

One of the most important conclusions to be drawn from the switching study is that the mechanism for switching depends on the value of control flow used. Slow switching occurs when values of control flow at or just above the minimum control flow required to switch are used. These values produce long unpredictable switching times.

Increasing the control flow decreases the switching time, but a point is reached where a further increase in control flow will not result in a reduction in switching time. This constant value of the switching time is the minimum switching time of the amplifier for the particular configuration of variables being used. The minimum switching time is produced by a completely different mechanism to slow switching. This mechanism is called rapid switching.

An increase in the setback results in an increase in the minimum control flow required to switch for all main flow rates examined. This agrees with Foster and Jones (10) result's for a model with a higher setback range. For slow switching increasing the setback increases the switching time. Whereas during rapid switching a change in the setback does not affect the switching time.

The minimum Strouhal number produced during rapid switching lies in the range of 40 - 110 for all main flow rates and setbacks examined. This range of Strouhal numbers is similiar to that found by Lush (3) so is the shape of the switching time versus control flow curve.

6.2 Switching Under Back Pressure

Increasing the back pressure, loading at the outlets, does not change the main flow rate. It results in the entrained flow in the passive leg reducing and eventually causing a spill-over of the main flow into the passive leg. With increasing back pressure there is a decrease in the interaction region pressure drop.

Increasing back pressure initially results in an increase in the minimum control flow required to switch and in the minimum Strouhal number. A further increase results in the minimum control flow required to switch reducing to that for the unrestricted case and the minimum Strouhal number range reducing to 11-19.

Using an alternative method of measuring back pressure, the back pressure tanks, a capacitance was introduced at the outlets. The capacitances increased the minimum Strouhal number range of 11-19, produced by simply restricting the outlet area to 30-75.

Increasing the back pressure with the capacitance in the circuit results in a minimum value of the ratio of minimum control flow required to switch divided by the main flow rate of 2% compared with 5% for the unrestricted case.

REFERENCES

1 Kirshner, J. M., "Fluid Amplifiers", McGraw-Hill Book Company, (1966).

2 Fluidics Seminar, Sponsored by A.S.M.E. and E.S.D., presented on October 24th, 1967.

3 Lush, P. A., "Investigation of the Switching Mechanism in a Large Scale Model of a Turbulent Reattachment Amplifier", Second Cranfield Fluidics Conference, Cambridge, (1967).

4 Savkar, Hansen and Keller. "Experimental Study of Switching in Bistable Fluid Amplifier." A.S.M.E. publication No. 67 - WA/FE-37.

5 Muller, H. R., Switching Mechanism in a Jet Amplifier. Fluid Control Systems, P 112, 1965.

6 Bourque and Newman, "Reattachment of a Two-Dimensional Jet to an Adjacent Flat-Plate. Aero.Quarterly, Vol.11, P.201, 1960.

7 Sawyer, R. A., The Flow Due to a Two-Dimensional Jet Issuing Parallel to a Flat Plate,J. Fluid Mech, Vol.9, P. 543-560, 1960.

8 Sawyer, R. A., "Two-Dimensional Reattaching Jet Flows Including the Effects of Curvature on Entrainment. J. Fluid Mech., Vol. 17, P.481, 1963.

9 Muller, H. R., "A Study of the Dynamic Features of a Wall-Reattachment Fluid Amplifier", A.S.M.E., J. Basic Eng., 86D(4):819-826 (1964).

10 Foster and Jones, "An Examination of the Effect of Geometry on the Characteristics of a Turbulent Reattachment Device. First Cranfield Fluidics Conference, Cranfield, (1965).

11 Wilson, M. P., Jr., "The Switching Process in Bistable Fluid Amplifiers". A.S.M.E. publication No. 69-FLCS-28.

12 Moses and McRee, "Switching in Digital Fluid Amplifiers", A.S.M.E. publication No. 69-FLCS-31.

13 Sarpkaya, T., "The Performance Characteristics of Geometrically Similar Bistable Amplifiers", A.S.M.E. paper No. 68-WA/FE-18.

14 A.S.M.E. Research Report on Fluid Meters. (1959)

15 Baker, P.J. " Future Looks Bright for Fluidic Devices in Process Control Systems", Process Engineering, October 7, 1970, p. 39.

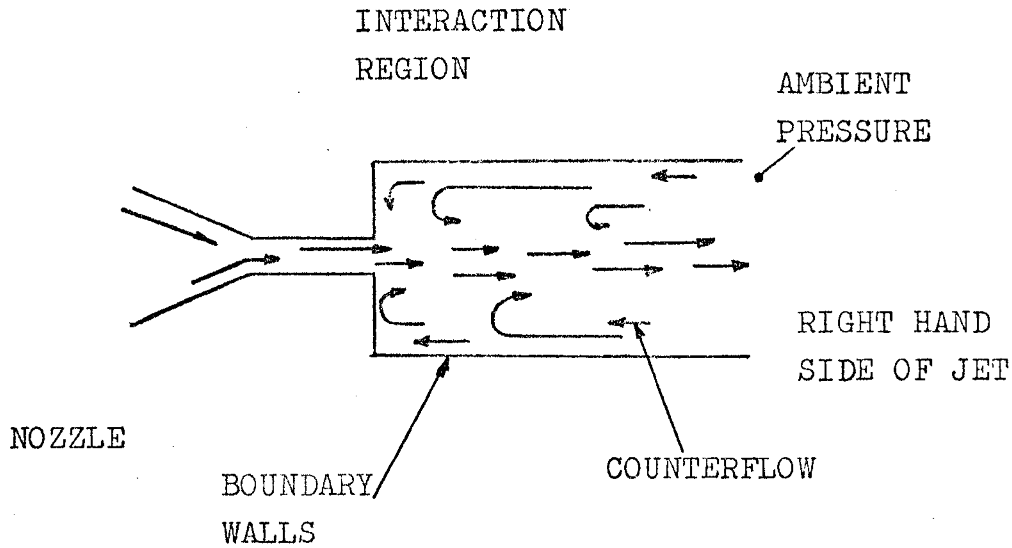

FIG.1 INITIAL FLUID FLOW BETWEEN PARALLEL WALLS

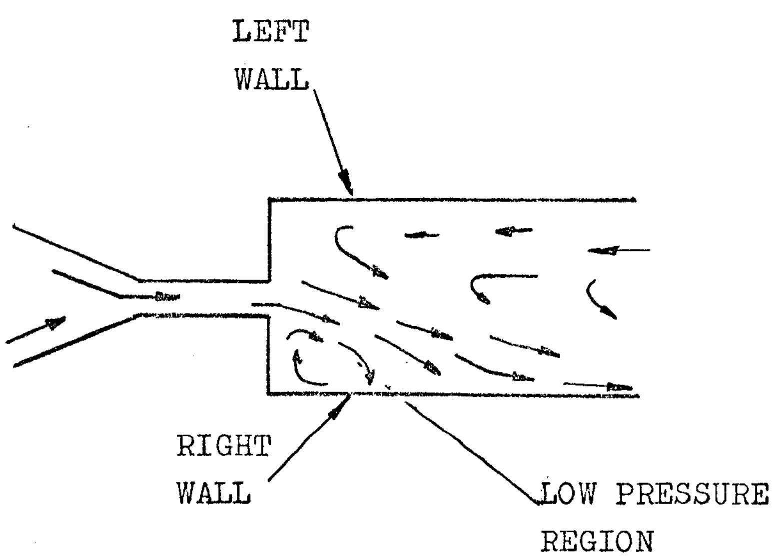

FIG.2 FINAL FLUID FLOW BETWEEN PARALLEL WALLS

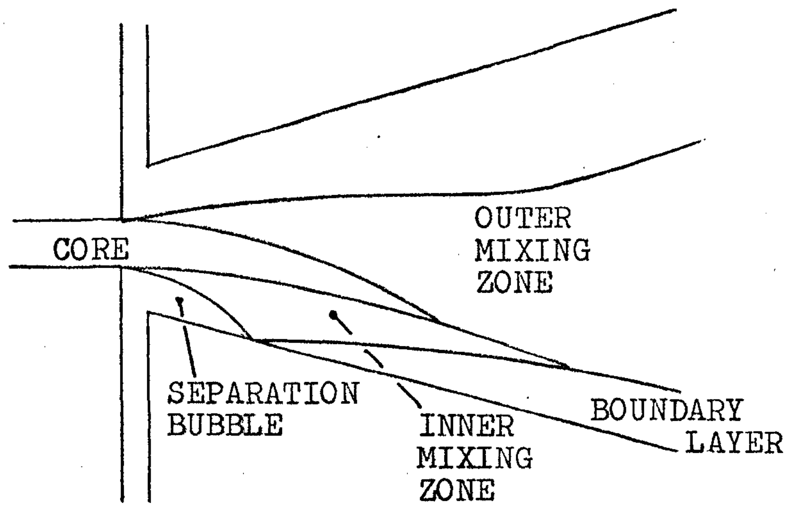

FIG.3a SCHEMATIC DIAGRAM OF ATTACHED JET

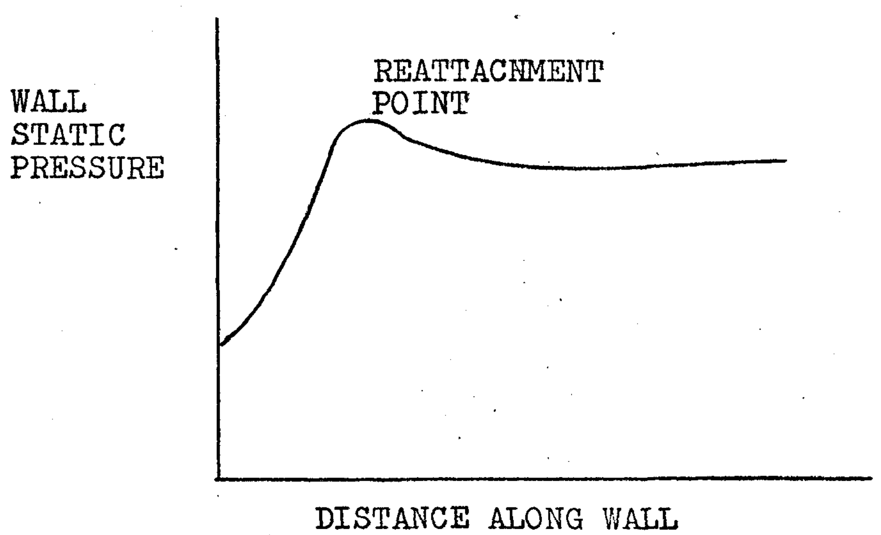

FIG.3b PRESSURE DISTRIBUTION ALONG ATTACHMENT WALL

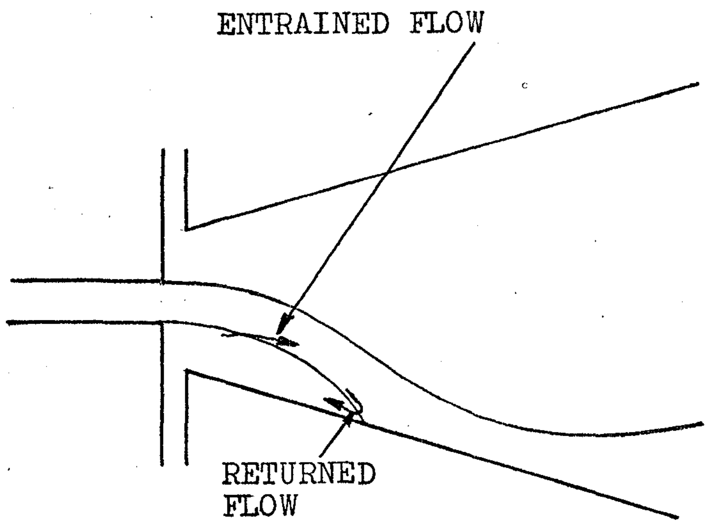

FIG.4 SEPARATION BUBBLE FLOWS

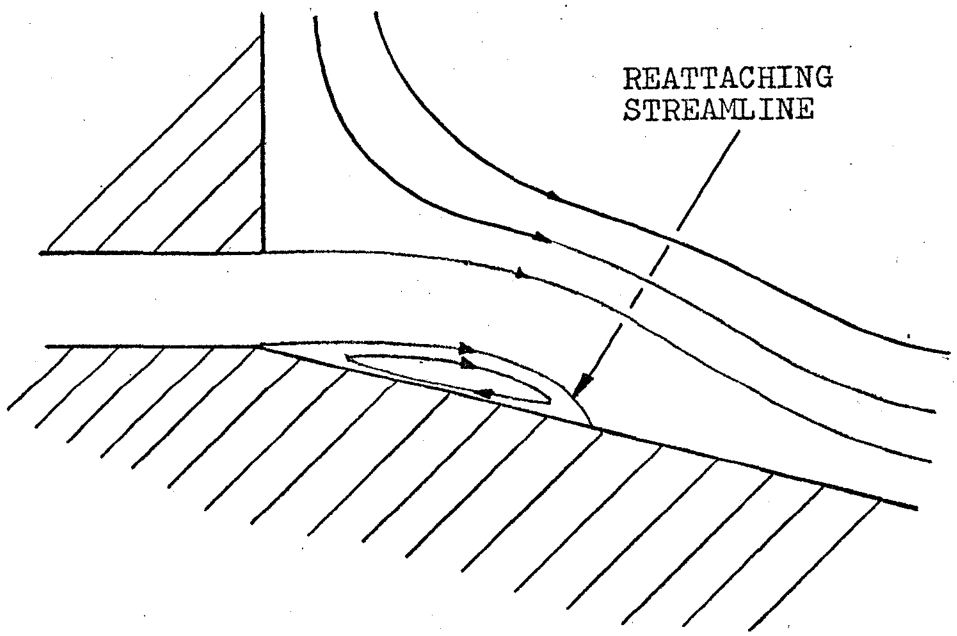

FIG.5 STREAMLINES OF THE COANDA EFFECT

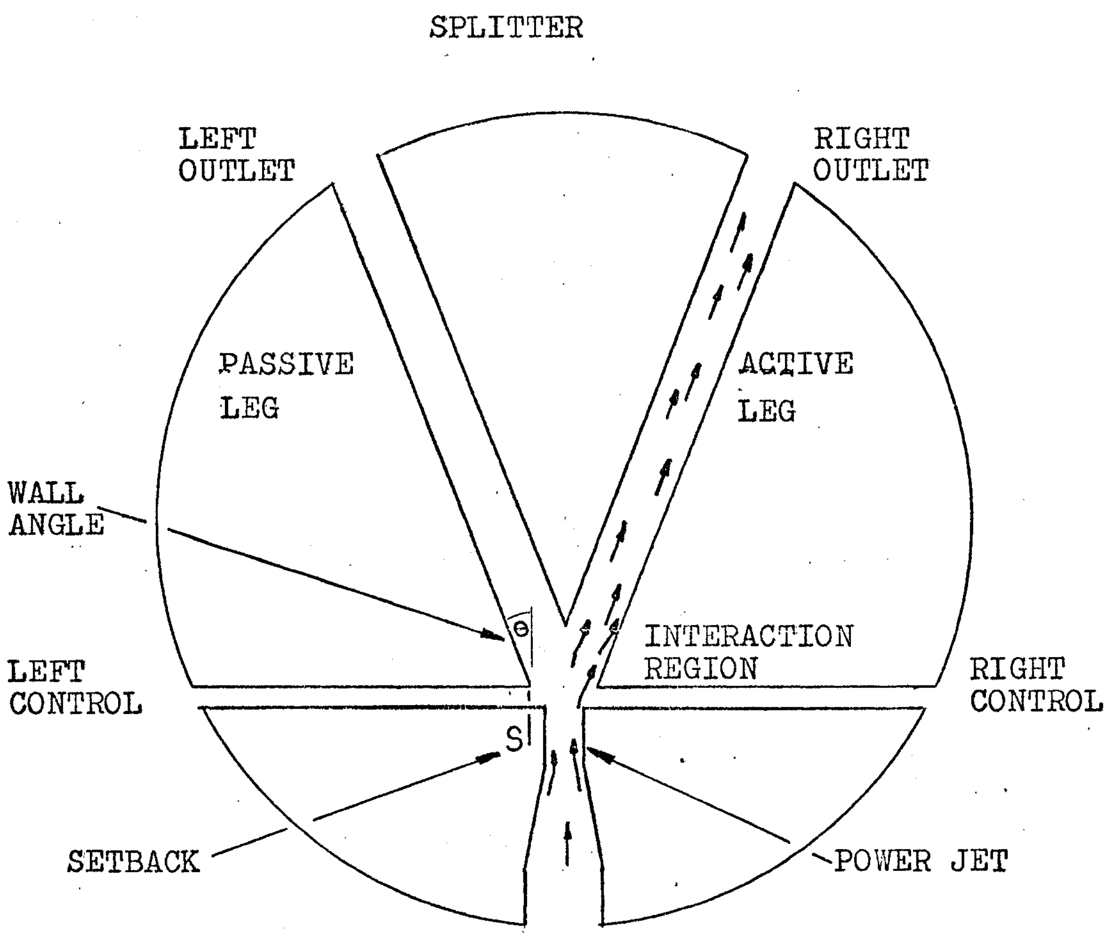

FIG. 6 DIAGRAM OF THE BISTABLE ELEMENT

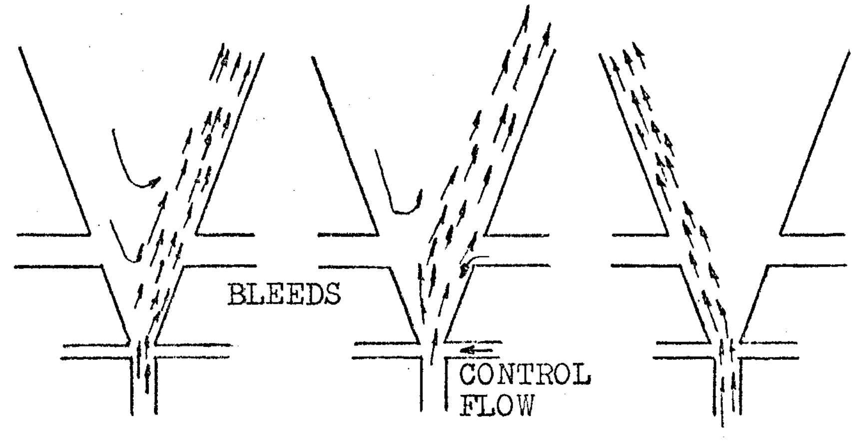

FIG.7 TERMINATED WALL OR BLEED SWITCHING

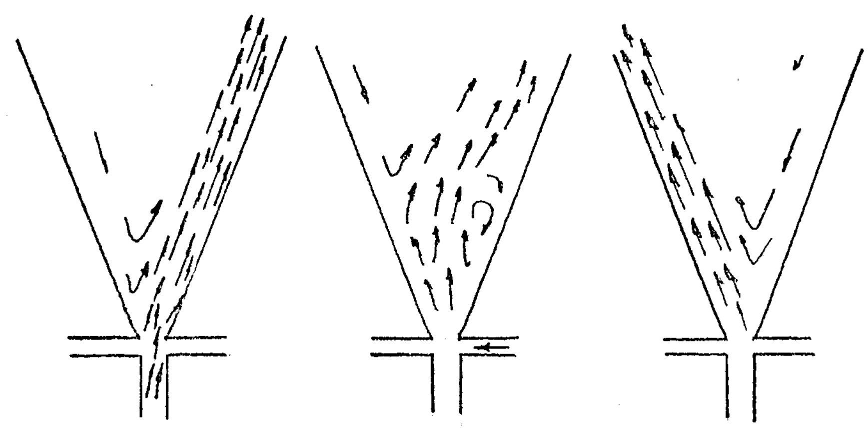

FIG.8 CONTACTING BOTH WALLS SWITCHING

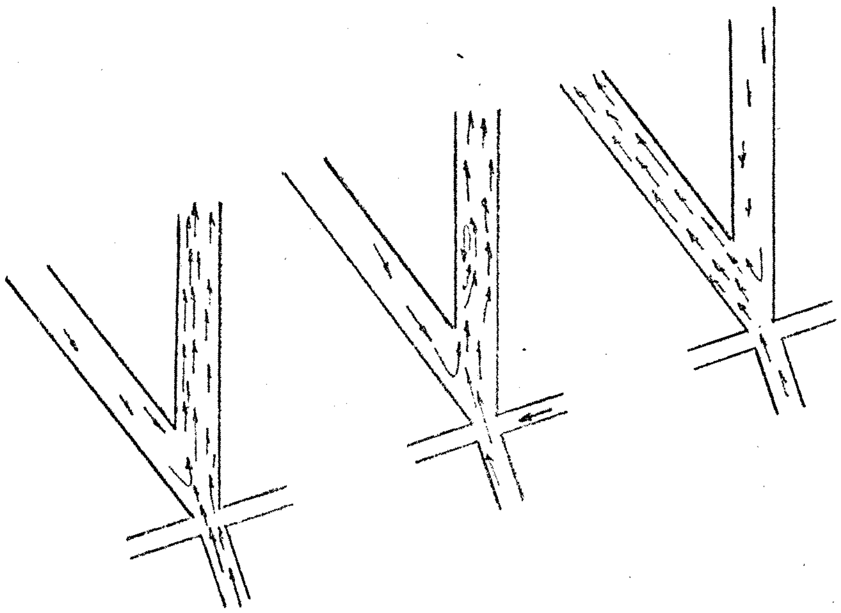

FIG.9 SPLITTER SWITCHING

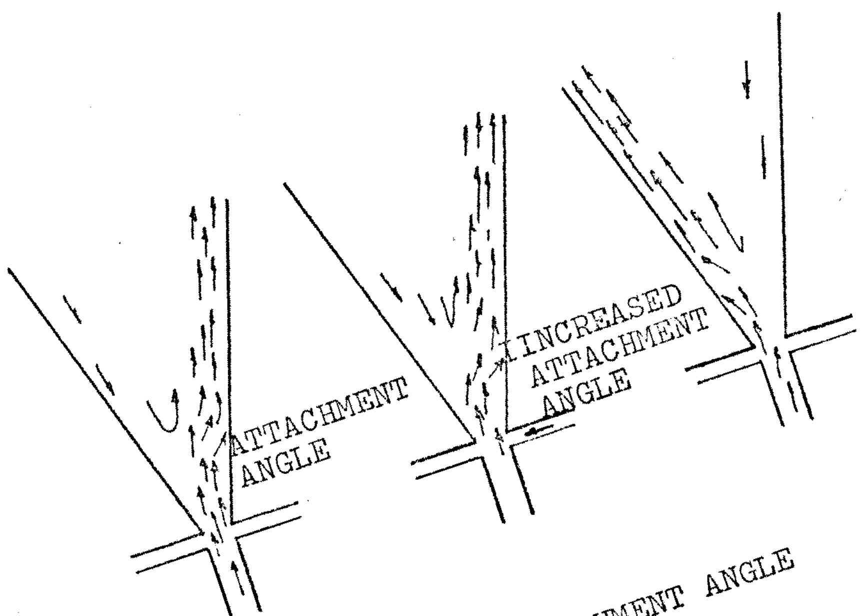

FIG.10 CRITICAL ATTACHMENT ANGLE

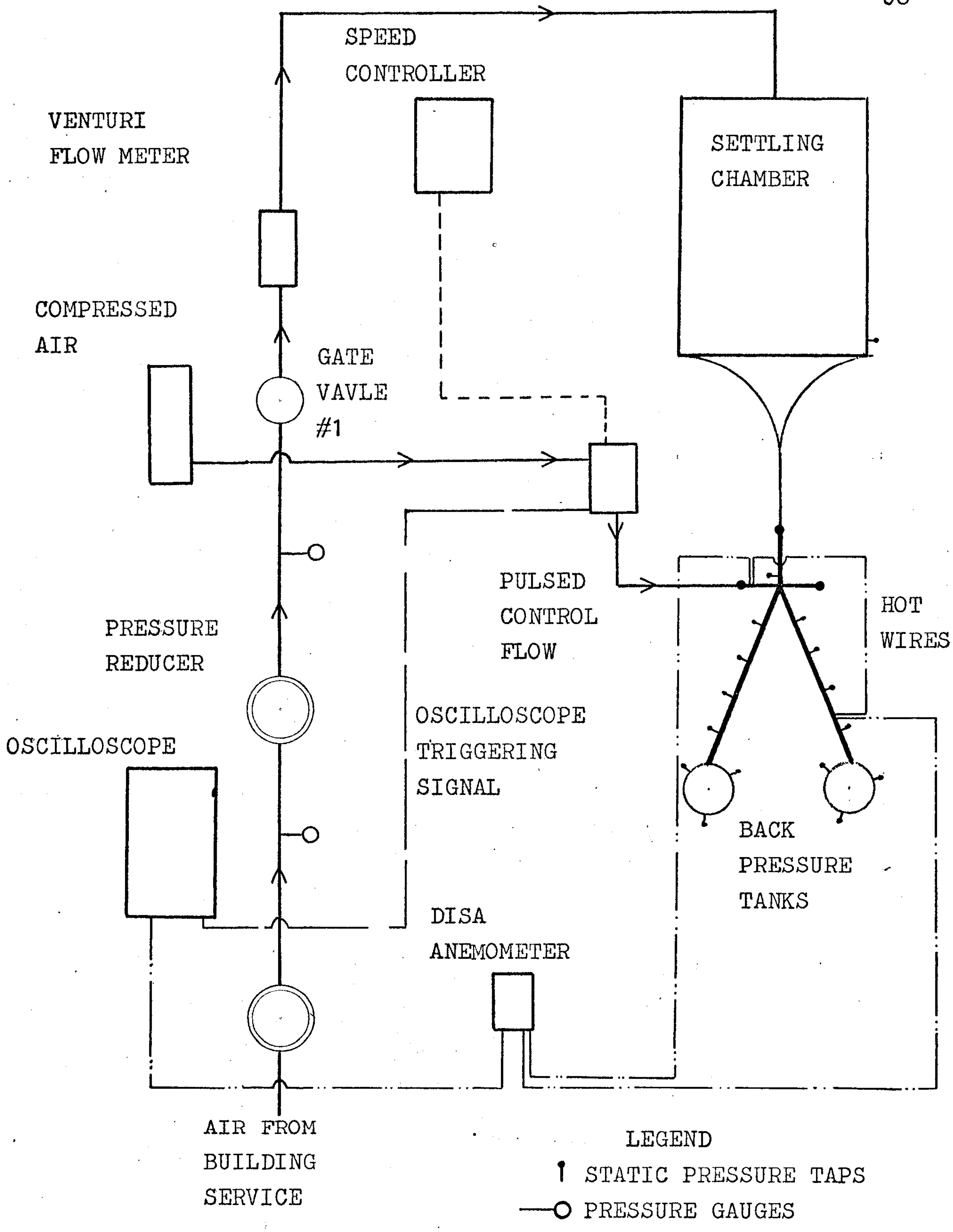

FIG.11 SCHEMATIC DIAGRAM OF APPARATUS

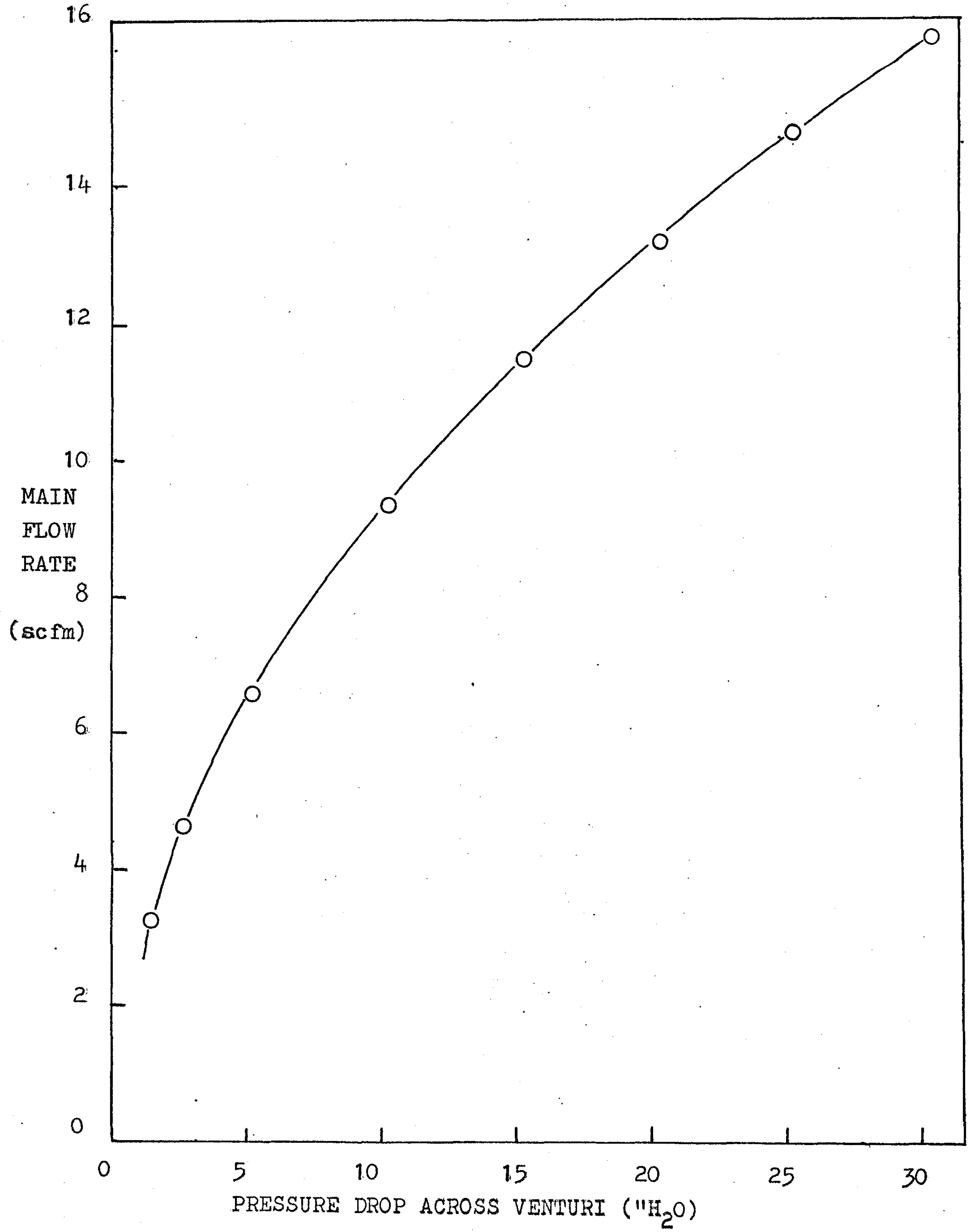

FIG. 12 VENTURI FLOW METER CALIBRATION

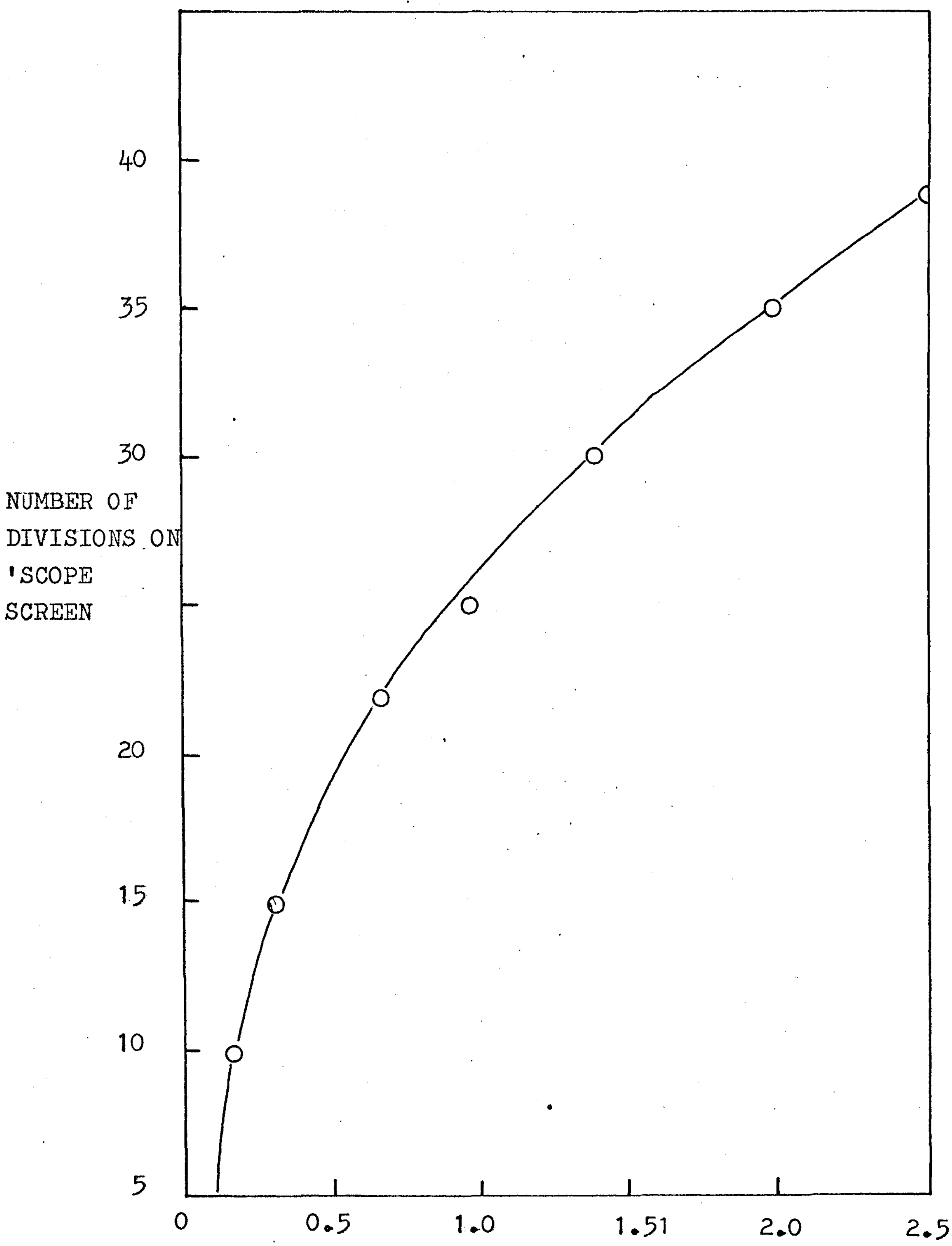

FIG. 13 CALIBRATION OF CONTROL CHANNEL HOT WIRE AGAINST ROTAMETER

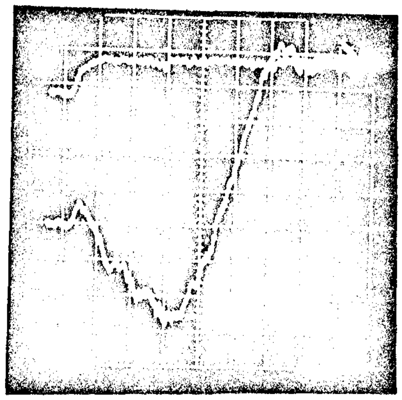

FIG. 14a CONTROL FLOW AND SWITCHING TRACE FOR SLOW SWITCHING
QC=10 DIVISIONS =0.18 scfm
t=2.7 DIVISIONS WITH TIME BASE AT 50 msecs./div.
=135 msecs.

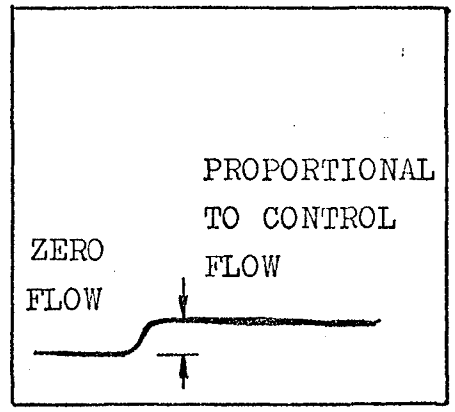

FIG. 14b CONTROL JET RECORDED BY HOT WIRE IN CONTROL CHANNEL

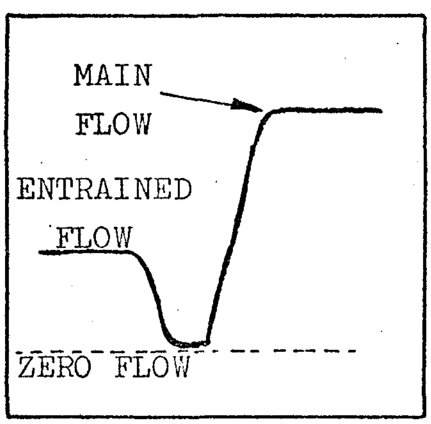

FIG. 14c MAIN JET RECORDED BY HOT WIRE IN LEFT OUTPUT LEG

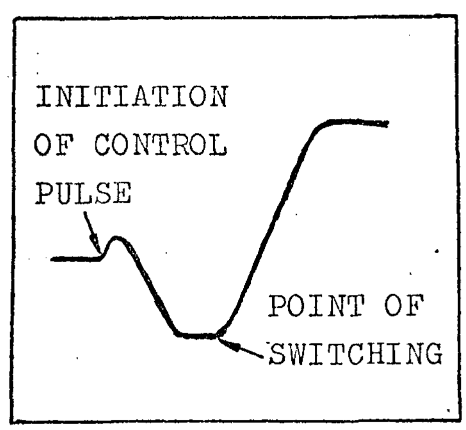

FIG. 14d EXPLANATION OF COMPLETE SWITCHING PATTERN

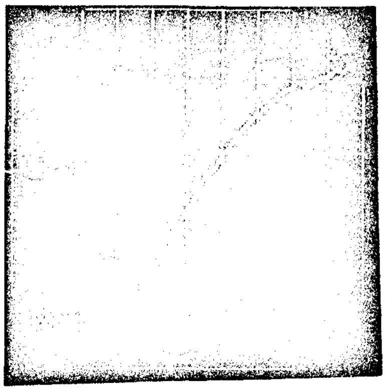

FIG. 14e RAPID SWITCHING
QC=2.9 DIVISIONS =1.29 scfm
t=1.4 DIVISIONS WITH TIME
BASE AT 10 msecs./div.
=14 msecs.

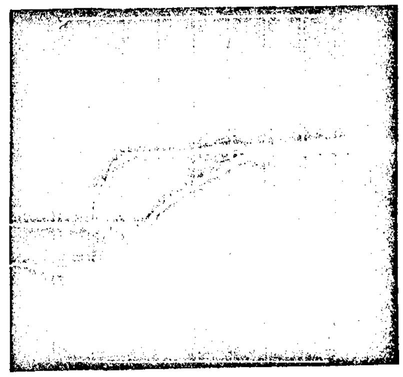

FIG. 14f SWITCHING UNDER A
BACK PRESSURE
QC=2.1 DIVISIONS =0.65 scfm
t=1.05 DIVISIONS WITH TIME
BASE AT 10 msecs./div.
=10.5 msecs.

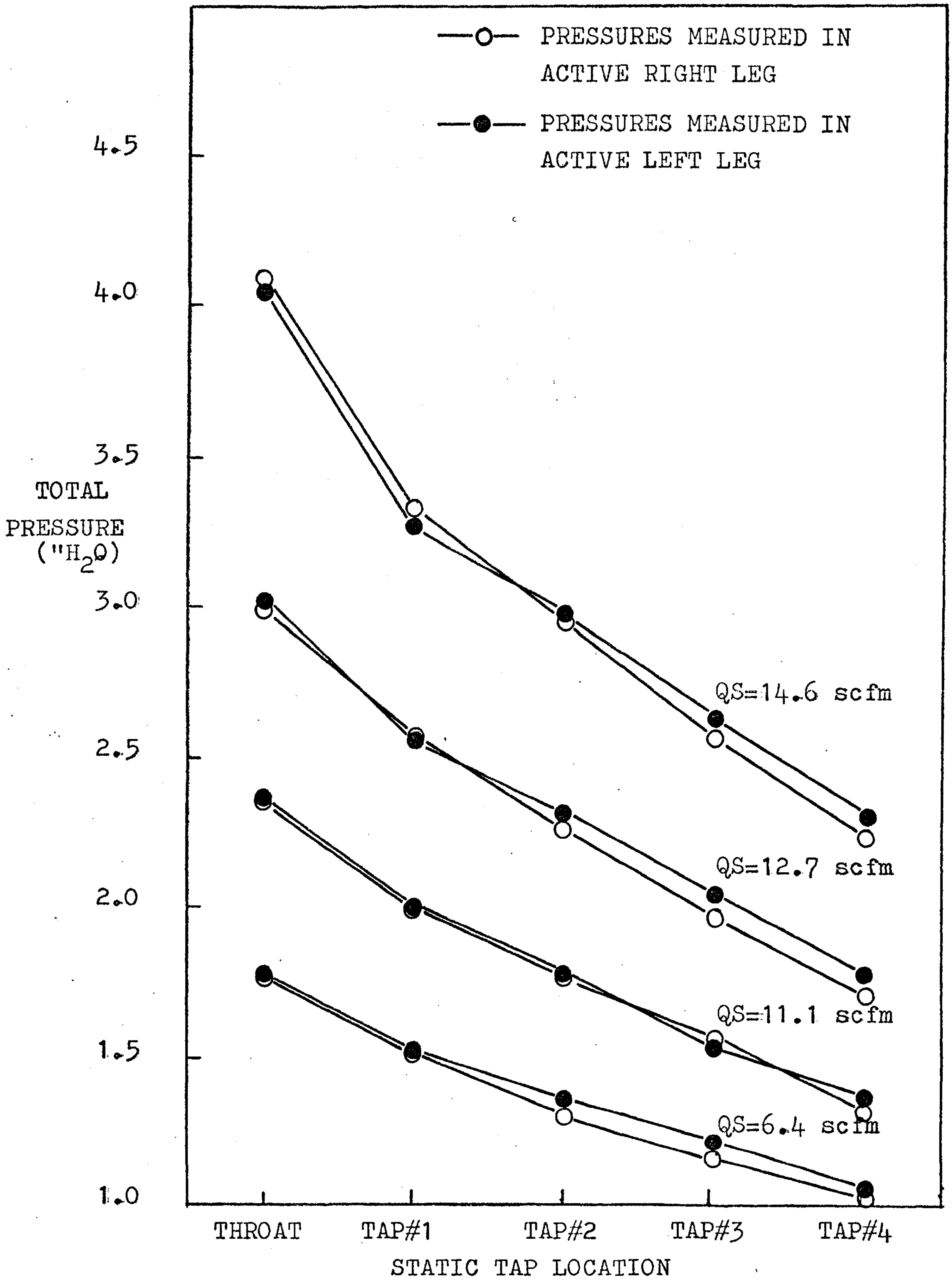

FIG.15 PRESSURES IN LEGS WHEN ACTIVE

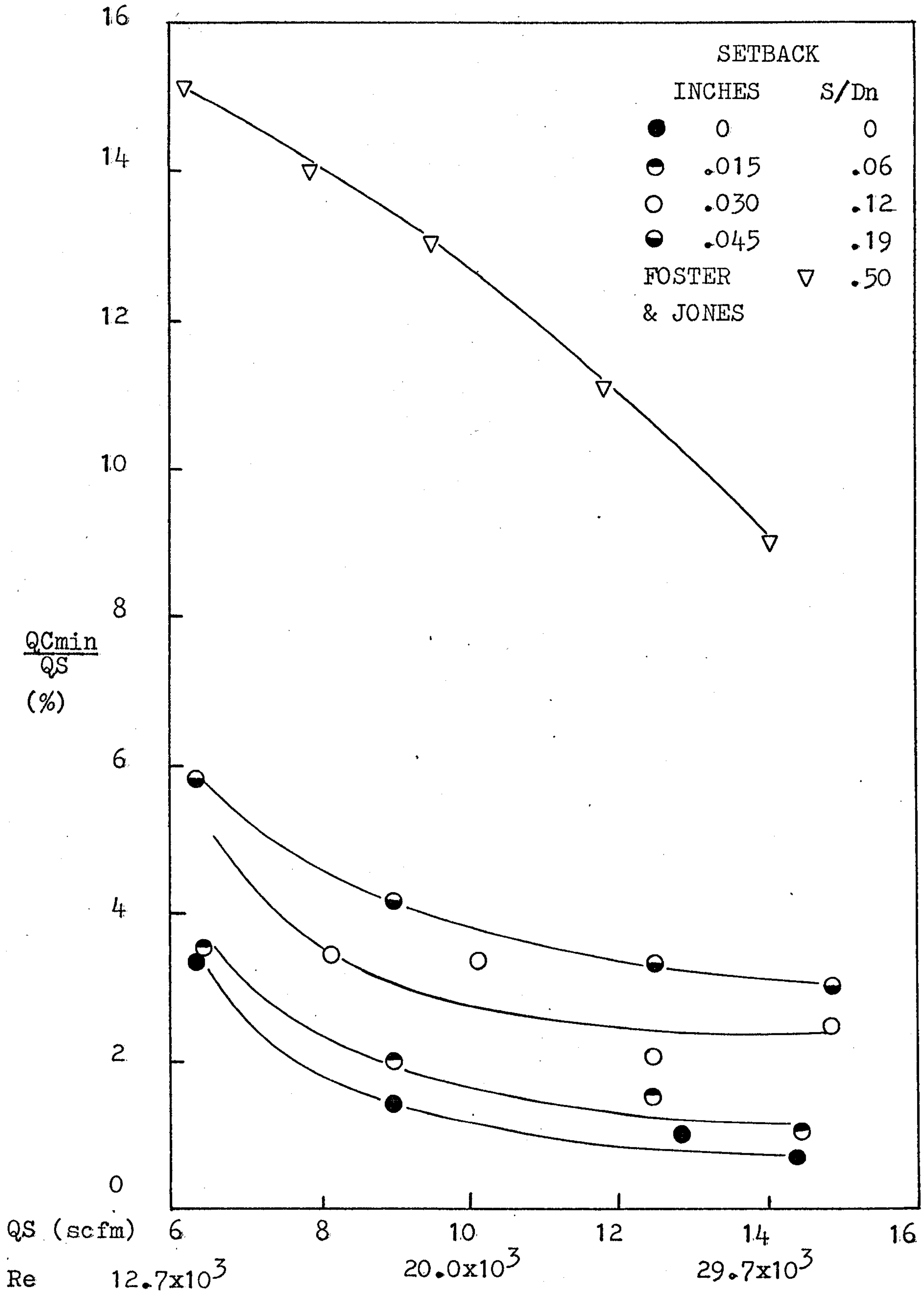

FIG.16 EFFECT OF SETBACK AND MAIN FLOW RATE ON QCmin

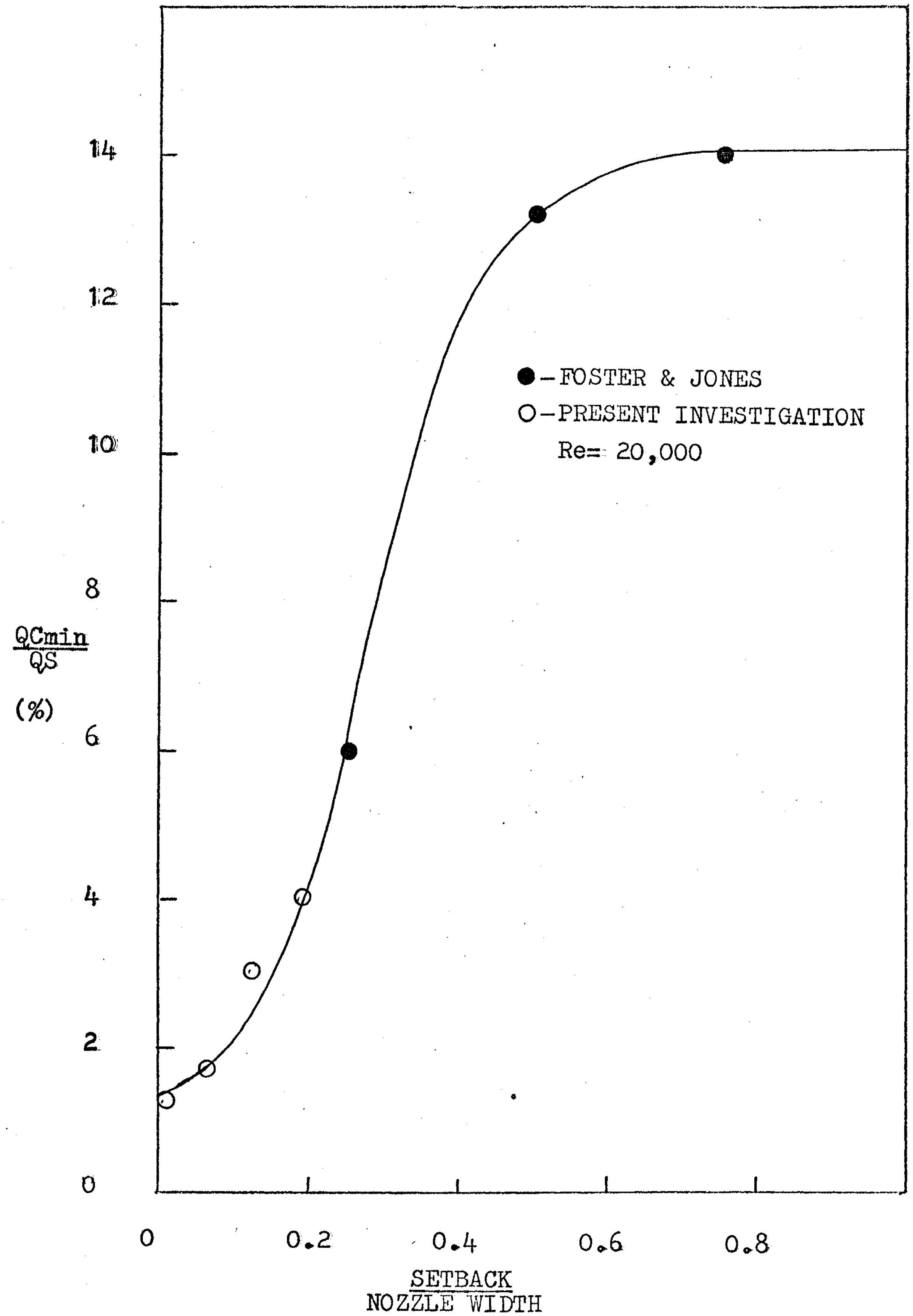

FIG.17 EXTENSION OF FOSTER AND JONES RESULTS ON EFFECT SETBACK ON QCmin

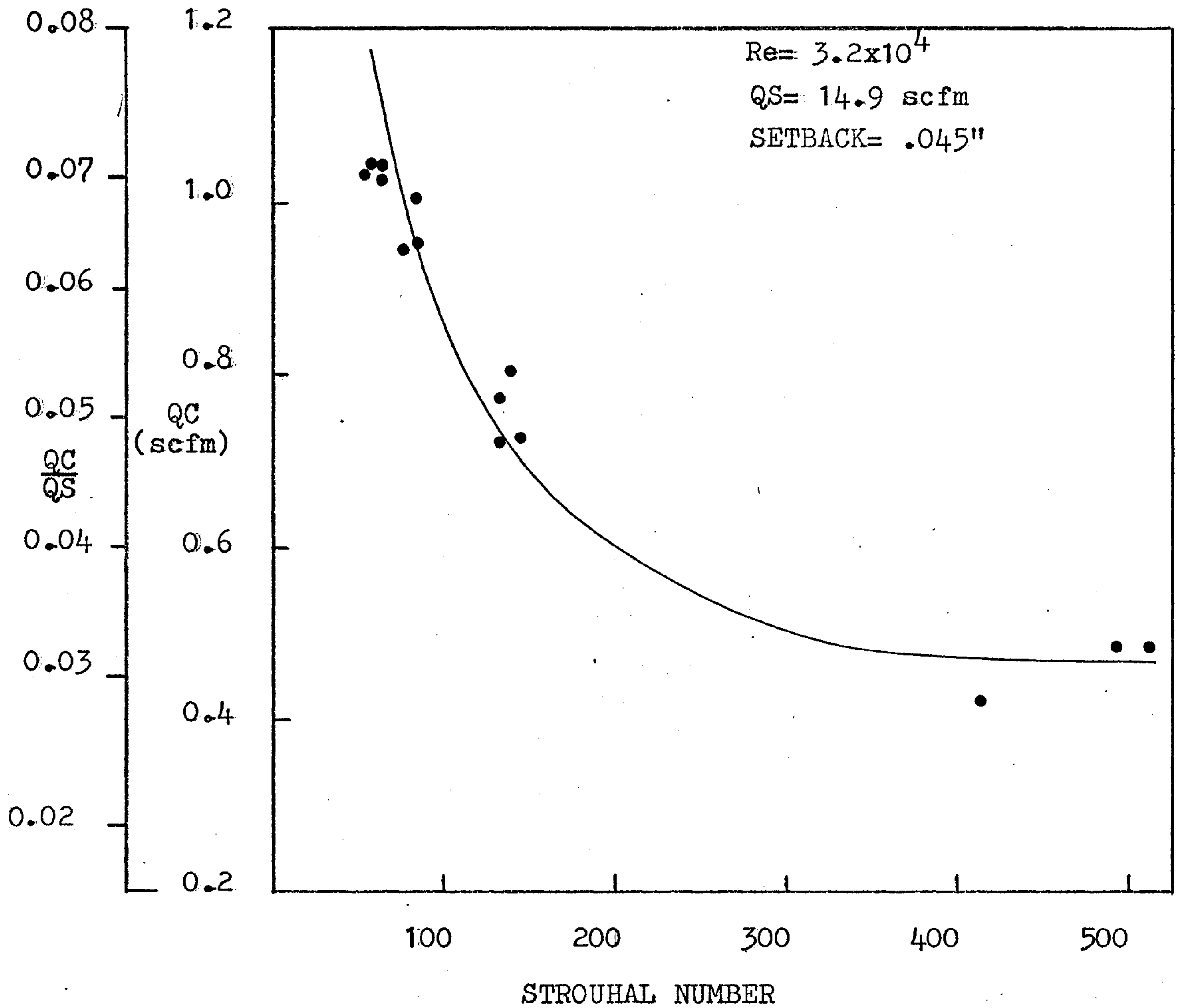

FIG. 18 EFFECT OF CONTROL FLOW ON SWITCHING TIME

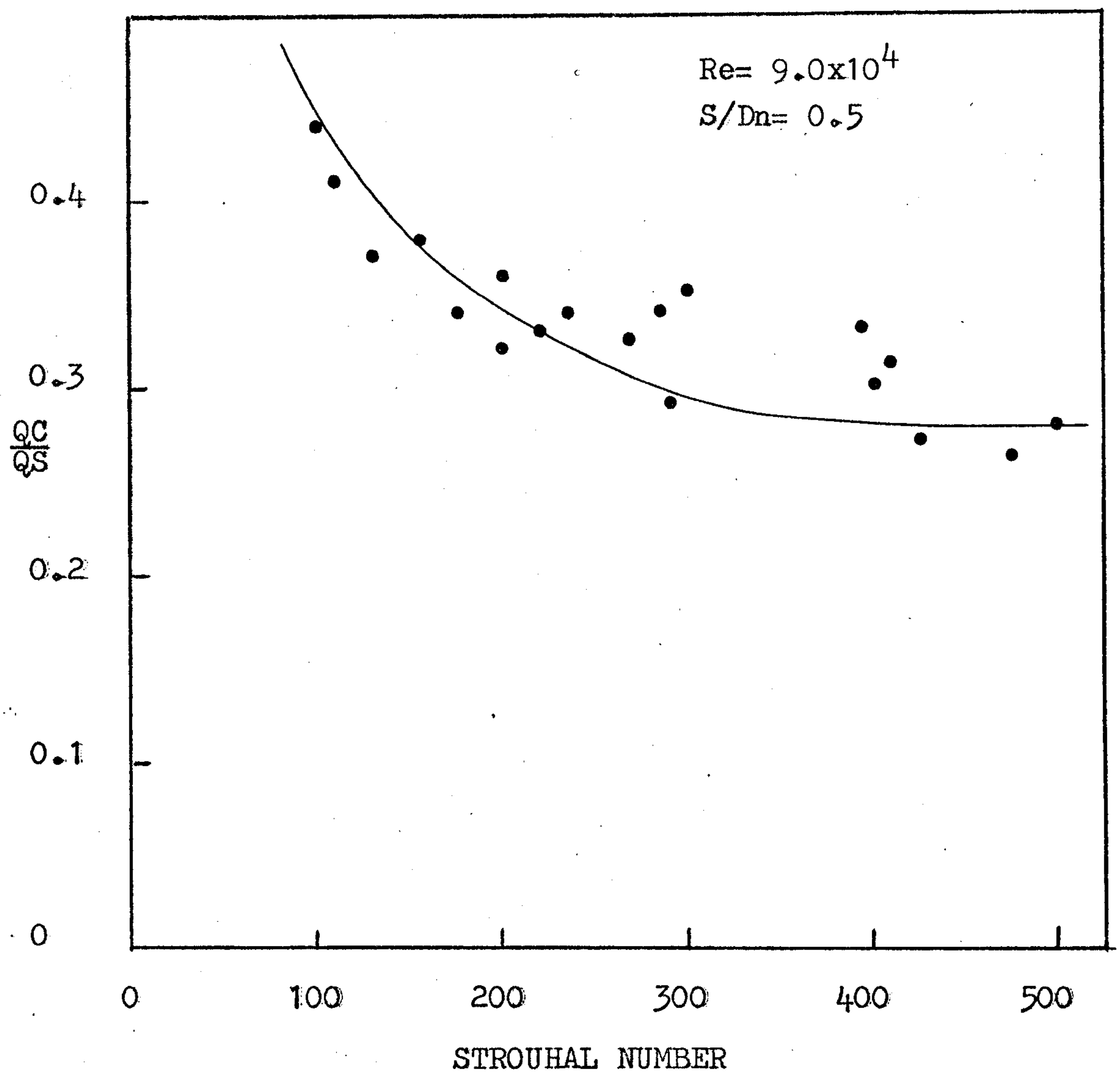

FIG. 19 LUSH'S RESULTS ON EFFECT OF CONTROL FLOW ON SWITCHING TIME

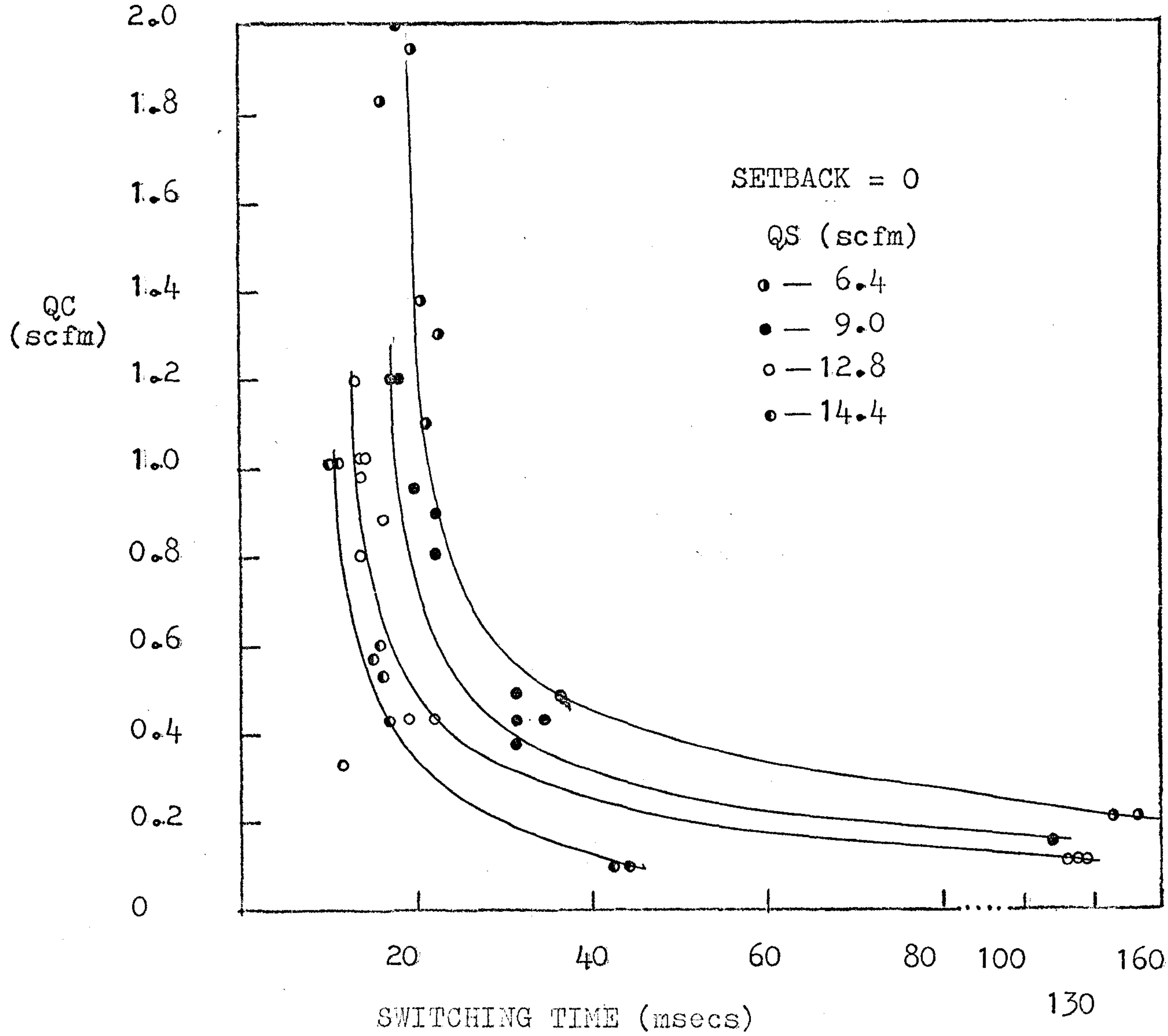

FIG.20 EFFECT OF MAIN FLOW RATE ON SWITCHING TIME

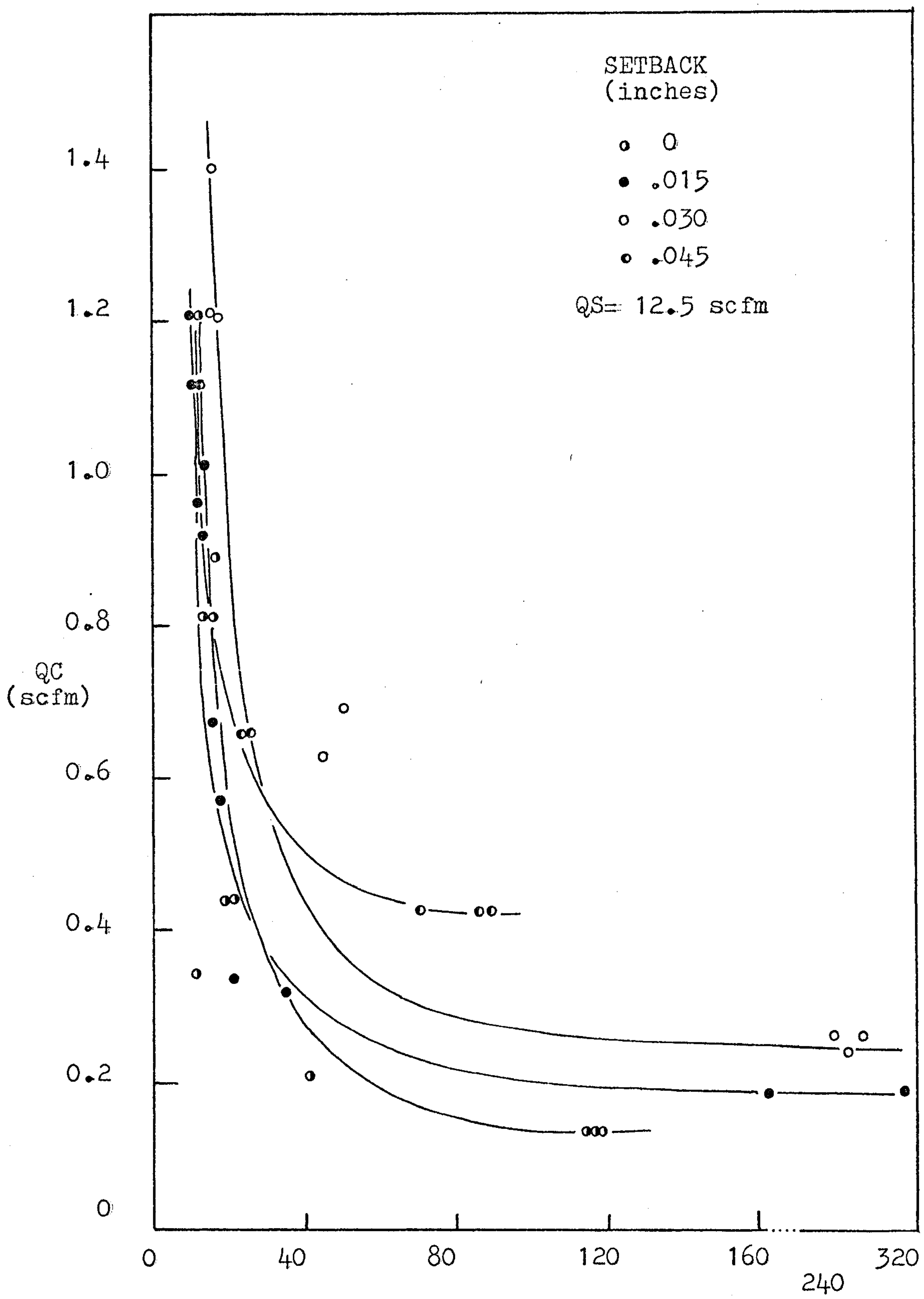

FIG.21 EFFECT OF SETBACK ON SWITCHING TIME

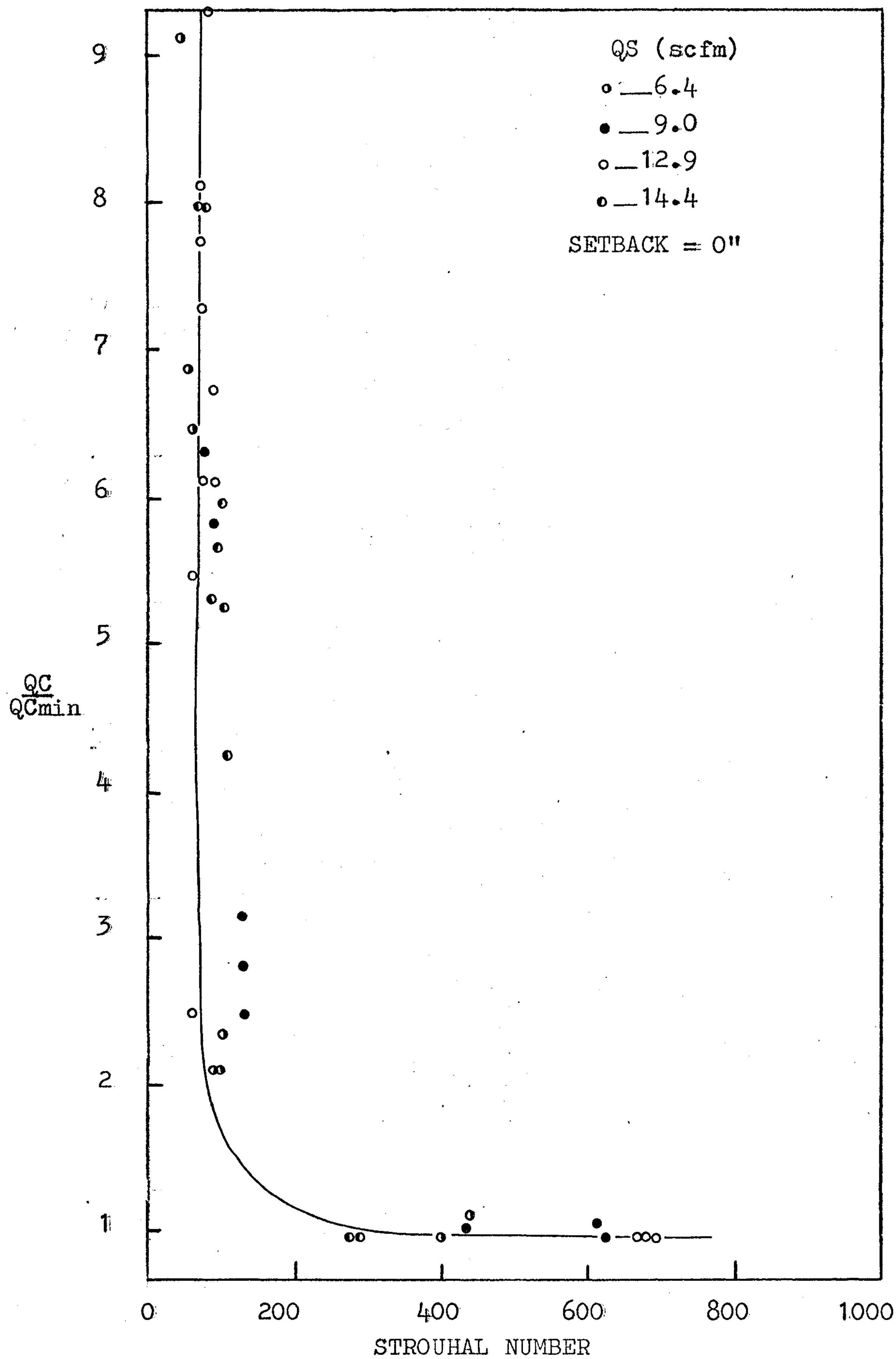

FIG.22 EFFECT OF MAIN FLOW AND CONTROL FLOW ON STROUHAL NUMBER

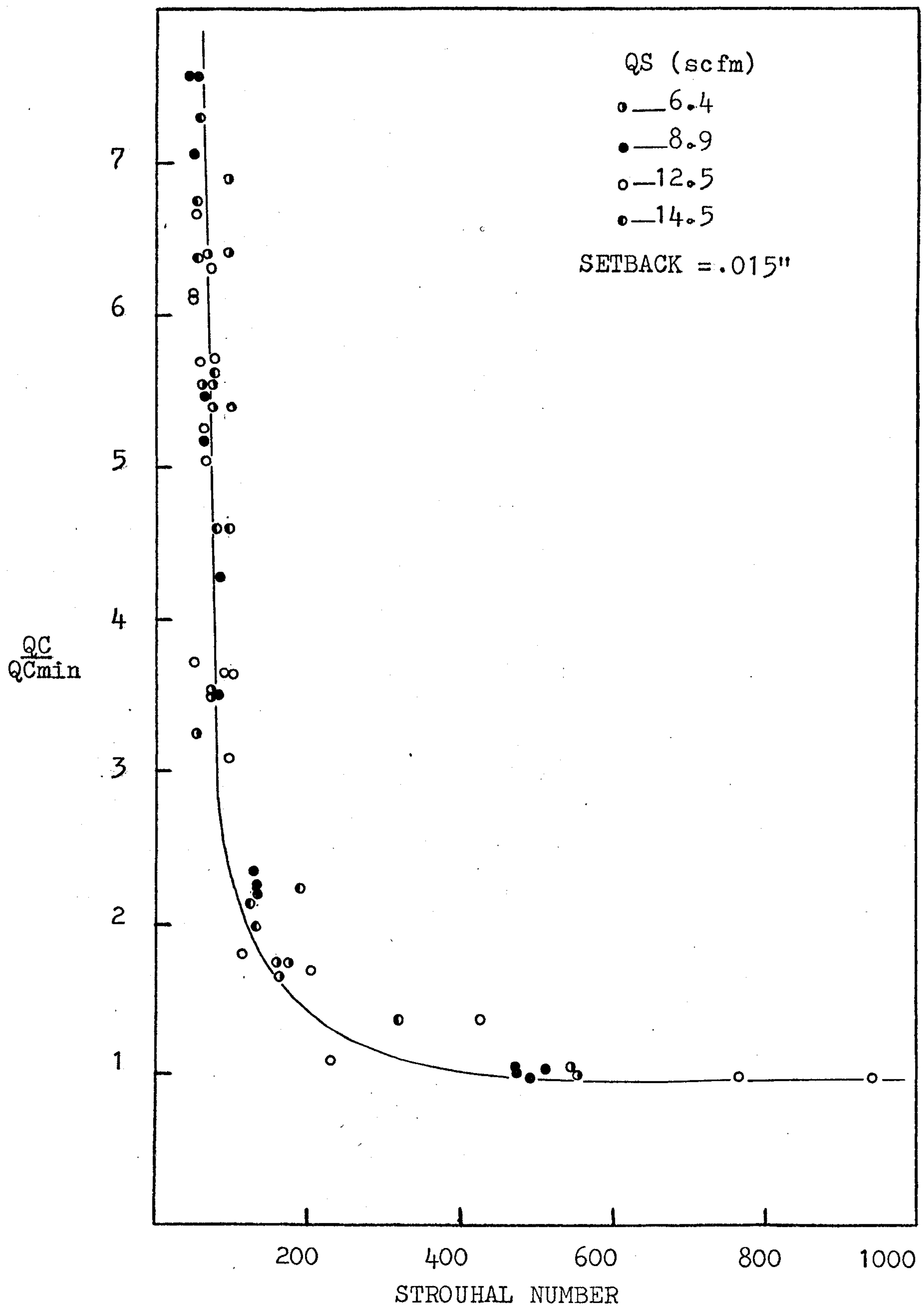

FIG.23 EFFECT OF MAIN FLOW AND CONTROL FLOW ON STROUHAL NUMBER

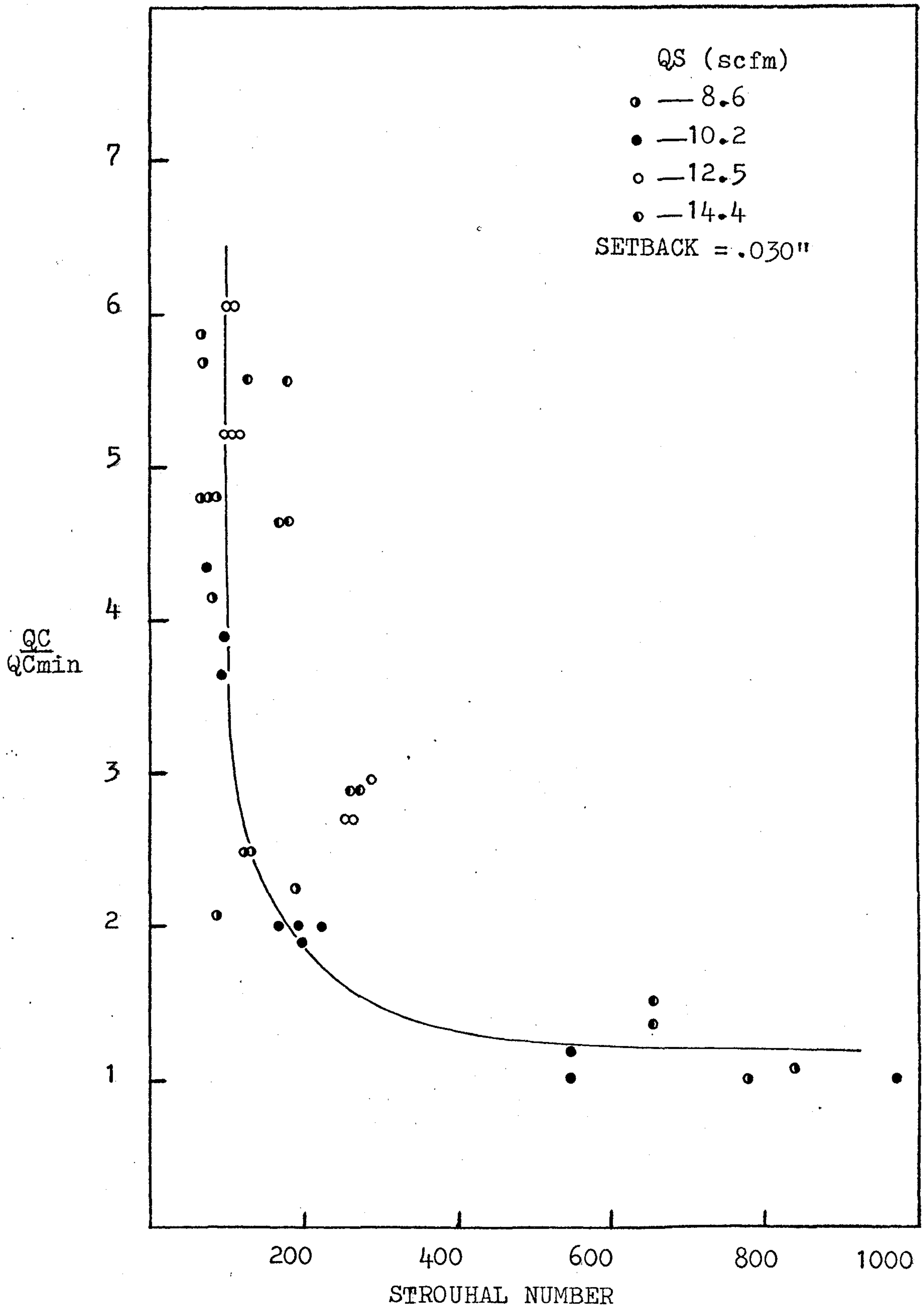

FIG. 24 EFFECT OF MAIN FLOW AND CONTROL FLOW ON STROUHAL NUMBER

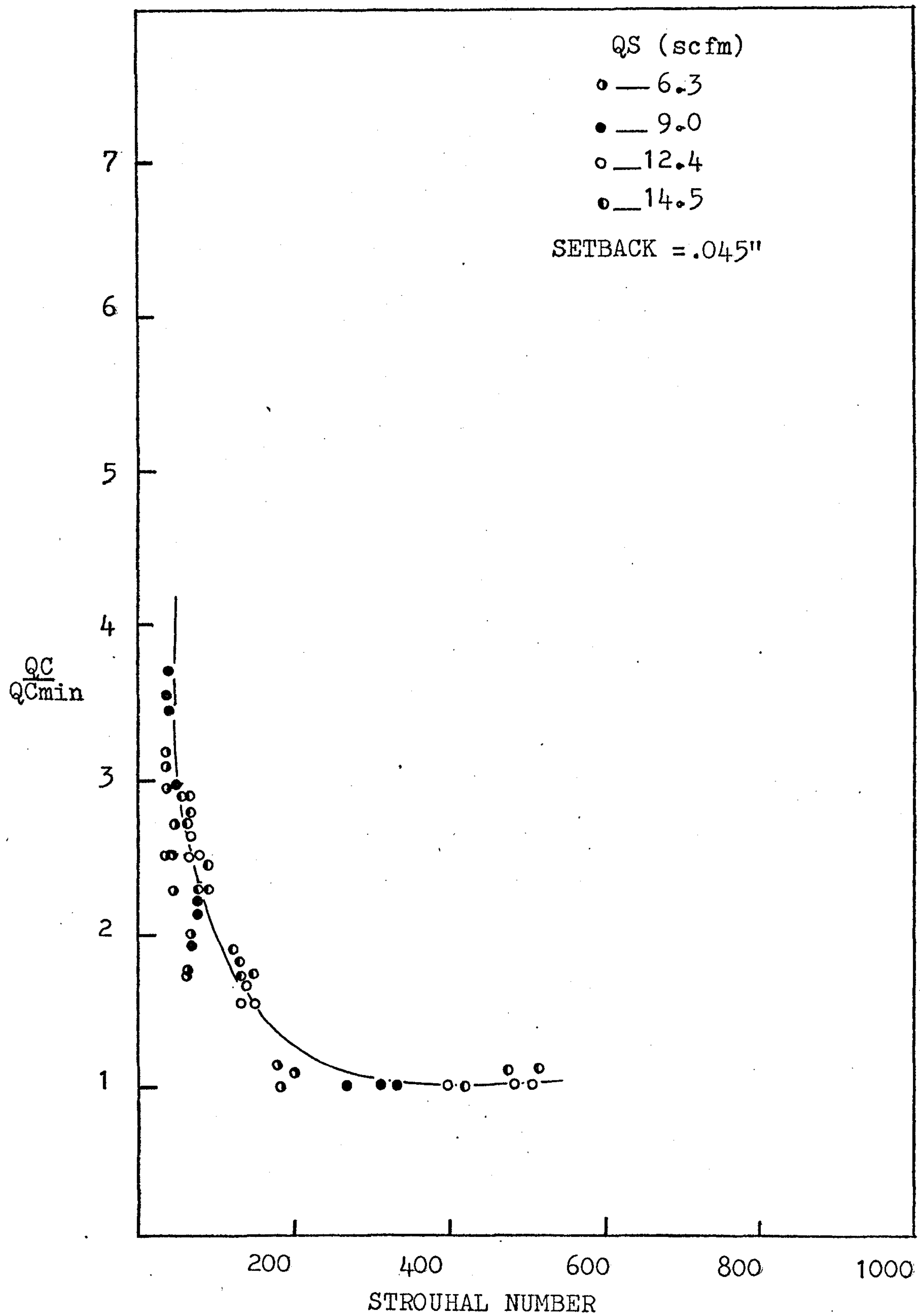

FIG.25 EFFECT OF MAIN FLOW AND CONTROL FLOW ON STROUHAL NUMBER

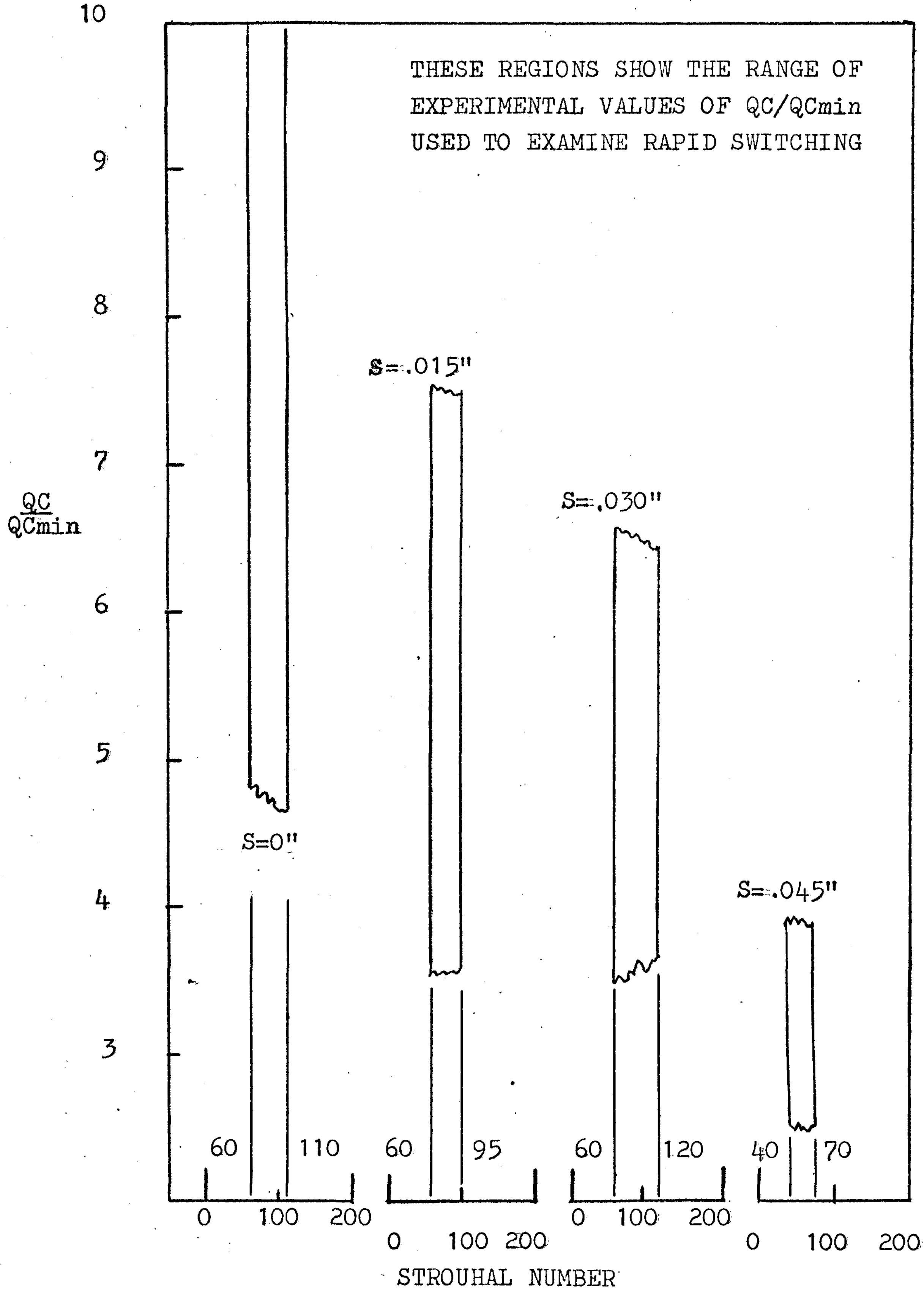

FIG.26 EFFECT OF SETBACK ON STmin AND QCmin(ST)

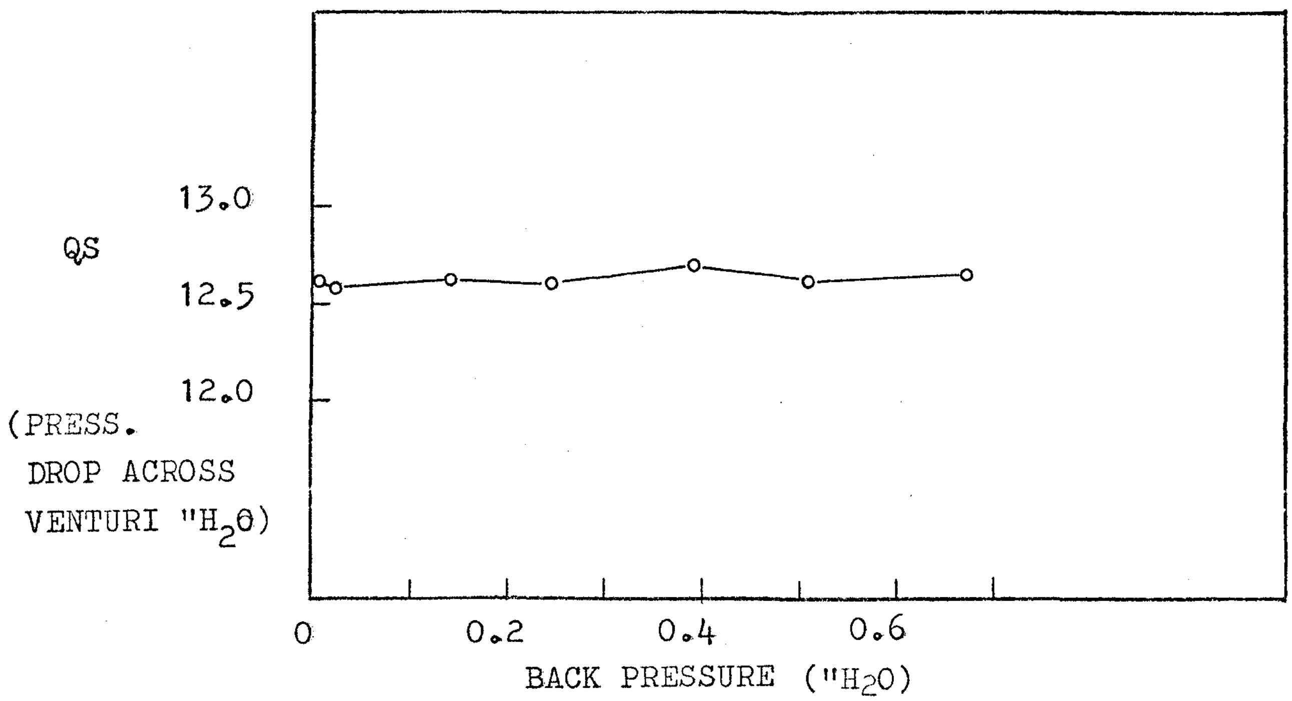

FIG.27 EFFECT OF BACK PRESSURE ON MAIN FLOW RATE

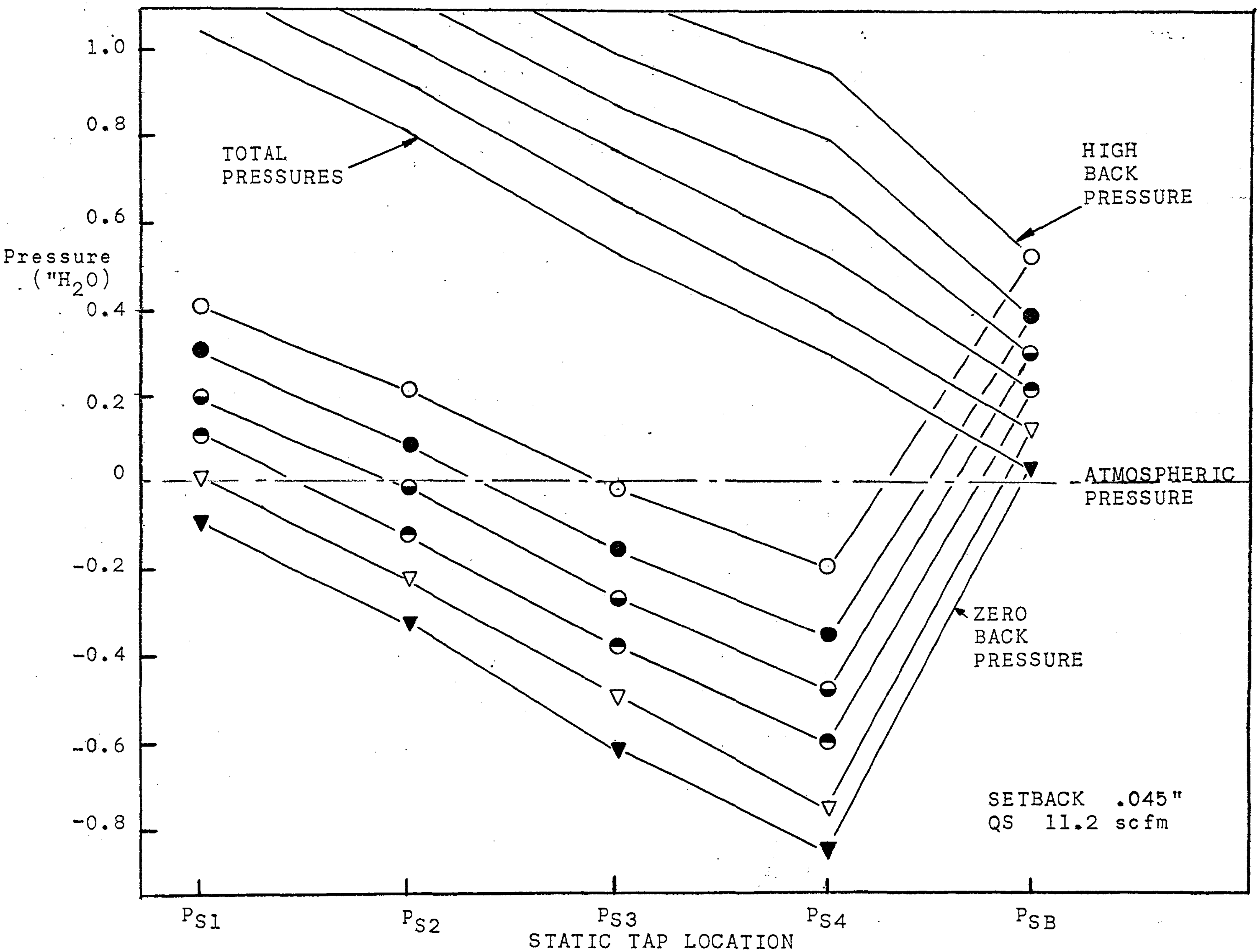

FIG.28 EFFECT OF BACK PRESSURE ON INTERNAL PRESSURES

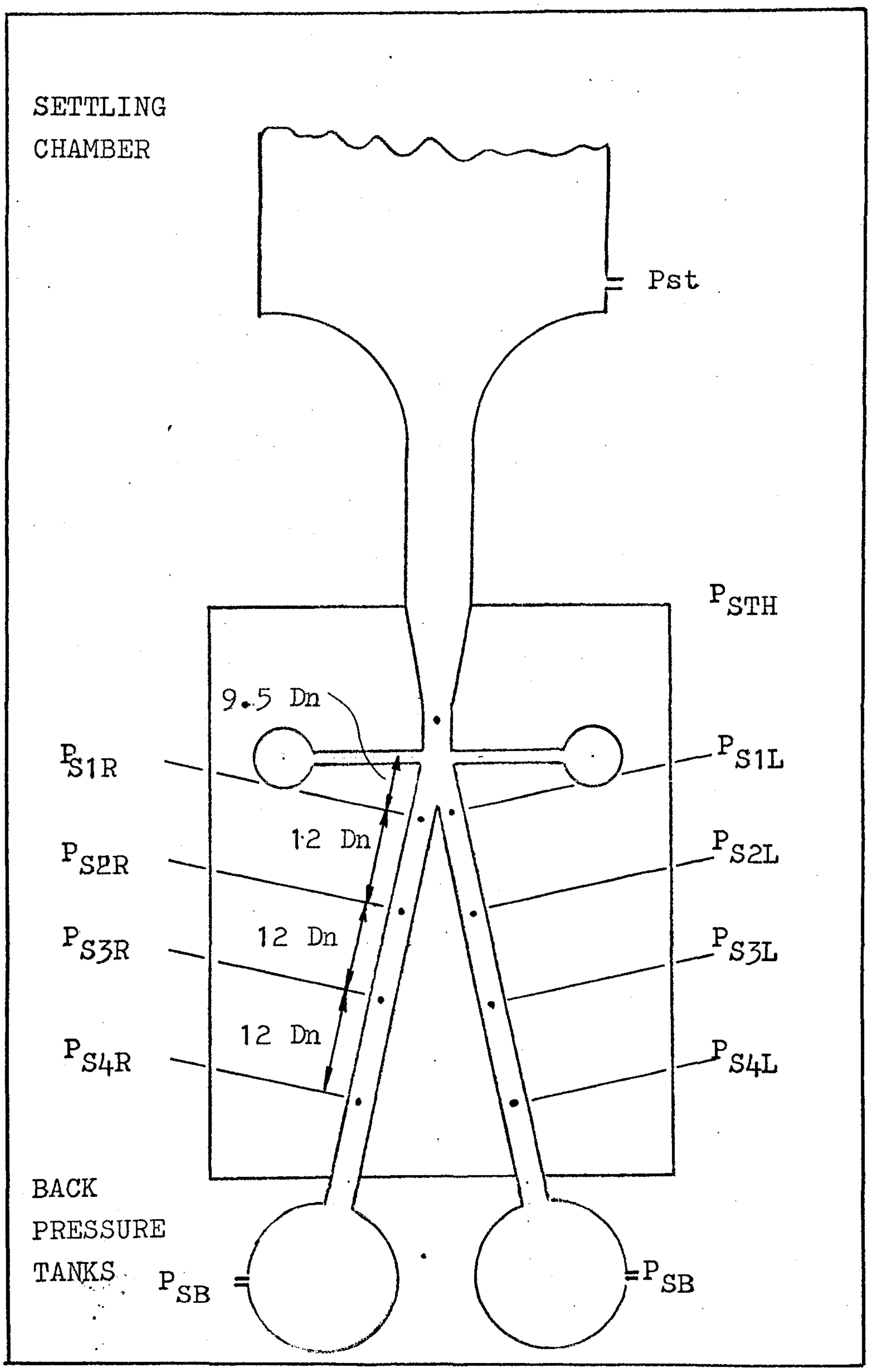

FIG.29 NOMENCLATURE FOR STATIC PRESSURE TAPS

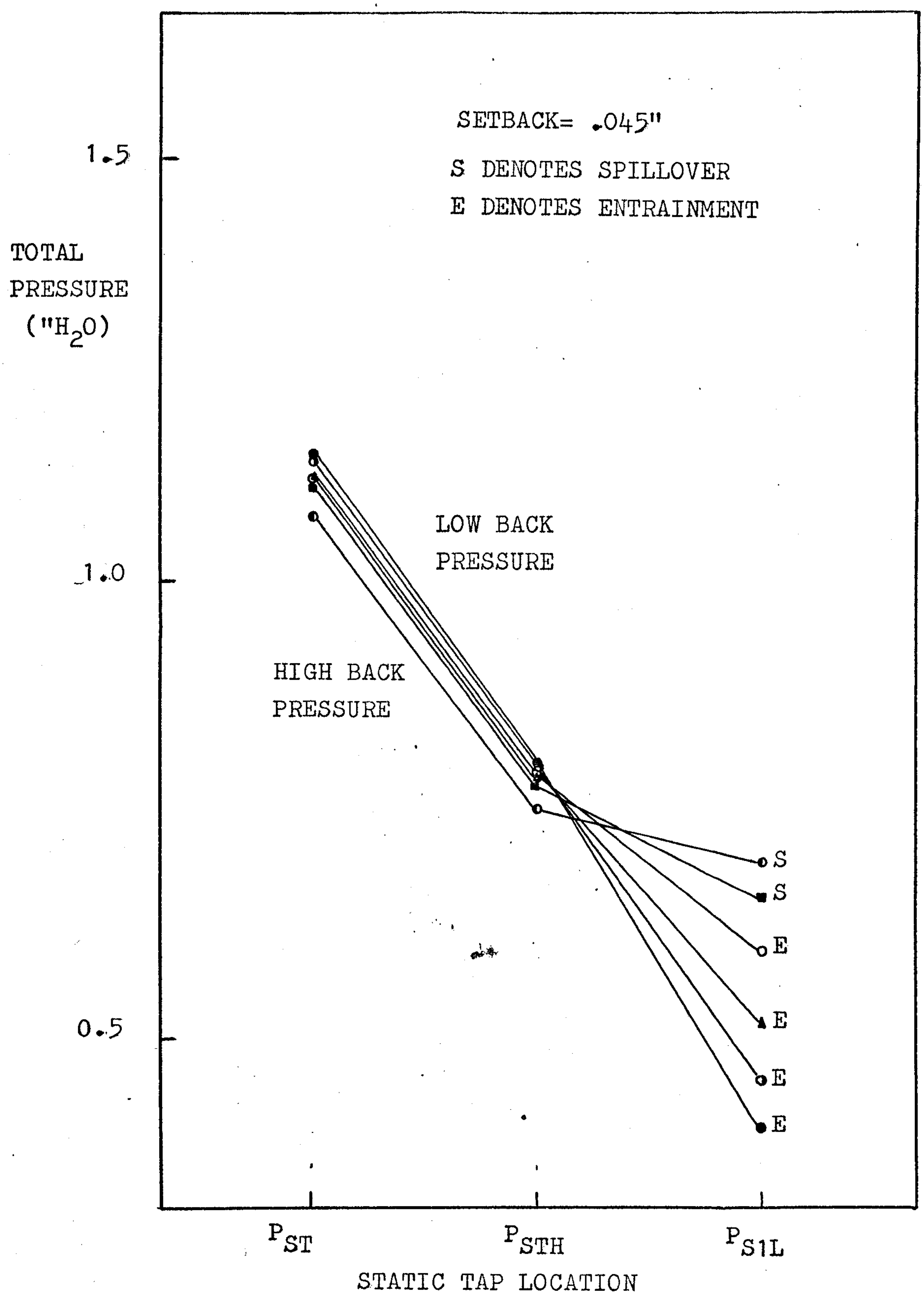

FIG.30 INTERACTION REGION PRESSURE DROPS, QS=6.4scfm

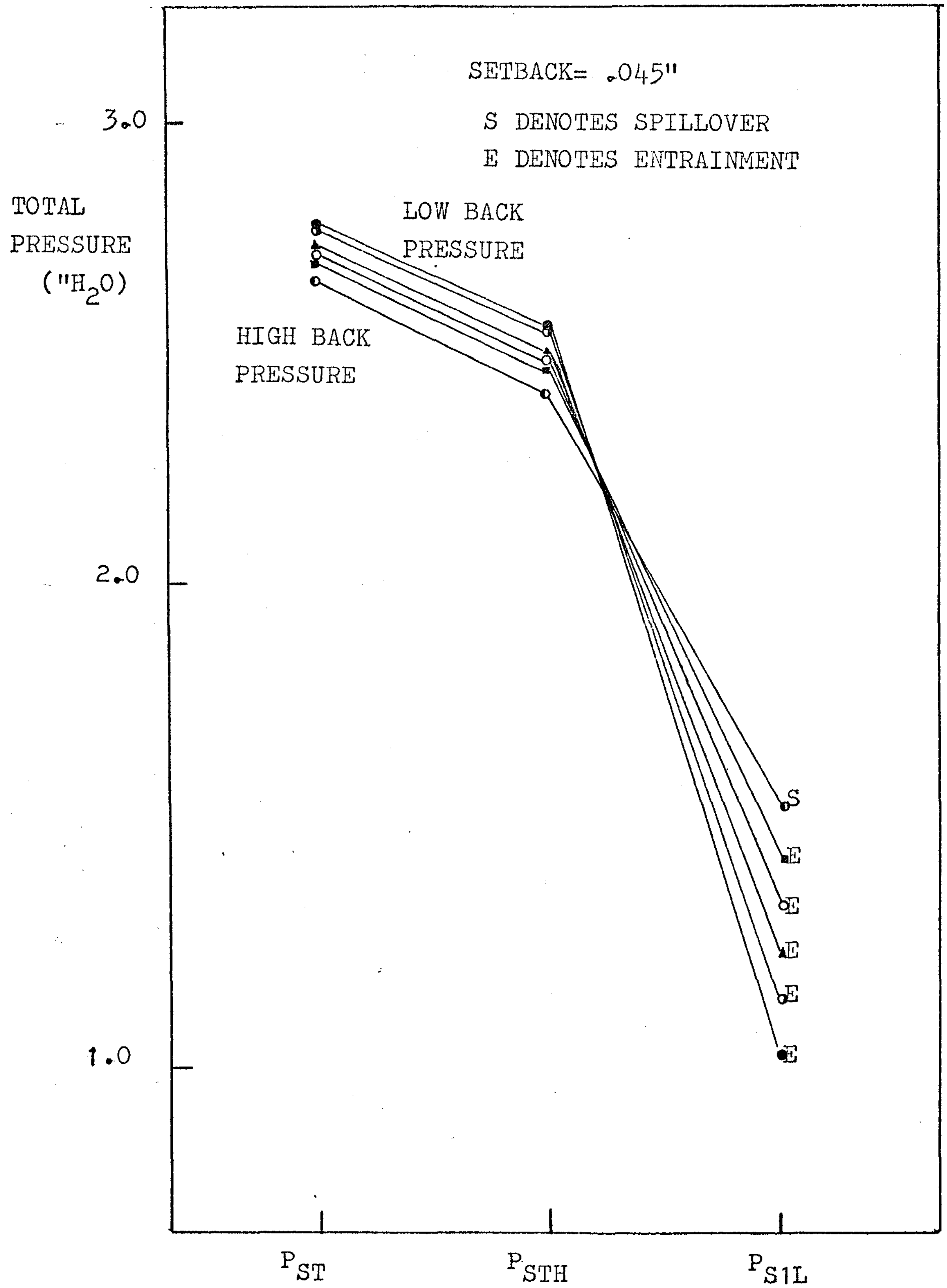

FIG.31 INTERACTION REGION PRESSURE DROPS, QS=11.2 scfm

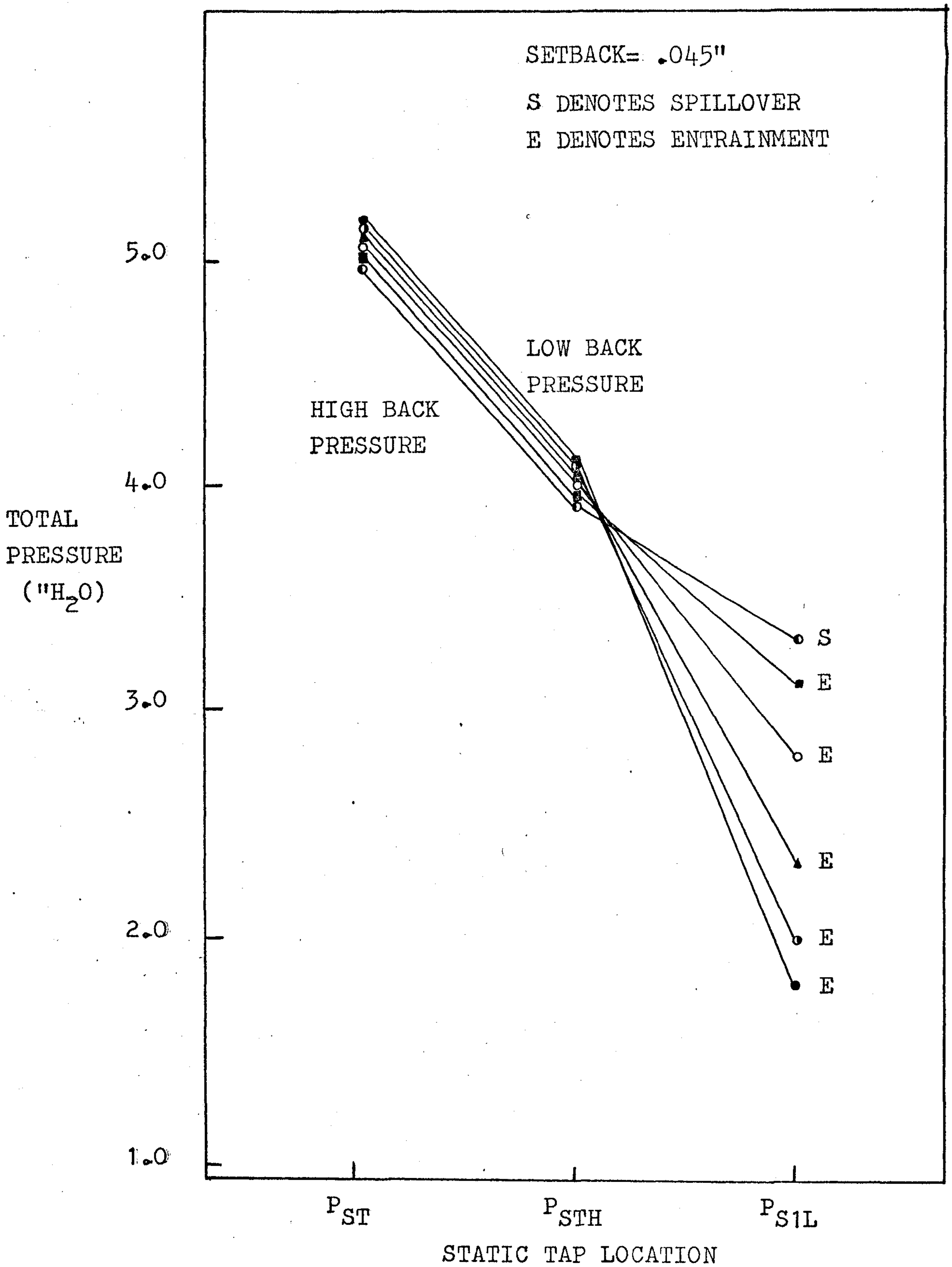

FIG. 32 INTERACTION REGION PRESSURE DROPS, QS=14.5 scfm

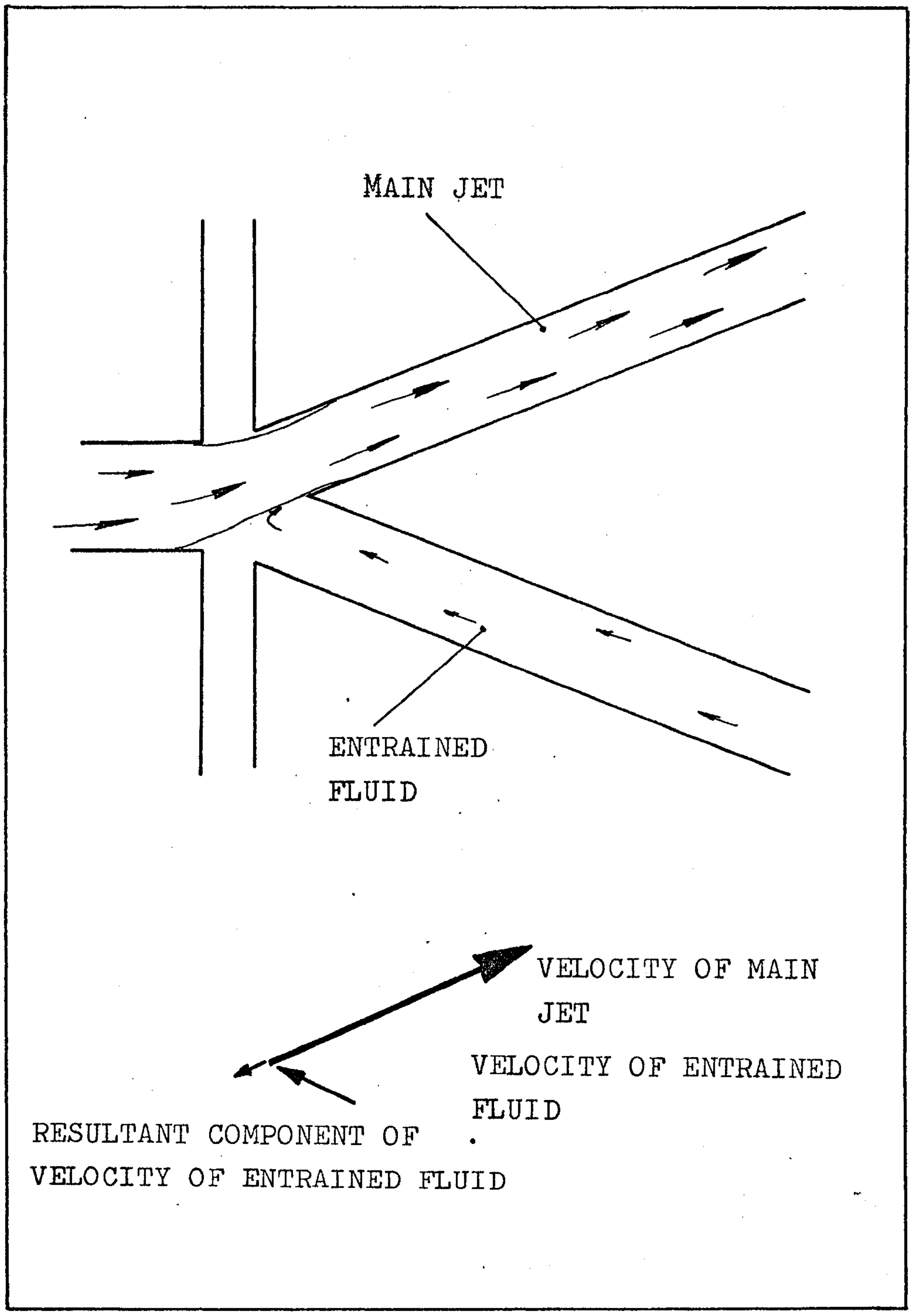

FIG.33 EFFECT OF ENTRAINED FLOW

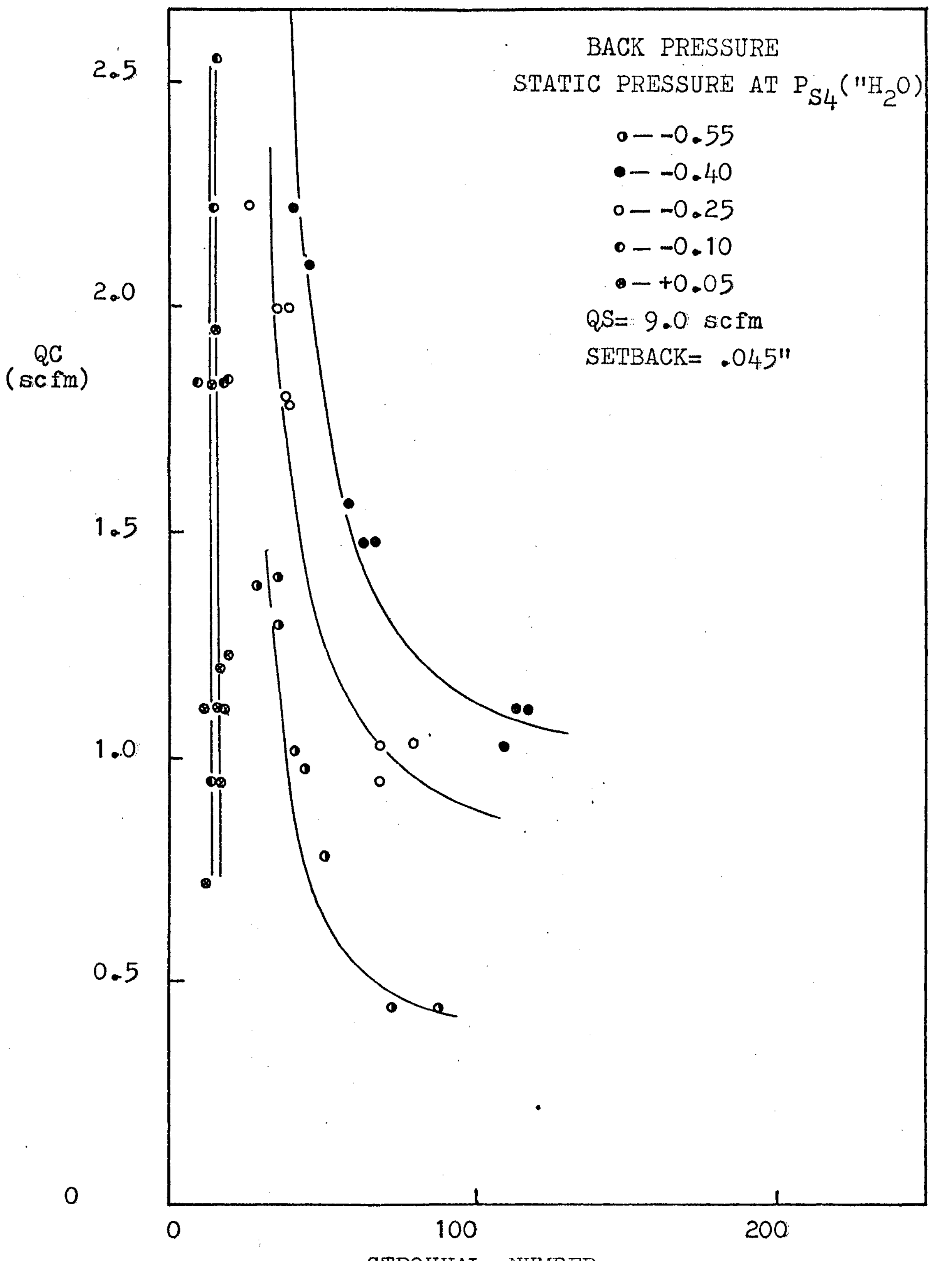

FIG.34 EFFECT OF BACK PRESSURE (MEASURED WITHOUT BACK PRESSURE TANKS) AND CONTROL FLOW ON STROUHAL NUMBER

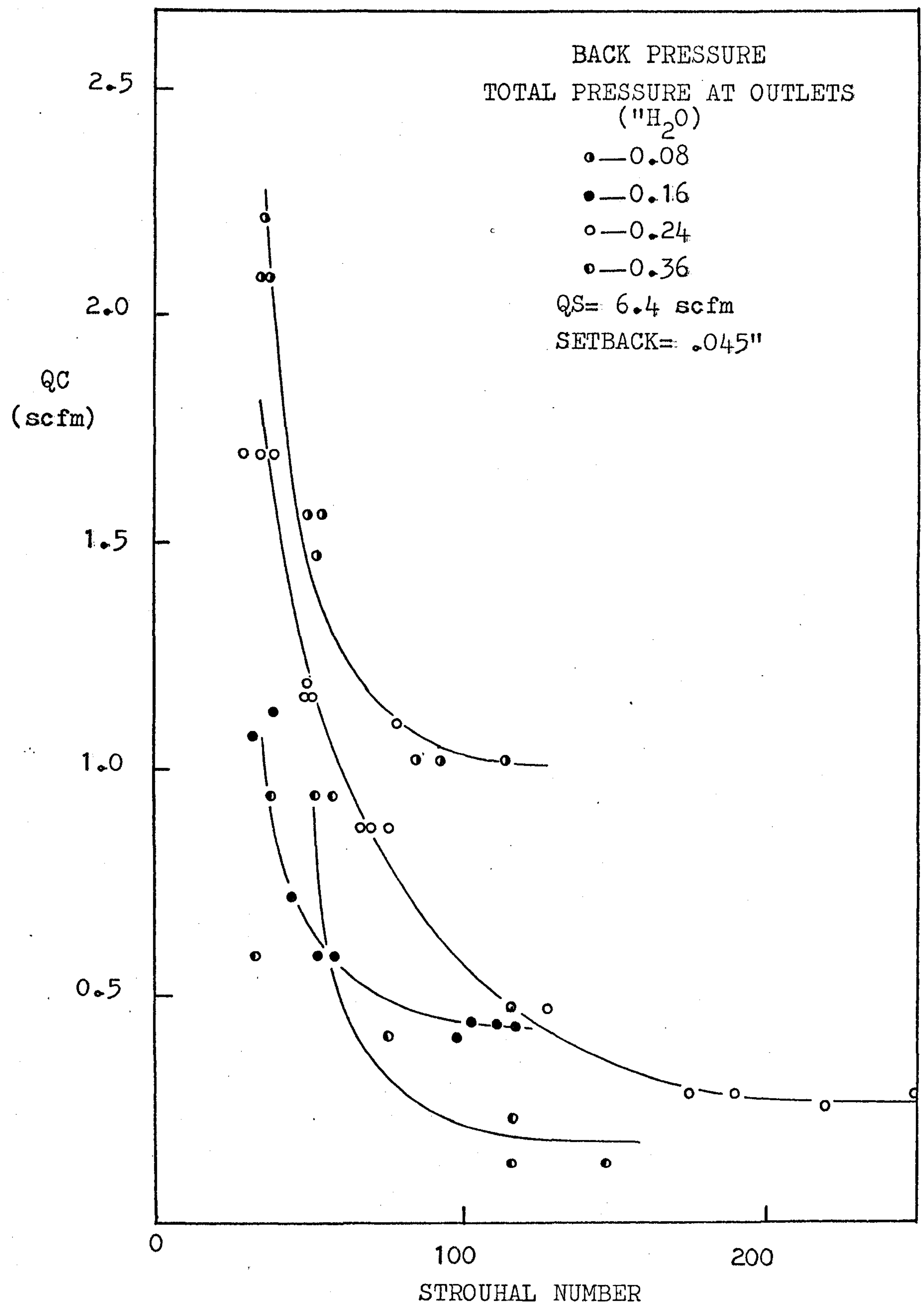

FIG.35 EFFECT OF BACK PRESSURE AND CONTROL FLOW ON STROUHAL No.

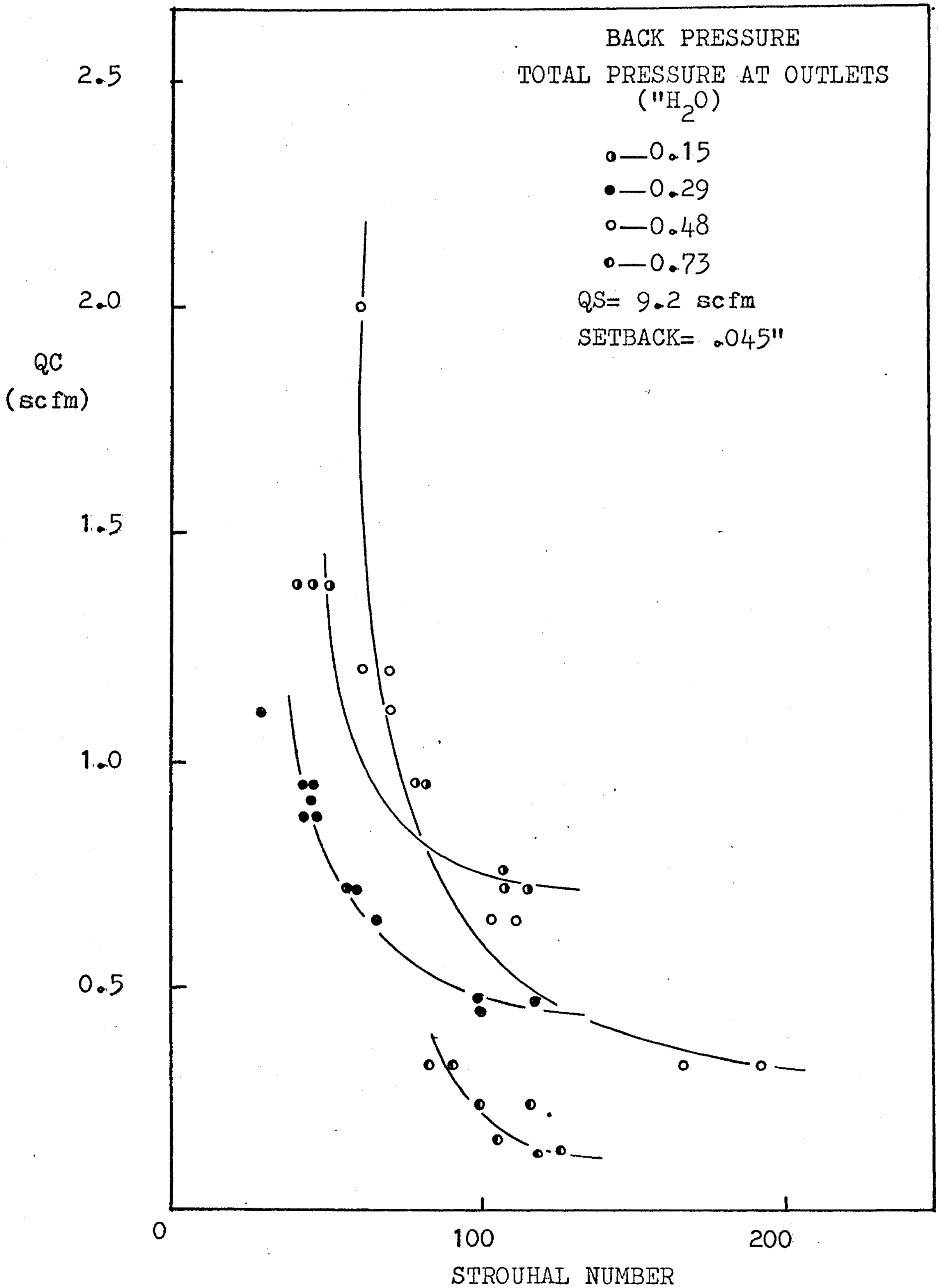

FIG.36 EFFECT OF BACK PRESSURE AND CONTROL FLOW ON STROUHAL No.

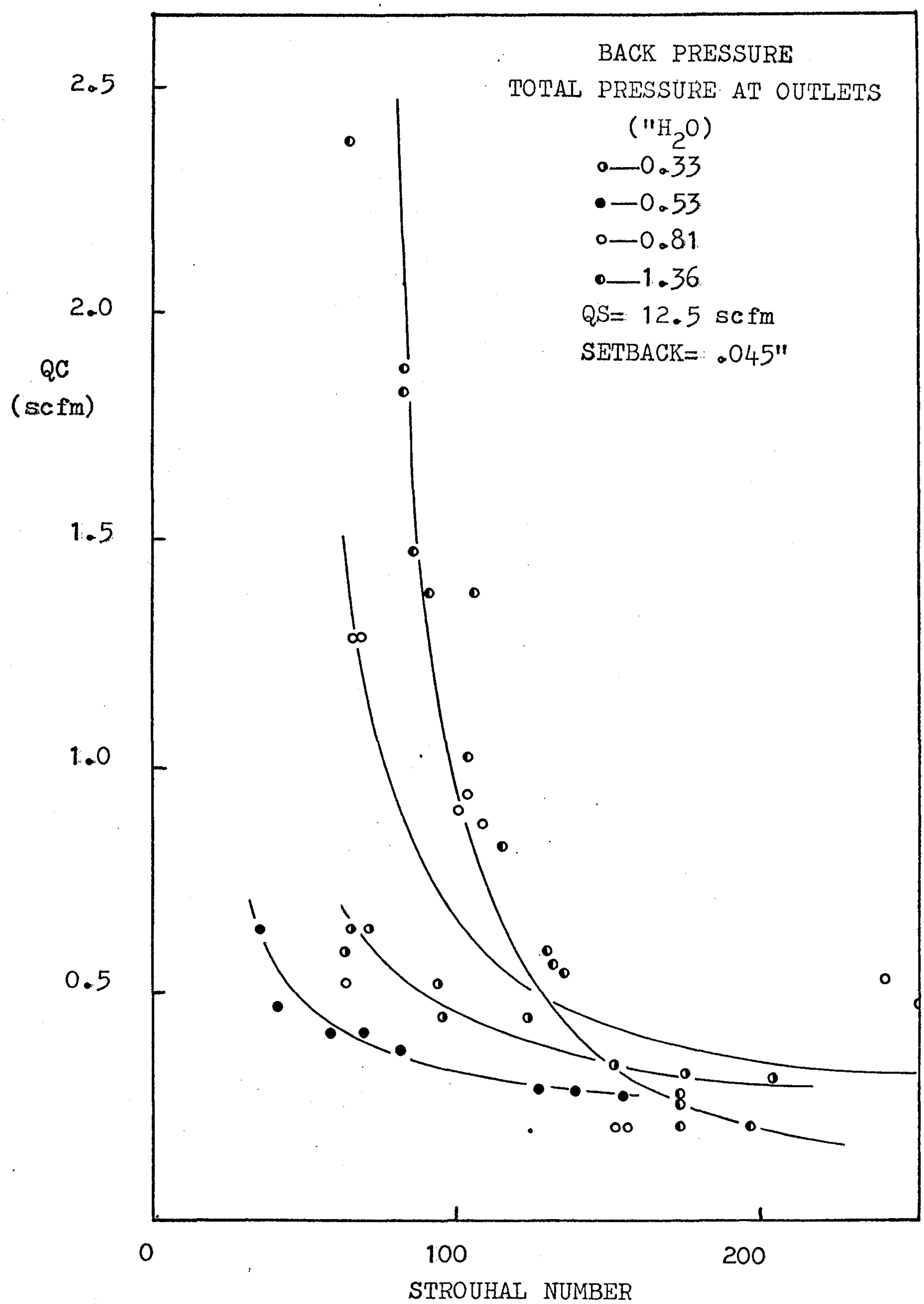

FIG.37 EFFECT OF BACK PRESSURE AND CONTROL FLOW ON STROUHAL No.

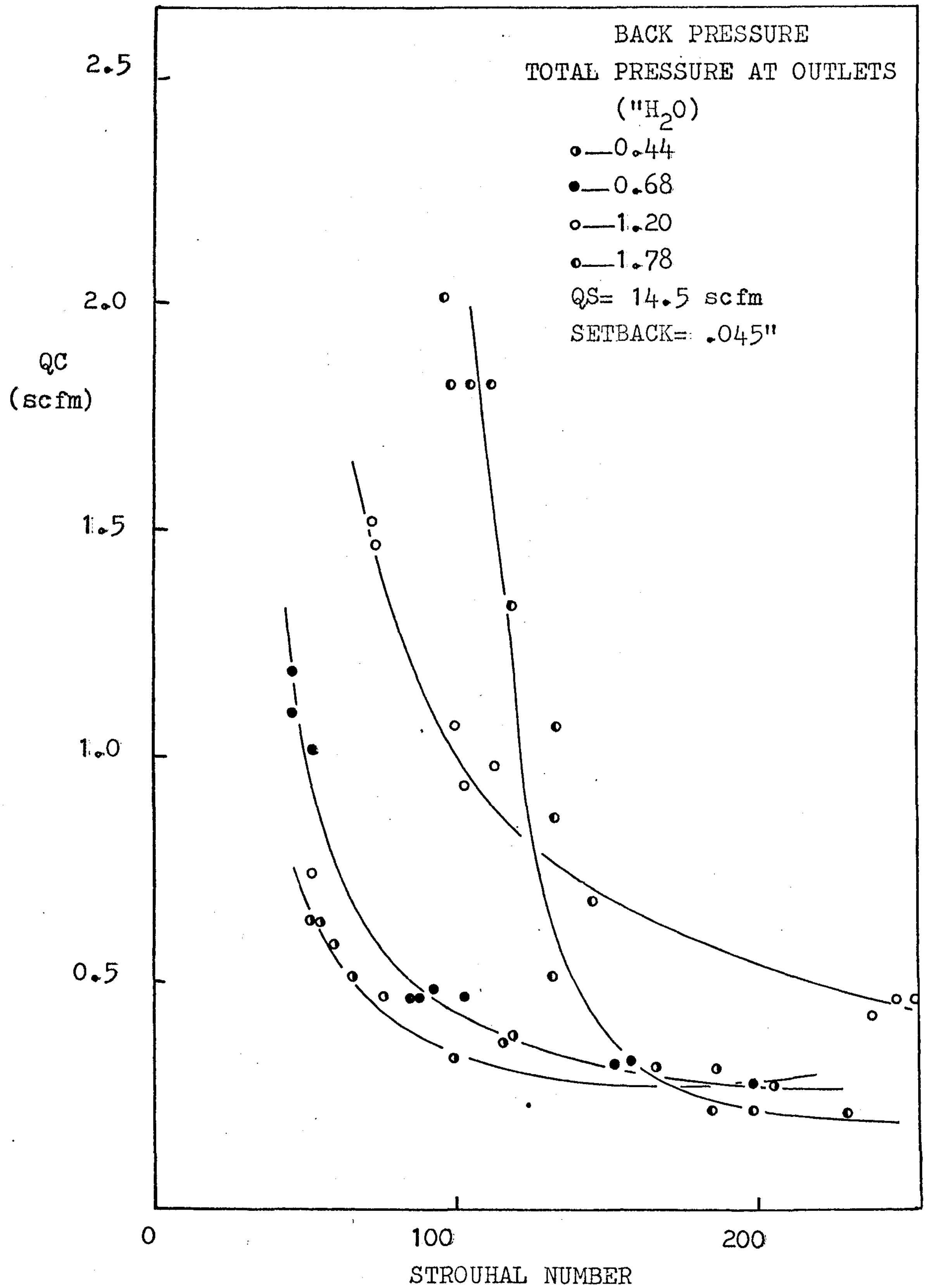

FIG.38 EFFECT OF BACK PRESSURE AND CONTROL FLOW ON STROUHAL No.

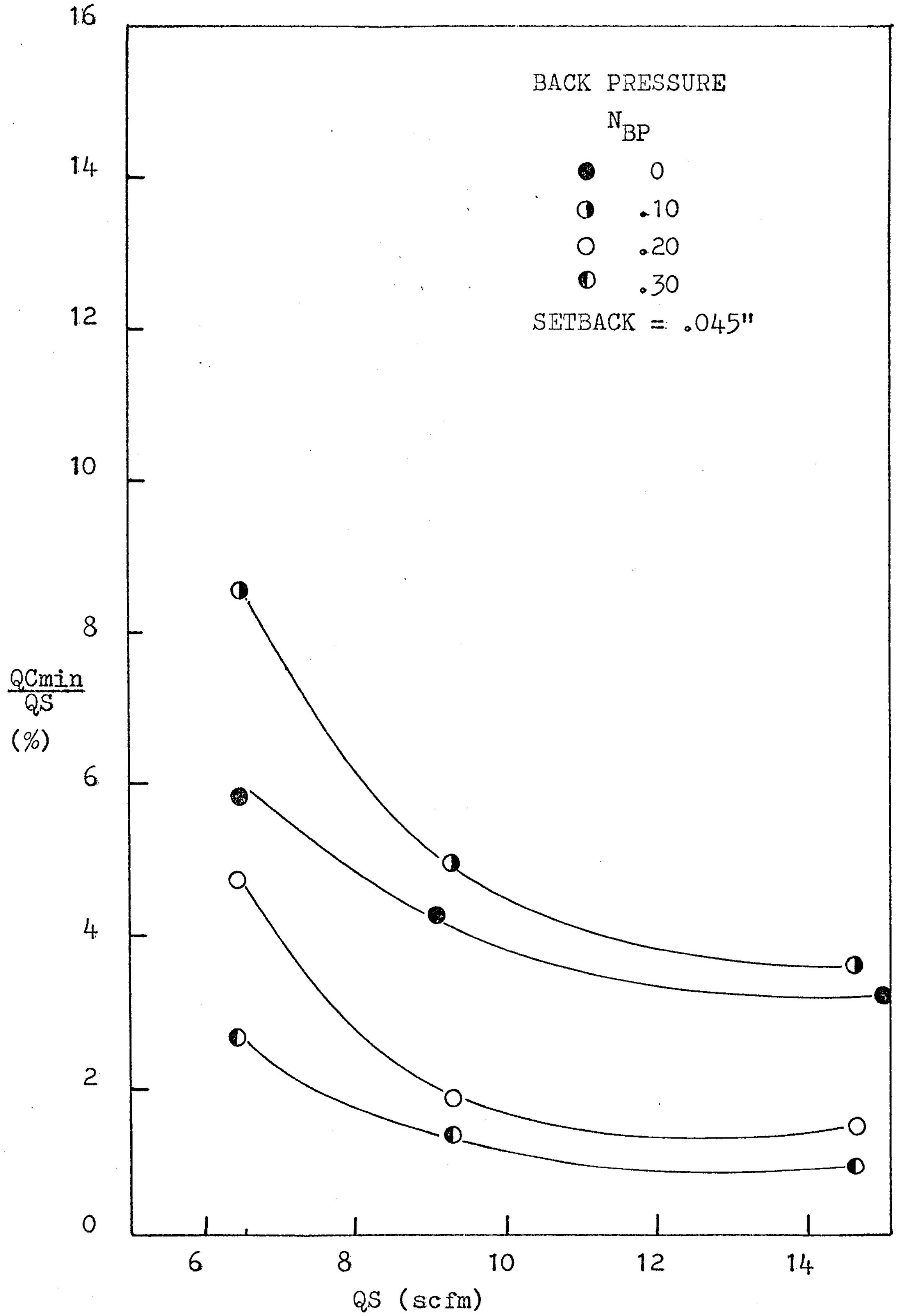

FIG.39 EFFECT OF BACK PRESSURE AND MAIN FLOW RATE ON QCmin

Plate 1 Savkar, Hansen and Kellar's Illustration of Coanda Flow

Plate 2 The Apparatus

Plate 3 Dimensions of the Bistable Amplifier

Plate 4 Overhead View of the Amplifier

APPENDIX A TABLES

TABLE 1

Pressures in Legs When Active

Setback = .030"

Manometer Reading From Venturi ("H_2O")		Flow Rate (scfm)	Re +10^3	Static Pressure ("H_2O")					
Before Test	After Test			Throat	P_{S1}	P_{S2}	P_{S3}	P_{S4}	Leg Which is Active
10.4	10.4	9.6	20.4	-0.15	+0.66	+0.51	+0.36	+0.20	Left
				-0.16	+0.66	+0.47	+0.31	+0.15	Right
13.9	13.9	11.1	23.5	-0.23	+0.82	+0.62	+0.38	+0.21	Left
				-0.24	+0.85	+0.60	+0.42	+0.17	Right
18.2	18.2	12.7	26.9	-0.27	+1.05	+0.80	+0.55	+0.27	Left
				-0.30	+1.08	+0.75	+0.47	+0.20	Right
24.1	24.2	14.6	30.9	-0.45	+1.27	+0.98	+0.65	+0.30	Left
				-0.38	+1.35	+0.93	+0.57	+0.23	Right

Flow Rate (scfm)	Re	Total Pressure ("H_2O")					
		Throat	P_{S1}	P_{S2}	P_{S3}	P_{S4}	Leg Which is Active
9.6	20.4	1.78	1.52	1.37	1.22	1.06	Left
		1.76	1.52	1.31	1.17	1.01	Right
11.1	23.5	2.36	1.97	1.77	1.53	1.36	Left
		2.36	2.00	1.75	1.58	1.32	Right
12.7	26.9	3.14	2.55	2.30	2.05	1.78	Left
		3.12	2.58	2.25	1.97	1.71	Right
14.6	30.9	4.04	3.27	2.87	2.14	2.30	Left
		4.09	3.34	2.94	2.07	2.23	Right

TABLE 2

Effect of Setback and Main Flow Rate on QC min

Setback (inches)	QC min (scfm), QS shown in Parenthesis, (scfm).			
0	.215 (6.4)	.155 (8.9)	.13 (12.5)	.10 (14.5)
.015	.205 (6.4)	.175 (8.9)	.18 (12.5)	.13 (14.5)
.030	.30 (8.6)	.38 (10.2)	.24 (12.5)	.36 (14.4)
.045	.37 (6.4)	.38 (9.0)	.42 (12.5)	.46 (14.9)

TABLE 3

Effect of Control Flow on Switching Time

S = .045"   QS = 14.9 scfm.

Re = 31 x 103

Switching Time (milliscecs)	Control Flow (scfm)	Strouhal Number
60.0	.42	411
75.0	.48	514
70.0	.48	480
19.0	.72	130
19.5	.77	133
21.0	.72	144
20.0	.80	137
12.0	.95	82
12.0	.95	82
11.0	.95	75
12.0	1.03	82
9.0	1.15	61
8.0	1.11	54
8.0	1.2	54
9.0	1.2	61

TABLE 4

Effect of Setback, Main Flow Rate and Control

Flow on Switching Time

S = 0; QS = 6.4 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
135.0	0.20	398	1.00
150.0	0.23	442	1.15
36.0	0.48	106	2.40
34.0	0.43	100	2.15
33.0	0.43	97	2.15
21.0	1.10	61	5.50
22.0	1.30	64	6.50
20.0	1.38	58	6.90
17.5	2.08	51	10.40
19.5	1.95	57	9.75
16.0	1.83	47	9.15

S = 0"; QS = 9.0 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
150.0	0.15	622	1.00
105.0	0.16	435	1.06
32.0	0.38	132	2.53
32.0	0.43	132	2.86
31.0	0.48	128	3.20
22.0	0.88	91	5.86
22.0	0.80	91	5.33
19.5	0.95	80	6.33
18.0	1.20	74	8.00
18.0	1.20	74	8.00
17.0	1.20	70	8.00

S = 0"; QS = 12.88 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
120.0	0.13	707	1.00
117.0	0.13	690	1.00
114.0	0.13	672	1.00
19.0	0.43	112	3.30
11.0	0.33	64	2.53
22.0	0.43	129	3.30
16.0	0.88	94	6.76
13.5	0.80	79	6.15
17.5	0.80	103	6.15
13.0	1.20	76	9.23
13.5	1.01	79	7.76
13.5	0.95	79	7.30
13.0	1.06	76	8.15

S = 0"; QS = 14.4 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
44.0	0.10	291	1.00
44.0	0.10	291	1.00
42.0	0.10	278	1.00
32.0	0.40	212	4.00
30.0	0.40	199	4.00
17.0	0.43	112	4.30
16.0	0.53	106	5.30
15.0	0.57	99	5.70
16.0	0.60	106	6.00
10.0	1.03	66	10.30
11.0	1.03	72	10.30

S = .015" QS = 6.4 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
215.0	0.20	634	1.00
190.0	0.20	560	1.00
187.0	0.21	551	1.05
55.0	0.35	162	1.75
60.0	0.35	176	1.75
56.0	0.33	165	1.65
20.0	0.65	58	3.25
19.0	0.65	56	3.25
27.0	0.70	79	3.50
21.0	1.11	61	5.55
27.0	1.08	79	5.40
35.0	1.08	103	5.40
26.0	1.11	76	5.55
24.0	1.28	70	6.40
33.0	1.28	97	6.40
33.0	1.38	97	6.90

S =.015"; QS = 8.9 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
120.0	0.17	492	1.00
127.0	0.18	520	1.05
117.0	0.18	479	1.05
33.0	0.38	135	2.23
34.0	0.38	139	2.23
32.0	0.40	131	2.35
21.0	0.60	861	3.52
21.5	0.60	88	3.52
21.0	0.73	86	4.29
16.0	0.88	65	5.17
16.0	0.88	65	5.17
16.5	0.93	67	5.47
13.0	1.20	53	7.05
12.0	1.29	49	7.58
14.0	1.29	57	7.58

S = 0.15"; QS = 12.5 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
165.0	0.18	950	1.00
295.0	0.18	1699	1.00
41.0	0.20	236	1.11
21.0	0.33	120	1.83
36.0	0.31	207	1.72
17.5	0.56	100	3.11
17.0	0.66	97	3.66
18.0	0.66	103	3.66
12.5	0.91	72	5.05
12.0	0.95	69	5.27
12.0	0.95	69	5.27
14.0	1.03	80	5.72
11.0	1.03	63	5.72
9.0	1.10	51	6.11
11.0	1.15	63	6.38
9.0	1.11	51	6.16
10.0	1.20	57	6.66
10.0	1.20	57	6.66

S = .015"; QS = 14.5 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
155.0	0.13	1035	1.00
195.0	0.13	1302	1.00
157.0	0.13	1049	1.00
72.0	0.18	481	1.38
64.0	0.18	427	1.38
48.0	0.18	320	1.38
28.5	0.29	190	2.23
20.0	0.26	133	2.00
19.0	0.28	126	2.15
12.5	0.60	83	4.61
15.0	0.60	100	4.61
11.5	0.73	76	5.61
8.5	0.83	56	6.38
8.5	0.88	56	6.76
9.0	0.95	60	7.30
8.7	0.83	58	6.38

S = .030"; QS = 8.6 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
250.0	0.29	990	1.00
198.0	0.29	784	1.00
212.5	0.31	842	1.06
47.5	0.65	188	2.24
22.0	0.60	87	2.06
32.0	0.72	126	2.48
33.0	0.72	130	2.48
20.5	1.39	81	4.79
18.8	1.39	74	4.79
20.6	1.20	81	4.13
18.0	1.39	71	4.79
17.5	1.65	69	5.68
17.0	1.70	67	5.86

S = .030"; QS = 10.17 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
212.0	0.38	986	1.00
118.0	0.38	549	1.00
118.0	0.45	549	1.18
48.0	0.76	223	2.00
42.5	0.72	197	1.89
41.0	0.76	190	2.00
36.0	0.76	167	2.00
20.0	1.39	93	3.65
20.0	1.39	93	3.65
21.0	1.48	97	3.89
16.3	1.65	75	4.34

S = .030"; QS = 12.54 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
268.0	0.26	1543	1.13
249.0	0.23	1434	1.00
227.0	0.26	1307	1.13
50.0	0.68	288	2.95
46.0	0.62	264	2.69
45.0	0.62	259	2.69
20.0	1.20	115	5.21
21.3	1.20	122	5.21
20.0	1.20	115	5.21
18.0	1.20	103	5.21
18.0	1.39	103	6.04
18.8	1.39	108	6.04

S = .030"; QS = 14.4 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
100.0	0.33	663	1.00
100.0	0.38	663	1.15
100.0	0.38	663	1.15
40.0	0.72	265	2.18
41.0	0.72	272	2.18
41.0	0.72	272	2.18
27.5	1.16	182	3.51
27.0	1.16	179	3.51
20.0	1.39	132	4.21
27.5	1.39	182	4.21

S = .045"; QS = 6.4 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
70.0	0.38	203	1.08
62.0	0.40	179	1.14
63.0	0.35	182	1.00
22.0	0.62	63	1.77
22.0	0.60	63	1.71
23.0	0.70	66	2.00
15.0	0.80	43	2.28
16.0	0.88	46	2.51
13.5	0.88	39	2.51
16.0	0.95	46	2.71
13.0	1.03	37	2.94
13.0	1.11	37	3.17
12.5	1.08	36	3.08

S = .045"; QS = 9.0 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
75.0	0.38	311	1.01
80.0	0.38	331	1.01
65.0	0.38	269	1.01
18.0	0.80	74	2.13
16.0	0.72	66	1.92
18.0	0.83	74	2.21
13.0	0.95	53	2.53
12.0	1.11	49	2.96
12.0	1.11	49	2.96
10.0	1.29	41	3.44
9.5	1.33	39	3.54
10.0	1.39	41	3.70

S = .045"; QS = 12.5 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
90.0	0.42	514	1.00
85.0	0.42	485	1.00
70.0	0.42	399	1.00
26.0	0.65	148	1.54
23.0	0.65	131	1.54
24.5	0.70	139	1.66
12.0	1.06	68	2.52
11.5	1.06	65	2.52
12.0	1.11	68	2.64

S = .045"; QS = 14.9 scfm

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number	QC/QC min
60.0	0.42	411	1.00
75.0	0.48	514	1.14
70.0	0.48	480	1.14
19.0	0.72	130	1.71
19.5	0.77	133	1.83
21.0	0.72	144	1.71
20.0	0.80	137	1.90
12.0	0.95	82	2.26
12.0	0.95	82	2.26
11.0	0.95	75	2.26
12.0	1.03	82	2.45
9.0	1.15	61	2.73
8.0	1.11	54	2.64
8.0	1.20	54	2.85
9.0	1.20	61	2.85

TABLE 5

Effect of Back pressure on Internal Pressures

QS = 11.2 scfm, S = .045"

Tap Location Static Pressure ("H_2O)						
Settling Chamber	Throat	P_{S1}	P_{S2}	P_{S3}	P_{S4}	Back Pressure
+2.67	-0.20	+0.40	+0.21	--0.01	-0.19	+0.49
+2.72	-0.15	+0.29	+0.08	-0.16	-0.35	+0.39
+2.73	-0.14	+0.20	-0.02	-0.27	-0.48	+0.31
+2.74	-0.12	+0.09	-0.13	-0.39	-0.60	+0.21
+2.75	-0.07	0	-0.24	-0.50	-0.75	+0.12
+2.75	-0"07	-0.10	-0.35	-0.63	-0.86	+0.01

QS = 6.4 scfm, S = .045"

Tap Location Total Pressure ("H_2O)			
Settling Chamber	Throat	P_{S1}	Back Pressure
1.15	0.81	0.42	0.05
1.15	0.81	0.48	0.10
1.13	0.81	0.53	0.15
1.12	0.80	0.61	0.24
1.12	0.80	0.67	0.28
1.08	0.76	0.71	0.34

QS = 14.5 scfm, S = .045"

Tap Location RTotal Pressure ("H_2O)			
Settling Chamber	Throat	P_{S1}	Back Pressure
5.23	4.17	1.81	0.29
5.22	4.17	2.02	0.45
5.21	4.14	2.36	0.78
5.20	4.09	2.81	1.17
5.15	4.05	3.20	1.45
4.85	3.85	3.50	2.01

TABLE 6

Effect of Back Pressure (Measured Without Back Pressure Tanks) and Control Flow on Strouhal Number

Setback = .045", QS = 9.0 scfm

Switching Time (millisecs)	B.P. = 0.05"H_2O Control Flow (scfm)	Strouhal Number
2.8	0.70	11
3.0	0.73	12
3.2	1.11	13
4.3	0.95	17
4.4	1.11	18
4.2	1.11	17
4.2	1.11	17
4.2	1.20	17
4.0	1.11	16
4.4	1.20	18
3.8	1.83	15
3.8	1.95	15

Switching Time (millisecs)	B.P. = 0.10 Control Flow (scfm)	Strouhal Number
3.8	0.95	15
4.0	0.95	16
4.3	0.95	17
4.0	0.95	16
4.4	1.83	18
4.0	1.83	16
2.3	1.833	9
4.1	2.00	17
3.9	2.22	16
4.2	2.55	17

Switching Time (millisecs)	B.P. = 0.25"H_2O Control Flow (scfm)	Strouhal Number
17.0	0.95	70
17.0	1.03	70
20.0	1.03	82
9.7	1.80	40
9.8	2.00	40
9.0	2.00	40
6.5	2.22	26
6.5	2.22	26
6.5	2.22	26

Switching Time (millisecs)	B.P. = 0.40 Control Flow (scfm)	Strouhal Number
27.0	1.03	111
28.0	1.11	116
29.0	1.11	120
16.0	1.48	68
14.5	1.57	60
11.5	2.09	47
10.0	2.22	41
8.3	2.85	34

TABLE 7

Effect of Back Pressure, Control Flow and

Main Flow on Strouhal Number

Setback = .045" For All Tests

QS = 6.4 scfm, B.P. = 0.08"H_2O

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number
32.0	1.03	94
29.0	1.03	85
39.0	1.03	115
17.0	1.57	50
18.5	1.57	54
18.0	1.48	53
12.0	2.09	35
12.4	2.22	36
13.0	2.09	38

QS = 6.4 scfm, B.P. = 0.16"H_2O

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number
38.0	0.45	112
35.0	0.45	103
38"0	0.45	112
34.0	0.42	100
20.0	0.60	58
18.0	0.60	53
18.0	0.72	53
15.0	1.11	44
12.0	1.08	35
11.0	1.08	32
11.0	1.11	32

QS = 6.4 scfm, B.P. = 0.24" H_2O

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal number
65.0	0.29	191
60.0	0.29	176
75.0	0.26	221
85.0	0.29	250
44.0	0.48	129
40.0	0.48	117
40.0	0.48	117
40.0	0.48	117
24.0	0.88	70
23.0	0.88	67
26.0	0.88	76
17.0	1.17	50
17.5	1.17	51
17.0	1.20	50=
10.0	1.70	29
12.0	1.70	35
13.5	1.70	39

QS = 6.4 scfm, B.P. = 0.36"H_2O

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number
50.0	0.14	147
40.0	0.14	117
40.0	0.24	117
34.0	0.42	100
26.0	0.42	76
11.0	0.60	32
13.0	0.95	38
20.0	0.95	58
18.0	0.95	53

QS = 9.2 scfm, B.P. = 0.15"H_2O

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal number
28.0	0.72	118
26.0	0.72	110
20.0	0.78	110
19.0	0.95	84
19.0	0.95	80
10.0	0.95	80
11.0	1.39	42
12.5	1.39	46

QS = 9.2 scfm, B.P. = 0.29"H_2O

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal number
28.0	0.48	118
24.0	0.48	101
24.0	0.48	101
26.0	0.48	110
16.0	0.65	67
14.5	0.72	61
13.5	0.72	57
11.5	0.88	48
7.0	1.11	29
11.0	0.95	46
10.5	0.88	44
10.5	0.95	44
11.0	0.92	46

$QS = 9.2$ scfm, B.P. = 0.48"H_2O

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number
100.0	0.21	423
100.0	0.21	423
95.0	0.21	402
60.0	0.21	254
64.0	0.33	271
40.0	0.33	169
46.0	0.33	195
25.0	0.65	105
27.0	0.65	114
27.0	0.65	114
15.0	1.20	63
17.0	1.11	72
17.0	1.20	72
15.0	2.00	63
15.0	2.00	63

QS = 9.2 scfm, B.P. = 0.73" H_2O

Switching Time (millisecs)	Control Flow (scfm)	Strouhal Number
30.0	0.14	127
29.0	0.13	122
26.0	0.15	110
28.0	0.24	118
24.0	0.24	101
25.0	0.24	105
20.0	0.33	84
22.0	0.33	93
24.0	0.45	101

QS = 12.5 scfm, B.P. = 0.33"H_2O

Switching Time (millisecs)	Control Flow (scfm)	Strouhal Number
35.0	0.33	201
30.0	0.33	172
26.0	0.35	149
16.0	0.53	92
21.0	0.45	120
16.0	0.45	92
12.0	0.65	69
11.0	0.65	63
10.5	0.60	60

QS = 12.5 scfm, B.P. = 0.53" H_2O

Switching Time (millisecs.)	Control Flow (scfm)	Strouhal Number
27.0	0.28	155
22.0	0.29	126
24.0	0.29	138
14.0	0.42	80
14.0	0.38	80
12.0	0.42	69
10.0	0.42	57
7.0	0.48	40
11.0	0.53	63
6.0	0.65	34

QS = 12.5 scfm, B.P. = 0.86"H_2O

Switching Time (millisecs)	Control Flow (scfm)	Strouhal Number
58.0	0.29	334
80.0	0.29	460
80.0	0.29	460
55.0	0.48	316
42.0	0.53	240
46.0	0.48	264
19.0	0.88	109
18.0	0.95	103
17.5	0.91	100
12.0	1.29	69
11.5	1.29	66
12.0	1.29	69

QS = 12.5 scfm, B.P. = 1.36"H_2O

Switching Time (millisecs)	Control Flow (scfm)	Strouhal Number
27.0	0.21	155
26.0	0.21	149
34.0	0.21	195
30.0	0.21	172
30.0	0.28	172
24.0	0.29	138
30.0	0.26	172
23.0	0.57	132
22.5	0.60	129
20.0	0.83	115
18.0	1.03	103
18.5	1.39	106
15.0	1.48	86
16.0	1.39	92
14.5	1.88	83
13,5	2.00	77
14.5	2.38	66

QS = 14.5 scfm, B.P. = 0.44"H_2O

Switching Time (millisecs)	Control Flow (scfm)	Strouhal Number
31.0	0.29	207
28.0	0.32	187
25.0	0.32	167
18.0	0.40	120
17.5	0.38	116
15.0	0.35	100
11.5	0.48	76
10.0	0.53	66
9.0	0.60	60
8.0	0.65	53

QS = 14.5 scfm, B.P. = 0.68"H_2O

Switching Time (millisecs)	Control Flow (scfm)	Strouhal Number
24.0	0.35	160
23.0	0.35	160
31.0	0.29	207
30.0	0.29	200
14.0	0.50	93
15.5	0.48	103
13.0	0.48	86
13.5	0.48	90
8.0	0.76	53
8.5	0.65	56
8.0	1.03	53
7.0	1.20	46
7.0	1.11	46

$QS = 14.5$ scfm, B.P. = 1.20"H_2O

Switching Time (millisecs,)	Control flow (scfm)	Strouhal Number
160.0	0.16	1069
95.0	0.16	634
85.0	0.18	567
70.0	0.29	467
53.0	0.29	354
62.0	0.29	414
37.0	0.48	247
38.0	0.48	253
36.0	0.45	240
15.5	1.08	103
15.0	0.99	100
17.0	0.99	113
11.0	1.48	73
11.0	1.53	73

QS = 14.5 scfm, B.P. = 1.79"H_2O

Switching Time (millisecs)	Control Flow (scfm)	Strouhal Number
35.0	0.23	233
30.0	0.23	200
28.0	0.23	187
24.0	0.33	160
20.0	0.53	133
20.0	0.53	133
22.0	0.70	146
20.0	0.88	133
20.0	1.08	133
18.0	1.34	120
15.0	1.83	100
17.0	1.83	113
16.0	1.83	106
8.0	2.38	53
6.5	2.38	43

APPENDIX B

USEAGE OF NON-DIMENSIONAL NUMBERS

B.1 The Strouhal Number

The Strouhal Number is defined as $\frac{QS' \times t}{Dn^2}$ or $\frac{Un \times t}{Dn}$ where Un is the main flow velocity measured at the throat. If the terms are rearranged to $\frac{t}{Dn/Un}$ then the signifigance of the numerator is that it is a measurement of the time taken for a change in the flow situation to occur. This is the switching time of the bistable amplifier. the ratio Dn/Un is that of a length, Dn, which is characteristic of the amplifier geometry to the velocity which is characteristic of the main flow. The parameter Dn has been chosen as the throat width of the nozzle which in these experiments has been held constant.The denominator of the Strouhal Number is, in this case, a measure of the time taken for a particle of the fluid to travel a distance proportional to Dn.

With an increase in the main flow rate the denominator will become less as a disturbance which will be necessary to enforce a change in the flow situation will be propogated faster.

The ratio $\frac{t}{Dn/Un}$ is constant with changing main flow rate as both numerator and denominator are time dependent upon the main flow rate.

B.2 Non-Dimensional Control Flow

In many of the figures the ratio of actual control flow to minimum control flow required to switch the amplifier has been used as the ordinate. The latter, QCmin, is a characteristic of the flow situation inside the amplifier as it gives a measure of the difficulty to switch an amplifier. An amplifier which is difficult to swi ch will require more control flow to produce switching in a given Strouhal Number range.

The increased required control flow is divided by the increased value of QCmin to acheive a similiar flow situation for any flow conditions of the amplifier.

B.3 Non-Dimensional Back Pressure

The Non-Dimensional back pressure is defined as:

$$N_{BP} = \frac{\text{Static Pressure at Outlet}}{\text{Total Pressure at Throat}}$$

This is a maesure of the amount of loading or restriction in output area applied to the amplifier. With a high main flow rate the total pressure at the outlet will be greater than that of a low main flow rate. Hence a larger increase in total pressure into which the fluid is exiting will be required to give the same loading for different main flow rates.

In order to determine whether a similiar flow condition exists in the amplifier with a constant N_{BP} the amount of spillover was examined. The easiest measure of this is when both the entrained flow and the spillover flow are zero. This is the value of back pressure at which the flow in the passive leg is zero, and can be determined by introducing a smoke trace into the passive leg.

At 6.4 scfm. this condition occurs at a total pressure at outlet of 0.85"H_2O, the total pressure at the throat in this case being 2.5"H_2O. Hence N_{BP} = 0.34. For a main flow rate of 14.5 scfm. the corresponding values required to compute N_{BP} at zero entrained and spilover flow are 4.5/12.8 = 0.34.

This shows that by measuring the back pressure using N_{BP} the amount of loading is similiar irrespective of the main flow rate.

B.4 Pressure and Flow Gains

The pressure gain is defined as the ratio of the output pressure change to control pressure change required for switching to occur.

The flow gain is the ratio of the output flow change to control flow change required for switching to occur.

APPENDIX C

SUMMARY OF EXPERIMENTS PERFORMED

Pressures in Legs When Active

Series No.	S (inches)	QS (scfm)	QC	Measurement Taken
1	.030	6.4	0	P_{STH}, P_{S1}, P_{S2}, P_{S3}, P_{S4}, Left Right
2	"	11.1	"	"
3	"	12.7	"	"
4	"	14.6	"	"

Effect of QS, S, and QC on Switching Time

Series No.	S (inches)	QS (scfm)	QC (No. of values used)	Measurement Taken
5	0	6.4	4	Switching Time
6	"	9.0	"	"
7	"	12.9	"	"
8	"	14.4	"	"
9	.015	6.4	4	Switching Time
10	"	8.9	"	"
11	""	12.5	"	"
12	"	14.5	"	"
13	.030	8.6	4	Switching Time
14	"	10.2	"	"
15	"	12.5	"	"
16	"	14.4	"	"

Series No.	S (inches)	QS (scfm)	QC (No. of values used)	Measurement Taken
17	.045	6.3	4	Switching time
18	"	9.0	"	"
19	"	12.5	"	"
20	"	14.9	"	"

Effect of Back Pressure on QS

Series	S (inches)	QS (scfm)	B."P. (No. values used)	Measurement Taken
21	.045	10	1	QS
22	"	"	"	"
23	"	"	"	"
24	"	"	"	""
25	"	"	"	"
26	"	"	"	"
27	"	"	"	"

Effect of Back Pressure on Internal Pressures

Series No.	S (inches)	QS (scfm)	B.P. (No. of values used)	Measurement Taken
28	.045	6.4	1	P_{ST}, P_{STH}, P_{S1}, P_{S2}, P_{S3}, P_{S4}
29	"	"	"	"
30	"	"	"	"
31	"	"	"	"
32	.045	11.2	1	P_{ST}, P_{STH}, P_{S1}, P_{S2}, P_{S3}, P_{S4}
33	"	"	"	"
34	"	"	"	"
35	"	"	"	"
36	.045	14.5	1	P_{ST}, P_{STH}, P_{S1}, P_{S2}, P_{S3}, P_{S4}
37	"	"	"	"
38	"	"	"	"
39	"	"	"	"

Effect of Back Pressure on Switching Time

Series	S (inches)	QS (scfm)	B.P. ("H_2O)	QC (No. of values used)	Measurement Taken
40	.045	6.4	0.08	4	Switching Time
41	"	"	0.16	"	"
42	"	"	0.24	"	"
43	"	"	0.36	"	"
44	.045	9.2	0.15	4	Switching Time
45	"	"	0.29	"	"
46	"	"	0.48	"	"
47	"	"	0.73	"	"
48	.045	12.5	0.33	4	Switching Time
49	"	"	0.53	"	"
50	"	"	0.86	"	"
51	"	"	1.36	"	"
52	.045	14.4	0.44	4	Switching Time
53	"	"	0.69	"	"
54	"	"	1.20	"	"
55	"	"	1.79	"	"

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