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INVESTIGATION OF METHODS FOR RE-ESTABLISHMENT OF A LAMINAR BOUNDARY LAYER FROM TURBULENT FLOW

(Unclassified)

FEBRUARY 1965

Prepared under Navy, Bureau of Naval Weapons

Contract NOw 63-0762-c

SUMMARY REPORT

NORTHROP NORAIR
A Division of
NORTHROP CORPORATION

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Administered under Direction of the Bureau
of Naval Weapons Fluid Mechanics and Flight
Dynamics Branch, RRRE-4.

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ABSTRACT

By means of area suction, laminar flow has been re-established in tripped turbulent boundary layers for a unit Reynolds number range from 0.4 to 1.0 million per foot in incompressible flow. The removal of about 1.5 times the turbulent boundary layer thickness is adequate to restart a maintainable laminar boundary layer. Hot wire observations show that the restarted laminar boundary layer is generally a composite layer with laminar velocity fluctuations from the wall out to about one boundary layer thickness and weak turbulent velocity fluctuations in the outer portion.

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SUMMARY

Area suction on a flat plate through a porous surface of 2 ft. chordwise length, consisting of three individual suction strips, enabled the re-establishment of a laminar boundary layer, after having become turbulent downstream of roughness trips, at unit length Reynolds numbers of $0.4 \cdot 10^6$ to $1 \cdot 10^6$/ft. In order to re-establish an undisturbed laminar boundary layer, which remained laminar for a considerable distance, it was necessary to stop first the generation of new turbulent eddies by means of relatively strong suction in the upstream suction region of the 4" wide strip 1. The remaining boundary layer oscillations had to be decreased further by additional weaker suction in the second 8" wide suction strip, followed by still further reduced suction rates in the 12" wide third strip which stabilized the newly formed laminar boundary layer such as to provide extensive laminar flow. The velocity fluctuations in the re-established laminar boundary layer should not exceed 0.5% of the free stream velocity to enable a long laminar run and prevent premature transition with the newly established laminar boundary layer further downstream, and somewhat more than the total turbulent boundary layer must be removed by means of suction. This result is not too surprising since the turbulent eddies of the original turbulent boundary layer, which will disturb a re-established laminar boundary layer, generally penetrate far into the potential flow field region. Lower suction values than the above mentioned rates were adequate though to re-establish laminar flow; however, the nonsucked turbulent eddies from the original turbulent boundary layer in the case of weaker suction were considerably stronger and more frequent and induced rather strongly amplified boundary layer oscillations in the newly established laminar boundary layer, causing premature transition.

Suction thus appeared to be quite effective in stopping the generation of new turbulent eddies in the lower part of the boundary layer. The disturbances induced into the re-established laminar boundary layer by the nonsucked turbulent eddies, however, presented a much more formidable problem. These eddies had to be largely eliminated by means of further increased suction in order to achieve extensive laminar flow with the re-established laminar boundary layer. Further progress might be accomplished in this direction if the dissipation of these nonsucked turbulent eddies could be accelerated by other means, perhaps by adding small amounts of liquids or by means of strongly accelerated flow or highly stable temperature gradients in the boundary layer. Other more powerful methods than suction alone may enable the stabilization of a newly established laminar boundary layer over long distances in the presence of the nonsucked turbulent boundary layer, perhaps a combination of suction with compliant coatings (if possible, active ones).

NOTATION

b	span of suction area
C_p	pressure divided by free stream dynamic pressure
C_Q	suction coefficient $\left(\frac{Q_a}{U_\infty S}\right)$, or $\left(\frac{-vo}{U_\infty}\right)$
Q_a	suction quantity, ft^3/sec, for b = 1 ft.
Q_δ	volume flow rate contained in the total turbulent boundary layer just ahead of the suction insert, ft^3/sec for b = 1 ft.
S	suction area, 2 ft^2
u'	root mean square velocity fluctuation in streamwise direction, ft/sec
U_∞	free stream velocity, ft/sec
u/U	velocity ratio in boundary layer
$-vo$	suction inflow velocity $\left(\frac{Q_a}{S}\right)$, ft/sec
y	height above surface, inches
δ	total boundary layer thickness, inches
δ^*	boundary layer displacement thickness
θ	boundary layer momentum thickness, inches; $\theta = \int_0^\delta \frac{u}{U}\left(1 - \frac{u}{U}\right) dy$
ν	kinematic viscosity, ft^2/sec

Moderate Suction = one turbulent burst per five seconds at specified distance downstream of suction insert

Strong Suction = velocity fluctuations reduced to 6 db above noise level on suction insert $\left(\frac{u'}{U_\infty} \approx .05\%\right)$

Intermediate Suction = velocity fluctuations reduced to $\frac{u'}{U_\infty} \approx .5\%$ on suction insert

INTRODUCTION

The ability to restart a laminar boundary layer has many important applications in boundary layer research, on laminar flow control vehicles and in some local regions on non-laminarized vehicles. In boundary layer research work, many cases arise where the ability to restart a laminar flow would simplify the design and reduce the cost of models. In addition the restarting of laminar flow on wind tunnel walls could be important, particularly in research where acoustical measurements are involved or where radiated turbulent boundary layer noise is a major contribution to the wind tunnel turbulence level. Moreover, on a laminar flow control vehicle, many areas where laminar flow cannot now be maintained could be re-established laminar. With an understanding of the re-establishment of laminar flow, compromises in surface requirements at control surfaces, doors or joints might be a practical possibility on laminar flow vehicles. On non-laminar vehicles, the ability to re-establish laminar flow would be useful in cases where the optical, heat transfer or acoustical properties of a laminar boundary layer are required in local areas.

A particularly important application is the case of a swept laminar suction wing, where laminar flow must be first established at the front wing stagnation or attachment line at the intersection between the wing and fuselage or nacelles. At higher Reynolds numbers turbulent bursts at the front attachment line of swept low drag suction wings have often prevented the maintenance of full chord laminar flow. According to hot wire observations (Figure 1) at the leading edge of swept wings with and without suction through vertical nose slots the turbulent bursts at the front attachment line developed rather suddenly and were generally preceded by a few exponentially growing laminar boundary layer oscillations of relatively low frequency. In general the number of turbulent bursts at the front attachment line of a swept wing increased along the wing span in downstream direction. It appeared that the turbulent bursts at the front attachment line were caused by rather strong disturbances as for example in Klebanoff's experiments on a flat plate, with turbulent bursts generated by an electric spark (Reference 1). Vortices, with the axis approximately parallel to the front attachment line, may have developed in the front attachment line boundary layer under the action of local chordwise fluctuations of the front attachment line caused by various kinds of relatively strong external disturbances. At sufficiently high boundary layer Reynolds number $R_{\theta a.\ell.} = \frac{W\theta}{\nu}$ (W and θ are the potential flow velocity and boundary layer momentum thickness, respectively, at the wing attachment line) the local boundary layer crossflow induced by such vortices at the front attachment line of swept wings may then become unstable and oscillate with a rapidly growing amplitude to cause turbulent bursts. Disturbances as outlined above, which might induce premature local transition at the front attachment line of swept wings, can originate among other sources from residual eddies of the initially turbulent boundary layer at the front attachment line of a swept wing at the location where laminar flow has been re-established. The question then arises as to how best to re-establish an undisturbed laminar boundary, after having become turbulent, at the front attachment line of swept wings or in other more general cases.

In order to answer this question, it appears necessary to have some notion about the flow in a turbulent boundary layer and about the mechanism of various methods, for example of boundary layer suction, in re-establishing laminar flow.

According to Klebanoff's experiments on a turbulent flat plate (Reference 2) or to smoke investigations of a turbulent boundary layer by Head at Cambridge some of the eddies of a turbulent boundary layer can penetrate far into the potential flow region (y > 1.3 to 1.4 δ). Thus, in order to reestablish an undisturbed laminar boundary layer without turbulent bursts for example at the attachment line of a swept wing, it appears necessary to eliminate practically all the turbulent eddies of the initially turbulent boundary layer by means of boundary layer suction. In other words suction has to extend rather far into the potential flow region beyond the edge of the turbulent boundary layer in order to stop turbulent eddies from penetrating into the downstream laminar region at the front attachment line of a swept wing where they might induce turbulent bursts.

In order to restart a laminar boundary layer the generation of new turbulent eddies must first be stopped. The question then arises as to where and why new turbulent eddies are continuously being created in a turbulent boundary layer. According to Klebanoff's measurements of the generation of vorticity in a turbulent boundary layer (Reference 2) the vorticity production has a sharp maximum close to the edge of the laminar sublayer, and it is thus suspected that the region at and somewhat beyond the edge of the laminar sublayer is probably the "eddy factory" where new turbulent eddies are being continuously produced. Energy considerations are probably insufficient to obtain a further improved understanding of the mechanism of the generation of new turbulent eddies, since these consider only integral effects. Detailed correlation measurements in a turbulent boundary layer by Willmarth (Reference 3) between the fluctuating wall static pressure and the turbulent velocity fluctuations u′, v′, w′ in three directions have shown relatively large correlation lengths in chordwise and rather short ones in spanwise direction, respectively. Within the inner part of a turbulent boundary layer close to the wall the turbulent velocity fluctuations are reasonably well correlated with the fluctuating wall static pressure as well as with the instantaneous velocity gradient $\frac{\partial u}{\partial y}$ in the laminar sublayer and thus with the local wall surface friction; in the outer part of the turbulent boundary layer this correlation ceased to exist. These correlation measurements seem to indicate a relatively orderly eddy motion in the laminar sublayer and the inner part of a turbulent boundary layer. Evidently, according to the correlation lengths observed by Willmarth in chordwise and spanwise direction, and to smoke flow observations of Pfenninger in a turbulent boundary layer, the newly created turbulent eddies must be relatively long in chordwise and rather short in spanwise direction. According to Willmarth the results of his correlation measurements are explainable under the assumption that hairpin type vortices exist in the lower part of the turbulent boundary layer. Under the action of lift and drag forces these vortices are pulled away from the surface and stretched in downstream direction. This vortex stretching increases their kinetic energy until they become unstable and disintegrate a relatively short distance away from the surface, where they loose their identity. The mechanism which continuously creates new hairpin type vortices in the lower part of the boundary layer appears to be the induction of new longitudinal vortices within the laminar sublayer under the action of the preceding turbulent eddies, which seem to be of the form of hairpin type vortices in the inner part of the turbulent boundary layer. These newly created longitudinal vortices are dynamically highly unstable and will break up soon into new hairpin type vortices, and so on. The first hairpin type vortex can originate in the transition region for example from a three-dimensional roughness spot, etc. It thus appears that new hairpin type vortices are being continuously generated in the lower part of the turbulent boundary layer under the action of the preceding turbulent eddies.

The generation of new hairpin type vortices at the upstream and downstream end of turbulent spots has been observed during smoke flow observations by Pfenninger and W. E. Meyer in a 40 ft. long 8" i.d. tube at low speeds. These hairpin vortices could only be observed close to the surface at the edges of the turbulent spot. Further away from the wall the eddy motion became irregular, and it was not certain whether or not secondary or tertiary, etc., hairpin type vortices developed out of the original hairpin vortex when it became unstable and exploded, as stipulated by Theodorsen (Reference 4). Neither could it be proven whether or not other than hairpin type vortices developed in the boundary layer of turbulent spots. Recent smoke flow observations in the same 8" i.d. tube by Pfenninger indicate at least part of the time the presence of hairpin type vortices in the lower part of a turbulent boundary layer.

In principle the generation of new turbulent eddies in a turbulent boundary layer can be stopped by artificially inducing longitudinal vorticity into the laminar sublayer in such a manner as to compensate everywhere for the longitudinal vorticity generated within the laminar sublayer under the action of preceding hairpin vortices, for example by means of an active compliant surface whose motion would be essentially controlled by the fluctuating pressure forces on the surface. The remaining turbulent eddies further away from the surface could dissipate under the action of viscosity. Nature may have applied similar principles in the skin of the porpoise. Whether or not man is able to make such a scheme work is another question.

A simpler but cruder approach to stop the generation of new turbulent eddies in a turbulent boundary layer is to pull the above mentioned newly generated turbulent eddies of the form of hairpin type vortices closer towards the surface by means of relatively strong local suction, thus opposing the stretching of these hairpin vortices and reducing their kinetic energy.* Expressed in other words: The vortex Reynolds number (based for example on local velocity and distance from the wall to the top of the hairpin vortex loop) can be reduced to sufficiently low values by means of relatively strong suction to prevent the breakup of the hairpin vortices. They would then be dissipated in downstream direction by viscosity. With the reduced strength of the hairpin vortices in the presence of suction, the longitudinal vortices induced by them in the laminar sublayer may eventually become sufficiently weak and stable to prevent the formation of new turbulent eddies of the hairpin type. The production of new turbulent eddies close to the edge of the laminar sublayer would thus be stopped and a new laminar boundary layer re-established. Rather strong suction would then have to be applied initially in order to rapidly pull the hairpin vortices towards the surface to weaken them as fast as possible and to stop the generation of new turbulent eddies. Reduced suction rates would probably be permissible further downstream as the hairpin vortices in the lower part of the boundary layer become progressively weaker. The remaining nonsucked turbulent eddies of the outer part of the initially turbulent boundary layer must be either dissipated by viscosity, requiring a rather long distance over which relatively weak suction may still have to be applied, or they may have to be completely removed by means of suction.

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*As verified by smoke flow experiments of Pfenninger in an 8" i.d. 40 ft. long tube at low speeds.

The dissipation of the remaining turbulent eddies may be accelerated for example by providing a very stable temperature gradient in the boundary layer, or by adding a non-Newtonian fluid, etc., in fluid flows.

Restoration of laminar flow by means of boundary layer suction has been investigated previously at the Institute for Aerodynamics, Zürich, as well as at the National Physical Laboratory, Teddington (References 5 and 6). In the Zürich experiments part of the turbulent boundary layer on a flat plate with zero pressure gradient was removed by means of suction through 35 slots. When a large percentage of the turbulent boundary layer was sucked off the boundary layer velocity fluctuations in the vicinity of the wall at the downstream end of the suction plate, as observed by hot wires, resembled those usually experienced in a laminar boundary layer. In the NPL investigations a laminar boundary layer was re-established on a symmetrical low drag airfoil by means of a single suction slot located at 0.20 chord. The boundary layer had been made turbulent at 5% chord by means of two- and three-dimensional surface roughness. Extensive laminar flow was re-established on this wing at a wing chord Reynolds number $R_c = 5.7 \cdot 10^6$ when a somewhat larger flow quantity than the air contained within the turbulent boundary layer at the suction location was removed by means of suction ($Q_a/Q_\delta \approx 1.3$ to 1.4).

In order to verify the theoretical expectations, as outlined in the Introduction, transition experiments were conducted on a flat plate, with area suction applied through a porous sheet.

EXPERIMENTAL SETUP, MEASUREMENTS

The experimental setup is shown in Figure 2. A slightly cambered 2 inch thick NACA 64 series airfoil of 8 ft. chord and 6 ft. span with a flat lower surface was installed vertically in the Northrop 8 x 11 ft. wind tunnel. Suction was applied on the lower flat surface (called flat plate in other parts of the report) through a porous sheet of 2 ft. chordwise length, divided into three separate spanwise sections with individual suction chambers of 4", 8" and 12" chordwise length.

Suction started 30" downstream of the leading edge. A small positive angle of attack was chosen to provide a slightly accelerated flow on the test surface (Figure 2), as measured with static pressure orifices located on both spanwise ends of the test area.

The porous suction surface was a stainless steel cloth with a mesh of 1200 x 200 wires per inch. This cloth was rolled to improve the surface finish and to reduce the permeability to the desired values.* In accordance with the anticipated chordwise suction distribution high permeability cloth was applied over the first two chambers and a low permeability cloth over the third chamber. Maximum suction rates were generally applied in the first chamber, followed by decreasing suction rates in the second and third chamber.

During the first series of experiments the sp suction area was 2 ft. After discovering that further increased suct re required, particularly in chamber 1, to re-establish laminar f. er unit length Reynolds numbers it was decided to shorten the span of the suction area to 1 ft. Under such conditions turbulent wedges, originating from the outer edges of the suction region, caused transverse turbulent contamination and did not permit laminar flow at distances larger than 12 to 15 inches downstream of the suction area.

*The porous steel cloth was rolled by Mr. A. Glaze of Fort Wayne Metals, Inc., 3211 MacArthur Drive, Fort Wayne, Indiana.

The rolled cloth was stretched over the test surface and was supported on machined lands. The suction air was ducted from the porous sheet through holes in a thicker inner sheet into the suction chamber and through suction flow metering nozzles. The suction rates of the various chambers could be adjusted by means of individual needle valves outside of the wind tunnel test section.

Transition on the plate was induced by means of various trips 1 to 4.

Trip No.	Description	Distance Upstream of Suction Insert
1	0.070" ϕ spheres of 0.5" spacing	20"
2	0.020" ϕ wire	20"
3	0.020" ϕ wire	5"
4	0.025" x 0.050" ϕ disks of 0.5" spacing	5"

The state of the boundary layer was observed at several chordwise stations and for different suction rates and suction distributions at various tunnel speeds by means of hot wires* and a stethoscope connected to a boundary layer total pressure probe. The velocity fluctuations in the boundary layer were measured with hot wires and the boundary layer profiles by means of boundary layer total pressure tubes as well as with hot wires. Suction was first adjusted in such a manner as to allow about one turbulent burst per five seconds on the plate downstream of the suction region ("moderate suction"). In other cases further increased suction rates ("strong suction") were applied to entirely eliminate turbulent bursts downstream of the suction region.

*Shapiro and Edwards Model A50-C Hot Wire Set.

A view from the rear of the model looking upstream is presented in Photograph 1. In this picture, trip number 2 (a .020" diameter wire running spanwise 20" ahead of the suction section) is evident as well as two hot wire probes mounted 2 ft. aft of the test section. Photograph 2 is a front view of the model in the same configuration. The two white areas along the top and bottom of the suction insert are 6" wide mylar strips that were taped over the wire cloth to reduce the spanwise suction width from 2 ft. to 1 ft. Covering one-half of the test section increased the suction velocities such as to enable the re-establishment of a laminar boundary layer to a higher Reynolds number. The line down the middle of the test section is the vertical joint between the spanwise 12-inch wide forward and aft stainless steel wire cloth strips of different porosity. Under the front strip, there were two spanwise chambers 4" and 8" wide, while the rear strip covered a single 12" chamber. The typically high suction inflow operation of the 4" wide number 1 chamber had darkened the cloth between the 1/4 inch spaced spanwise supporting lands so that the extent of the first chamber and the lands are evident on Photograph 2. Though there was a small loss in porosity in the first chamber over a period of several hours of operation, most of the loss could be restored by flushing the screen with a jet of methyl-ethel-ketone followed by naphtha while maintaining maximum suction inflow. A continuing permeability check showed no measurable changes on the second and third chambers. Although the vertical joint between the fore and aft cloth strips did not appear to influence the flow it was subsequently filled for all data runs. The wire cloth had some residual waviness from the rolling process that could not be worked out during installation. The .003" spanwise waviness along the aft edge of the suction insert had an influence on transition downstream until the aft edge of the suction insert was lowered by about .002". This adjustment gave maximum steps of .002" up and .001" down at the rear edge of the suction section. These steps did not influence transition within the Reynolds number range of this experiment.

EXPERIMENTAL RESULTS

In order to avoid a negative pressure peak and laminar separation at the leading edge, the model was installed at a slight angle of attack. The net change in static pressure across the test section was 2% of the undisturbed dynamic pressure q_∞ and the corresponding change in potential flow velocity 1% of the undisturbed velocity U_∞ (Figure 2).

The Figures 3 through 6 show the measured turbulent boundary layer profiles at the beginning of the suction region with the four different boundary layer trips at several unit length Reynolds numbers $\frac{U_\infty}{\nu}$.

The suction flow rates required to re-establish laminar flow at various stations on the model are shown in Figures 7 through 10.* It was arbitrarily assumed that one turbulent burst per 5 seconds could be tolerated at the measuring station ("moderate suction"). Each point on Figures 7 through 10 represents the smallest suction coefficient obtained from a series of chordwise suction variations at one unit Reynolds number. The optimum chordwise suction distribution for minimum overall suction was a function of trip location and type. With trips 1 and 2, the best chordwise suction distributions averaged about 70% of the total suction quantity into the forward 4" wide chamber and about 15% each into the 8" and 12" chambers for the range of Reynolds numbers investigated. For trips number 3 and 4, the average distribution of suction quantity was 60% and 20%, 20% and 40%, 25% and 35% in the first, second and third chambers respectively. Specific values of suction quantity and suction

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*The reader should note that the abscissa scale $\frac{U_\infty}{\nu}$ does not start from a value of zero on Figures 7 through 9.

distribution at .7 million/ft. unit Reynolds number are listed on Table II. Variations of about 5% from these best values corresponded to a 10% increase in total suction quantity. At the highest Reynolds numbers for which laminar flow could be re-established, there was not enough suction capacity in the forward chamber to maintain the optimum suction distribution. The suction flow rates for these runs are plotted on Figures 7 through 9 to show that a laminar boundary layer had been re-established, but are connected by dotted lines to indicate that the chordwise suction distribution was inefficient. Figure 7 shows the suction flow rates as a function of unit length Reynolds number for trips number 2, 3 and 4 required to re-establish a laminar boundary layer that has one burst per five seconds when observed 6" downstream of the suction insert. Figure 8 similarly presents the suction flow rates required with trips number 1 and number 2 to restart a laminar layer that will carry 12" downstream into a nonsuction region, again with one turbulent burst every 5 seconds. The suction flow requirements for the restarted laminar boundary layer with trip 2 to carry from 3" to 24" beyond the suction area are shown in Figure 9 (one turbulent burst per 5 seconds). In addition the circle data on Figure 9 present the suction flow rates required to arbitrarily reduce the hot wire signal to a value 6 db above the amplifier noise level (strong suction with undisturbed laminar flow).

With moderate suction high frequency turbulent boundary layer fluctuations, originating from the nonsucked turbulent eddies of the initially turbulent boundary layer, were observed by hot wires above the suction insert. With increasing suction flow rates these high frequency fluctuations were reduced to smaller and smaller magnitudes but were never completely eliminated.* In effect, the 6 db criteria with these high suction flow rates is equivalent to sucking off the entire turbulent boundary layer plus the adjacent flow to the distance from the wall where turbulent eddies from the initially turbulent boundary layer still existed. The different slope with unit length Reynolds number of the suction flow rates for the data at the location 24" downstream of the suction region (Figure 9) probably results from a spreading of the turbulent boundary layer from the mylar strips onto the aft portion of the suction section at .6 million per foot and above. This turbulent wedge originating from the non-suction area had no effect on the data at the stations 3", 6" and 12" downstream of the suction region because it crossed downstream of these stations.

When transition was caused either by wires or three-dimensional roughness elements located at a station 20" upstream of the suction region the total turbulent boundary layer thickness was 0.4 to 0.45", as compared with approximately 0.20" when the wire or the three-dimensional roughness elements were located 5" upstream of the suction area (see boundary layer profiles at the beginning of the suction region, Figures 3, 4, 5 and 6). For this reason higher suction rates (ft^3/sec) or suction quantity coefficients C_Q would be required to re-establish laminar flow when transition to turbulent flow has been caused further upstream (see Figure 7). On the other hand when transition is caused by roughness elements located only 5" upstream of the suction area the turbulent velocity fluctuations shortly downstream of transition are generally stronger, as compared with the case when transition is induced much further upstream 20" ahead of the suction area. Under such conditions turbulent eddies will penetrate relatively far into the potential flow region (according to observations of the NBS on a flat plate, Reference 1), and a larger ratio Q_a/Q_δ (ratio of suction quantity Q_a to total flow rate Q_δ contained in the total turbulent boundary layer) must be applied to

*See hot wire oscilloscope traces on Figure 18 with intermediate suction.

re-establish laminar flow when transition is induced close to the beginning of suction, as shown in Figure 10. The suction quantities C_Q required to re-establish laminar flow, after having become turbulent, will generally be smaller when transition to turbulent flow has occurred close to the suction area, at least in the case when transition has been caused by three-dimensional roughness elements. In this case the flow remains either laminar, or transition occurs close to the roughness element. In the case of two-dimensional roughness strips such as wire transition to turbulent flow will occur primarily as a result of amplified boundary layer oscillations in the region downstream of the wire. With increasing unit RN $\frac{U_\infty}{\nu}$ transition will then gradually move upstream towards the wire. When transition due to the wire occurs at the beginning of the suction area (at $\frac{U_\infty}{\nu} = 0.46 \cdot 10^6$/ft with trip 2 or $0.60 \cdot 10^6$/ft with trip 3) the turbulent velocity fluctuations at transition are particularly intense, (according to NBS measurements) and turbulent eddies penetrate especially far into the potential flow region, requiring higher suction ratios Q_a/Q_i under these special conditions (Figure 10).

Hot wire measurements were conducted in the turbulent boundary layer just ahead of the suction insert, on the suction insert and in the boundary layer downstream of the suction area. A frequency range of 100 to 5,000 cps was chosen for these data. The three dimensional trip 4 was used since it showed very regular suction flow requirements at all Reynolds numbers. On Figures 11 and 12, the root mean square velocity fluctuations $\frac{u'}{U_\infty}$ just ahead of the suction insert and on the suction insert at the end of each chamber as well as in the non-suction area 6" downstream of the suction insert are shown for both moderate and strong suction at a unit length Reynolds number of $0.8 \cdot 10^6$/ft. Suction was applied over a span of one foot. The suction distribution for strong suction used 48% of the total suction quantity in the first chamber, 21% in the second, and 31% in the third. The corresponding total suction flow rate was $C_Q = 0.0216$ which was 2.1 times larger than for moderate suction. (C_Q is the average rate of suction inflow velocity v_o to the undisturbed velocity U_∞ in the suction area.) This strong suction then removed more than one turbulent boundary layer thickness in the first 4" wide chamber.

The velocity fluctuations in the turbulent boundary layer upstream of the suction region were similar to those measured at the NBS under similar conditions. The maximum turbulent velocity fluctuation at this station was $\frac{u'}{U_\infty} \approx 7\%$. With moderate suction $\frac{u'}{U_\infty}$ decreased rapidly in the suction region to values $\frac{u'_{max}}{U_\infty} = 3\%$ at the end of the first chamber, $\frac{u'_{max}}{U_\infty} = 1.8\%$ at the end of the second chamber and $\frac{u'_{max}}{U_\infty} = 1.2\%$ at the downstream end of chamber 3. In the vicinity of the wall towards the rear part of the suction region and downstream of the latter the observed velocity fluctuations were of relatively low frequencies and resembled those usually observed in laminar boundary layers, (Figure 13). Suction thus appeared to be effective in suppressing the formation of new turbulent eddies. In the outer part of the boundary layer in and downstream of the suction region, however, high frequency oscillations were observed with the hot wire in the case of "moderate" suction, indicating the presence of turbulent eddies from the nonsucked turbulent boundary layer (Figure 14). With moderate suction the high frequency velocity fluctuations in the outer part of the boundary layer in the suction region decreased rather slowly with increasing distance from the wall to the free stream turbulence level in a similar manner as in a turbulent boundary layer. It thus appeared that the flow close to the wall with moderate suction was laminar underneath a layer of nonsucked turbulent eddies originating from the outer part of the initial turbulent boundary layer.

These turbulent eddies probably act on the laminar layer close to the surface in a similar manner as a free stream with a relatively high turbulence level. Hot wire observations with moderate uction have shown indeed a rather rapid increase of the laminar boundary layer oscillations downstream of the suction region in downstream direction as a result of the presence of these remaining turbulent eddies, (Figure 11), and premature trans .ion with turbulent bursts was then observed further downstream. It thus appears that the nonsucked turbulent eddies from the original turbulent boundary layer dissipate rather slowly in chordwise direction. In order to establ. h an undisturbed laminar boundary layer and to avoid an excessive growth of the laminar boundary layer oscillations in downstream direction either a method should be found to accelerate the dissipation of these nonsucked turbulent eddies, or suction may have to be further increased until practically all the turbulent eddies of . ie initially turbulent boundary layer are removed by suction. Figure 12 shows the velocity fluctuations $\frac{u'}{U_\infty}(y)$ for strong suction in the re-established laminar boundary layer at various chordwise stations. The observed boundary layer velocity fluctuations $\frac{u'}{U_\infty}$ were then much smaller, as compared with the case of moderate suction, (Figure 12), even at the station immediately downstream of the first 4" wide suction strip where strong local suction was applied. In this case the boundary layer fluctuations in the nonsuction region downstream of the suction area seemed to grow along the chord essentially at the same rate as in the region of the plate upstream of the suction area, according to fluctuation measurements

20" downstream of the plate leading edge (Figure 15). Strong suction in the first $\left(\frac{-vo_1}{U_\infty} = .048\right)$ chamber established rather rapidly a laminar boundary layer with rather small velocity fluctuations, $\left(\frac{u'max}{U_\infty} = 0.55\%\right)$. The purpose of weak suction in chamber 2 $\left(\frac{-vo_2}{U_\infty} = .010\right)$ was primarily to further reduce the high frequency velocity fluctuations in the outer part of the boundary layer. The maximum velocity fluctuation in the boundary layer downstream of chamber 2 was $\frac{u'max}{U_\infty} = 0.1\%$. Suction in chamber 3 $\left(\frac{-vo_3}{U_\infty} = .010\right)$ did not materially alter the velocity fluctuations $\left(\frac{u'max}{U_\infty} \cong .06\%\right)$. It probably would have been permissible to reduce suction in chamber 2 and particularly chamber 3 without losing laminar flow, as confirmed by additional experiments (intermediate suction).

The Figures 11 and 12 present the velocity fluctuations in the boundary layer in the 100 cps to 5,000 cps band at a station 6" downstream of the suction region for moderate and strong suction. Downstream of the suction region the velocity fluctuations grew rather rapidly. Figures 13 and 14 present oscilloscope traces for the two typical frequency patterns that existed in the restarted laminar boundary 6" downstream for moderate suction. Three oscilloscope sweeps are presented on each photograph, and in some cases the fading trace of a previous sweep can be seen. Although the gain has been adjusted to give equal magnitude signals on the scope, the calculated values of $\frac{u'}{U}$ of .83% and 2.61% are indicated on Figures 13 and 14 and correspond to two of the triangle data points on Figure 11 for moderate suction. The high frequency spike like traces of the Figure 14 photograph are typical of the outer part of a turbulent boundary layer and typical of all the measurements at stations above the suction screen, indicating the presence of relatively weak turbulent eddies with moderate suction. Increasing the suction rates or moving further out from the surface reduced the magnitude of these high frequency oscillations. At 6" downstream, out to about 50 or 60 thousandths of an inch from the model surface, the boundary layer with moderate suction was typically laminar with strong low frequency oscillations illustrated by Figure 13.* A combined consideration of Figures 13 and 14 shows the following three situations in the boundary layer with moderate suction after 6" of travel without suction. First, the high frequency oscillations have been strongly damped near the wall; second, the outer part of the boundary layer is unchanged and third, strong laminar oscillations have grown in the re-established laminar boundary layer under the action of the remaining unsucked turbulent eddies in the outer part of the boundary layer, and the rate of growth of the laminar fluctuations in the restarted laminar boundary layer in the nonsuction region is then more rapid than in an initially laminar layer.

In conclusion it thus appears that relatively strong boundary layer suction through a porous surface is indeed effective in preventing the formation of new turbulent eddies and in re-establishing a new laminar boundary layer. The generation of new turbulent eddies, presumably hairpin

*For this case of moderate suction, there was on the average one turbulent burst for 5 seconds. The bursts were never caught by any of the 1/100 of a second scope pictures and, of course, were too infrequent to measurably influence the velocity fluctuation reading of the hot-wire equipment.

type eddies originating probably in the laminar sublayer can be stopped by relatively strong area suction over a short distance. This is not too difficult. It addition, however, most of the remaining turbulent eddies of the initially turbulent boundary layer must at the same time be removed by strong suction at the beginning of the suction region. The dissipation in chordwise direction of these residual nonsucked turbulent eddies is rather slow. Once the generation of new turbulent eddies has been stopped by means of strong initial suction additional weak suction has to be applied further downstream in order to reduce the remaining weak disturbances, which may still exist in the outer part of the boundary layer, as well as to sufficiently stabilize the laminar boundary layer, until these residual disturbances have become negligibly weak. Much reduced suction rates further downstream should stabilize the new re-established laminar boundary layer in such a manner as to prevent a rapid growth of the laminar boundary layer oscillations and transition.

The following experiments verified this reasoning. At $\frac{U_\infty}{\nu} = 0.71$ times 10^6/ft. the following suction rates were used in the first and second chamber: $\left(\frac{-v_o}{U_\infty}\right)_1 = .048$, $\left(\frac{-v_o}{U_\infty}\right)_2 = .012$. The boundary layer velocity fluctuations of Figure 16 downstream of chamber 2 showed laminar low frequency oscillations with $\left(\frac{u'}{U_\infty}\right)_{max} = 0.36\%$ without turbulent bursts. With suction in chamber 3 of a magnitude $\left(\frac{-v_o}{U_\infty}\right)_3 = .001$ the boundary layer velocity fluctuations remained constant in the suction area 3, in spite of the growing boundary layer.

Rather weak suction thus was adequate to maintain a newly established laminar boundary layer with small velocity fluctuations over a considerable distance, once turbulent bursts were eliminated by means of relatively strong suction in the upstream suction areas where the formation of new turbulent eddies was stopped. When smaller suction rates were applied in the second chamber $\left(\frac{vo_1}{U_\infty} = .049 , \frac{-vo_2}{U_\infty} = +0.0018 , \frac{U_\infty}{\nu} = 0.7 \cdot 10^6/\text{ft.} \right)$ the maximum velocity fluctuations in the boundary layer downstream of chamber 2 were reduced to $\frac{u'_{max}}{U_\infty} \approx 1\%$. The hot wire traces, however, showed spikes, indicating the presence of relatively weak turbulent eddies from the nonsucked turbulent boundary layer, as well as some turbulent bursts. As a result considerably higher suction rates $\left(\frac{-vo_3}{U_\infty} = .0028 \right)$ were required in the third suction chamber to keep the maximum velocity fluctuations at the end of the third chamber at or below 1%. The turbulent bursts, however, could not be completely eliminated in this case.

The lowest suction rates required to re-establish an undisturbed laminar boundary layer through the suction region were obtained with "intermediate" suction with the following suction rates: $\frac{-vo_1}{U_\infty} = .045$, $\frac{-vo_2}{U_\infty} = .005$, $\frac{-vo_3}{U_\infty} = .002$. Trip 4 was used, and the unit length Reynolds number was $\frac{U_\infty}{\nu} = 710{,}000$ ft.

Figures 17 and 20 show plots of the boundary layer fluctuations $\frac{u'}{U_\infty}(y)$ and the corresponding boundary layer profiles with intermediate suction at various stations in and downstream of the suction area. The boundary layer profiles in the suction region in strip 2 and 3 were laminar and quite thin. Immediately downstream of chamber 1 the maximum boundary layer velocity fluctuations were $\left(\frac{u_1'}{U_\infty} \right)_{max} = 0.85\%$. Suction in chamber 2 decreased these fluctuations to $\left(\frac{u_2'}{U_\infty} \right)_{max} = 0.47\%$ at the end of chamber 2. Weak suction in chamber 3 stabilized the boundary layer sufficiently in this area to maintain approximately the same velocity fluctuations $\left(\frac{u_3'}{U_\infty}\right)_{max} \cong 0.45\%$. In the nonsuction region downstream of the suction area the velocity fluctuations with intermediate suction increased to $\left(\frac{u'}{U_\infty}\right)_{max} = 0.87\%$ 6" downstream of the suction region, and one turbulent burst was observed every 10 seconds on the average at this location. High frequency oscillations of relatively low intensity were observed beyond the edge of the newly established laminar boundary layer, originating probably from the nonsucked turbulent eddies of the original turbulent boundary layer.

When less suction was applied in chamber 3 $\left(\frac{-vo_3}{U_\infty} = .001\right.$ instead $\left.\text{of } 0.002\right)$ the maximum boundary layer velocity fluctuations increased from $\frac{u'max}{U_\infty} = 0.45\%$ at the end of chamber 2 to $\frac{u'max}{U_\infty} = 0.82\%$ at the end of chamber 3 and to $\frac{u'max}{U_\infty} = 1.1\%$ 6" downstream of the suction area, with turbulent bursts occurring at the latter station every two to three seconds.

The essential features of the process of restarting a laminar boundary layer with distributed suction are illustrated by the oscilloscope traces on Figure 18. These traces are for the intermediate suction case and correspond to the data of Figure 17. On Figure 18, reading from top to bottom of a column of traces corresponds to moving downstream at approximately constant height above the surface, and reading across a row from left to right is equivalent to moving higher in the boundary layer at a fixed chordwise location. The significant change in the traces is the reduction and eventual elimination of the high frequency velocity fluctuations close to the surface originating probably from the nonsucked turbulent eddies. The data behind the first chamber exhibit a considerable amount of high frequency turbulent velocity fluctuations with no significant reduction of oscillation frequency near the model surface. The fact that the magnitude and the frequency spectrum of these traces correspond to the outer portion of the tripped turbulent boundary layer suggests that the strong suction in chamber 1 removes the lower portion of the turbulent layer completely. At the aft end of chamber 3 where the suction inflow is more nominal and extends over a longer chordwise length (1 ft.), the turbulent oscillations are definitely reduced and at 6" downstream of the suction area the flow is laminar with no high frequency fluctuations near the model surface. The fact that some turbulent vorticity persists in the outer part of the restarted laminar boundary layer is again indicated by the right hand trace of the 6" downstream data. The unsymmetrical shape of the turbulent traces with the high frequency spikes moving up to indicate a velocity reduction is typical of hot wire observations in strongly sucked turbulent boundary layers throughout this investigation. Overall, Figure 18 graphically illustrates the effects of the application of strong suction to remove the turbulent boundary layer and prevent the creation of new turbulent eddies, presumably of the form of hairpin vortices near the model surface for the purpose of restarting a laminar boundary layer.

Figure 19 shows a logarithmic plot of the maximum boundary layer velocity fluctuations $\frac{u'_{max}}{U_\infty}$ at various chordwise locations in the suction area versus the suction quantity coefficient C_Q (based on span of suction area and total chordwise length (2 ft.) of suction region) of the suction area upstream ot the corresponding measuring station for moderate, intermediate and strong suction. Trip 4 was used. The unit length Reynolds numbers were 800,000/ft. for moderate and strong suction, and 710,000/ft. for intermediate suction. With increasing suction rates the maximum boundary layer velocity fluctuations decreased rapidly at all measuring stations. The somewhat higher suction rates required to maintain a certain maximum boundary layer velocity fluctuation at the end of chambers 2 and 3, as compared with the station at the end of chamber 1, are partially explainable by the fact that weak additional suction in chambers 2 and 3 was required to avoid a growth of laminar boundary layer oscillations in this area. In addition the data on Figure 18 show that for the same value of $\frac{u'}{U_\infty}$ the strength of high frequency (turbulent) fluctuations is reduced in chambers 2 and 3, as compared to chamber 1.

In order to carry a reasonably undisturbed laminar boundary layer over longer distances the maximum boundary layer velocity fluctuations should probably not exceed those measured with intermediate suction $\frac{u'_{max}}{U_\infty} \leq 0.5\%$. The corresponding suction rates which are necessary to maintain a maximum boundary layer velocity fluctuation $\frac{u'_{max}}{U_\infty} = 0.5\%$ at the end of the first, second and third suction chamber with trip 4 are then 5%, 15% and 28% larger, respectively, as compared with the total suction quantity in all 3 chambers with trip 4 and moderate suction, as shown in Figures 7 and 10. These suction rates are somewhat larger than the total flow volume Q_δ contained in the initial turbulent boundary layer with trip 4; i.e. somewhat more than the total turbulent boundary layer must be removed by suction if an undisturbed laminar boundary layer must be re-established which can carry for a considerable distance without becoming turbulent.

Whether or not it is possible to re-establish laminar flow without removing essentially the entire turbulent boundary layer by means of suction depends on: 1) whether or not the dissipation of the remaining nonsucked turbulent eddies of the initially turbulent boundary layer can be strongly accelerated perhaps by means of a combination with non-Newtonian fluids, stable boundary layer temperature gradients, etc.; 2) whether or not the re-established laminar boundary layer can be sufficiently stabilized in the presence of the nonsucked turbulent eddies originating from the initially turbulent boundary layer by additional means (for example compliant surfaces, etc.).

The question arises as to how far a re-established laminar boundary layer can continue before transition to turbulent flow occurs. Figure 21 shows the growth in chordwise direction of the maximum velocity fluctuations u'_{max} in the re-established laminar boundary layer versus the length RN $\frac{U\Delta x'}{\nu}$, based on the chordwise distance measured from the end of the suction region, together with the corresponding values u'_{max} in the area upstream of the suction region versus length RN $\frac{Ux}{\nu}$ (x measured from the plate leading edge). In order to start with a length Reynolds number of zero the Reynolds number scale in Figure 21 has been shifted by an amount $\Delta Rx = 2.25 \cdot R_{\theta_E}{}^2$ to the right, where θ_E = boundary layer momentum thickness at the end of the suction plate.

According to Figure 21 the boundary layer velocity fluctuations downstream of the suction area with "strong" and "intermediate" suction are somewhat weaker and stronger, respectively, than the corresponding values on the plate in the area upstream of the suction region at the same length Reynolds numbers R_x and $\frac{U\Delta x'}{\nu}$. Thus, with intermediate suction the boundary layer velocity fluctuations under the action of the residual nonsucked turbulent eddies increase with length Reynolds number $\frac{U\Delta x'}{\nu}$ at a somewhat faster rate than in the area upstream of the suction region, and transition of the re-established laminar boundary layer would have to be expected somewhat earlier unless additional stabilization would be provided by weak suction or flow acceleration. On the other hand the velocity fluctuations in the newly established laminar boundary layer with strong suction are weaker than upstream of the suction region, and the re-established laminar boundary layer would carry at least as far as in an area of the plate where the boundary layer is everywhere laminar.

With "moderate" suction the velocity fluctuations induced into the re-established laminar boundary layer by the nonsucked turbulent eddies are probably much too high to enable a long laminar run without a further stabilization by means of relatively strong suction, etc.

In order to re-establish an undisturbed laminar boundary layer, after having become turbulent, which will remain laminar for a considerable length Reynolds number, it thus appears that it is necessary to remove essentially the entire turbulent boundary layer as well as most of the turbulent eddies which penetrate out into the potential flow region, unless more powerful methods can be established to drastically increase the dissipation of the remaining nonsucked turbulent eddies (in fluid flows perhaps by the addition of visco-elastic liquids, or possibly by highly stable temperature gradients within the boundary layer or very strong local flow acceleration, etc.).

It would be highly desirable to repeat the experiments of this report in a low turbulence wind tunnel up to much higher length Reynolds numbers on a low drag suction wing as well as on a suction body of revolution. In principle the present two-dimensional results should be applicable to the re-establishment of laminar flow on a body of revolution.

Drag estimates show that the suction quantities and the corresponding equivalent suction drag required to re-establish laminar flow in the front part of a wing are quite high and largely compensate for the reduction in friction drag (Reference 6) unless most of the rather large kinetic energy of the sucked turbulent boundary layer is recovered. In this case it is preferable to apply strong suction first through a few individual suction slots, shaped as diffusors, followed by weaker suction either through a series of slots (shaped if necessary as diffusors) or a porous or perforated sheet. Suction experiments with individual slots shaped as diffusors (References 7 and 8) have shown pressure recovery factors of the order of 70% to 80%. Another method to recover most of the kinetic energy of the suction air of the original turbulent boundary layer might be to strongly decelerate the flow at the beginning of the suction region, where strong suction is applied. (Instead of decelerating the sucked turbulent boundary layer in slot diffusors it is probably more efficient to rapidly decelerate the turbulent boundary layer in the first part of the suction region, with suction applied for example through several individual slots and chambers.)

A drag estimate is shown for a two-dimensional wing with a re-established laminar boundary layer. The following assumptions are made:

Wing chord RN $R_c = 50 \cdot 10^6$

Transition to turbulent flow at 0.05 C

Suction rate to re-establish laminar flow at 0.10 C $(Q_a/Q_\delta)_{0.10\ C} = 1.5$

With $\theta_{0.10\ C} = 0.00017 \cdot C$, (C = wing chord)

$$C_Q = \frac{Q_a}{U_\infty S_{wing}} = 0.0027$$

With an average kinetic energy of the suction air of $0.84 \cdot q_\infty$ and a pressure recovery factor $\eta = 0.75$ of the suction air the pressure rise coefficient $C_{p_g} = \frac{\Delta p_g}{q_\infty}$ to accelerate the suction air to free stream velocity U_∞ is:

$$C_{p_g} = (1 - 0.84) + (1 - \eta)\ 0.84 = 0.37$$

and the equivalent suction drag is

$$C_{D_s} = C_Q \cdot C_{p_g} = .00100 \text{ (for one wing side)}$$

The wing profile drag of the remaining laminarized wing from 0.10 C to the wing trailing edge is estimated for one wing side: $\Delta C_{D_\infty} = 0.00045$. The total wing profile drag coefficient, including the equivalent suction drag, is $C_{D_\infty} = 0.00045 + C_{D_s} = 0.00145$ (one wing side). The estimated corresponding value for one side of a fully turbulent wing is: $C_{D_{\infty turb}} \cong 0.0033$. The drag of a two-dimensional wing with a re-established laminar boundary layer thus can be reduced by more than 50% provided a large percentage of the kinetic energy of the suction air, where laminar flow is re-established, can be recovered.

Assuming no recovery of the kinetic energy of the sucked air the corresponding drag values are appreciably higher:

$$C_{D_\infty} = C_Q \cdot C_{p_g} + \Delta C_{D_\infty} \cong 0.0027 + 0.00045 = 0.00315$$

This value is practically the same as for the fully turbulent wing.

The suction rates and the equivalent suction drag required to re-establish laminar flow far forward on a suction body of revolution are lower than in the two-dimensional case of a wing, as long as the diameter of the body at the location, where laminar flow is re-established, is smaller than the average body diameter. Assuming transition to turbulent flow on a Reichardt body at 5% of its length and re-establishment of full length laminar flow beyond 10% body length the total body drag (including the equivalent suction drag) might be reduced by somewhat more than 60%, provided again that a large percentage of the suction air at the station, where laminar flow is re-established, is recovered in slots with diffusors.

By far the most economical application of boundary layer suction, with the purpose in mind of re-establishing laminar flow, is in the area of local disturbances, both on low drag suction wings and bodies. A particularly important example has been the re-establishment of laminar flow at the front attachment or stagnation line of swept low drag suction wings by means of local suction at the stagnation line (Reference 9). Compared with the total suction flow rates and profile drag of a swept low drag suction wing the suction quantity and the equivalent suction drag, due to re-establishment of laminar flow at the wing attachment line, are negligibly small.

Other applications of suction to re-establish laminar flow appear less attractive from a drag standpoint such as in the case of suction on a body of revolution at several annular stations, or at the downstream end of a region with an adverse pressure gradient.

In all cases the new re-established laminar boundary layer will be first quite thin and thus rather sensitive to surface roughness. Under otherwise the same conditions, however, the critical roughness Reynolds number in the re-established laminar boundary layer should be essentially the same as far the case of a continuously laminar boundary layer.

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9. W. Pfenninger; Flow phenomena at the leading edge of swept wings, "Recent developments in boundary layer research," AGARDograph 97, Part IV, May 1965.

TABLE I

TRIP NOMENCLATURE

NUMBER	DESCRIPTION	LOCATION (Inches Ahead of Suction Insert
1	1/2" spaced, .070" dia. spheres	20
2	.020" dia. wire	20
3	.020" dia. wire	5
4	1/2" spaced, .025" high x .050" dia. disks	5

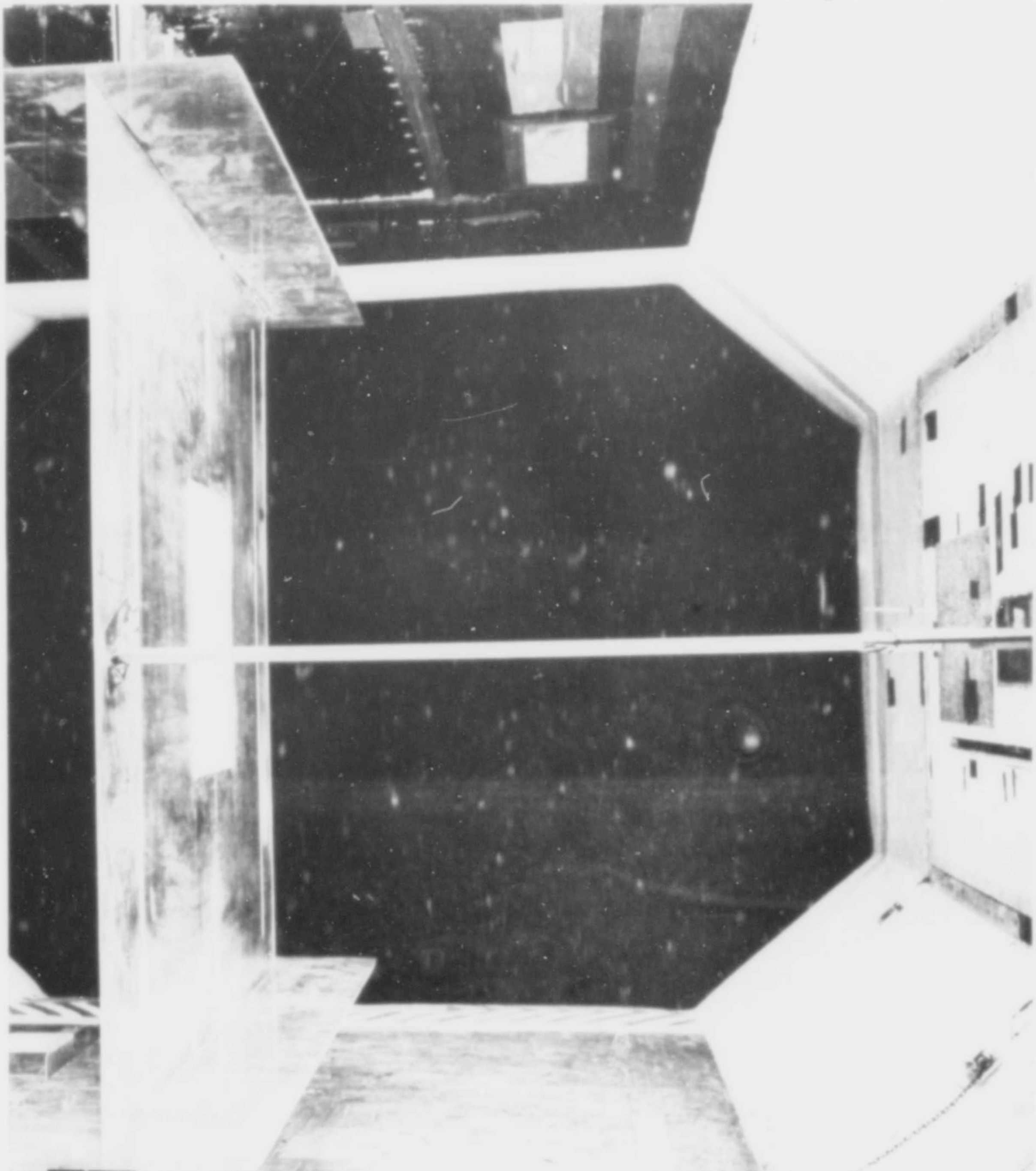
TABLE II

OPTIMUM CHORDWISE SUCTION DISTRIBUTION

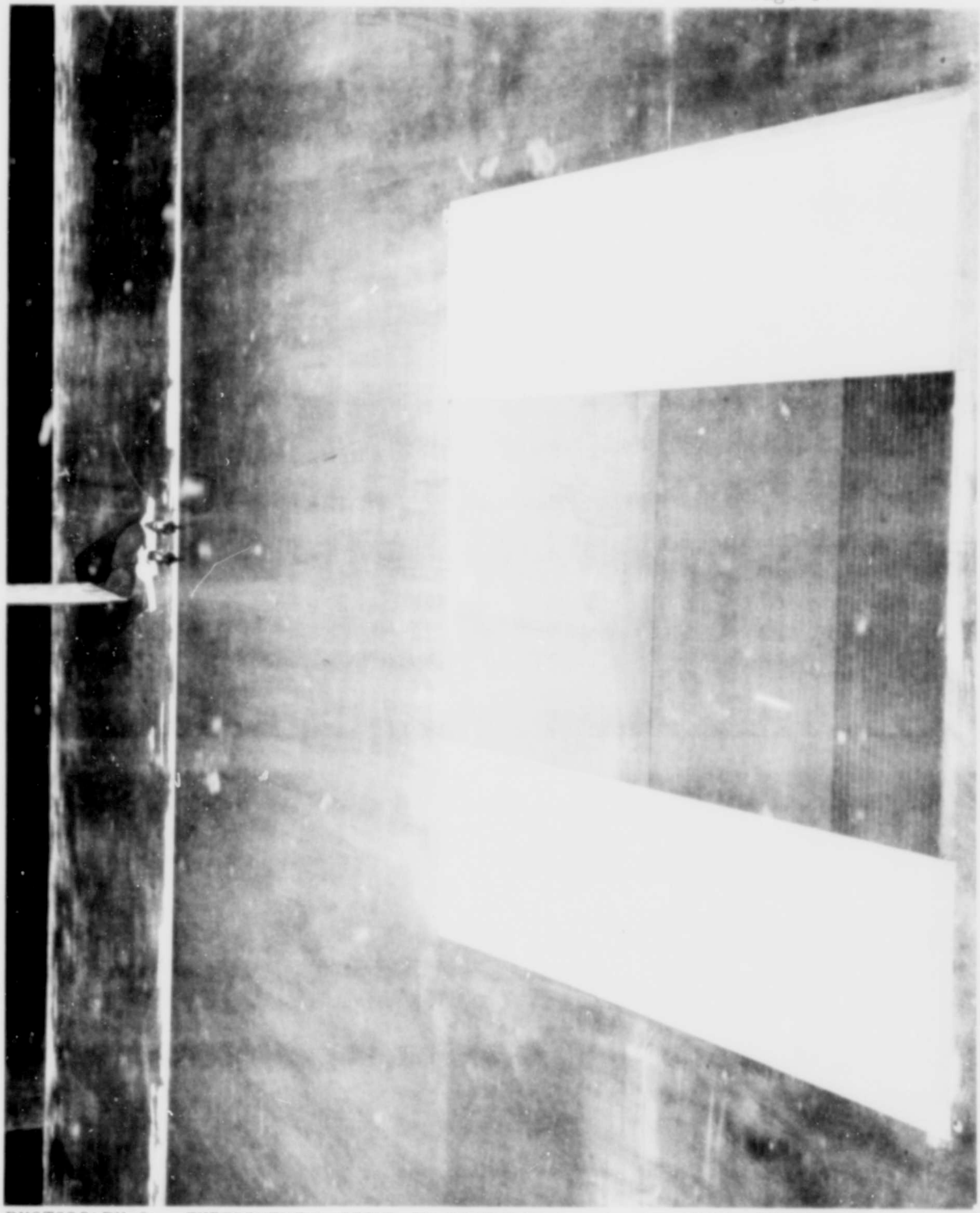
$$\frac{U_\infty}{\nu} \cong .7 \times 10^6/\text{ft.}$$

MODERATE SUCTION

TRIP	INCHES DOWNSTREAM FOR LAMINAR FLOW	SUCTION QUANTITY (FT³/SEC) Chamber Number: 1, Width (Inches): 4	Chamber Number: 2, Width (Inches): 8	Chamber Number: 3, Width (Inches): 12	PERCENT SUCTION QUANTITY Chamber Number: 1, Width (Inches): 4	Chamber Number: 2, Width (Inches): 8	Chamber Number: 3, Width (Inches): 12
1	12	2.55	.65	.66	66	17	17
2	12	2.50	.58	.59	68	16	16
2	6	2.54	.38	.47	75	11	14
3	6	1.38	.44	.38	63	20	17
4	6	.73	.47	.63	40	26	34

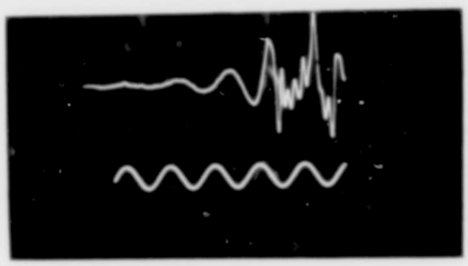


PHOTOGRAPH 1: EXPERIMENTAL SETUP IN NORTHROP 8 x 11 ft. WIND TUNNEL



PHOTOGRAPH 2: EXPERIMENTAL SETUP IN NORTHROP 8 x 11 ft. WIND TUNNEL

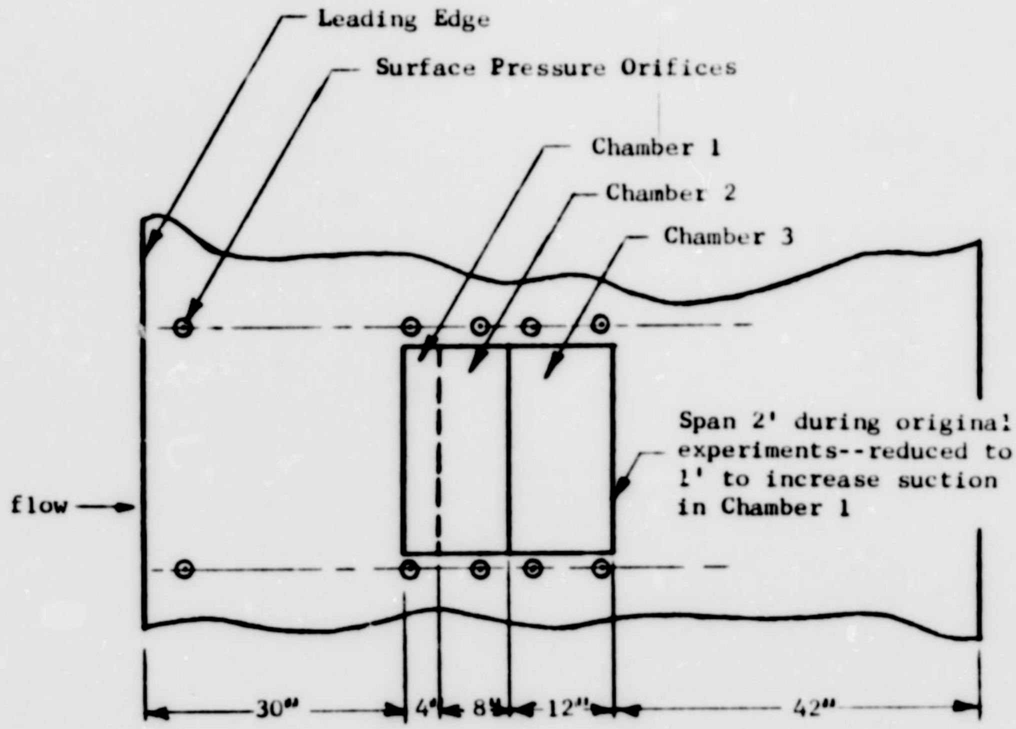
FIGURE 1: HOT WIRE OSCILLOSCOPE PICTURE OF TURBULENT BURST AT FRONT ATTACHMENT LINE OF SWEPT WING

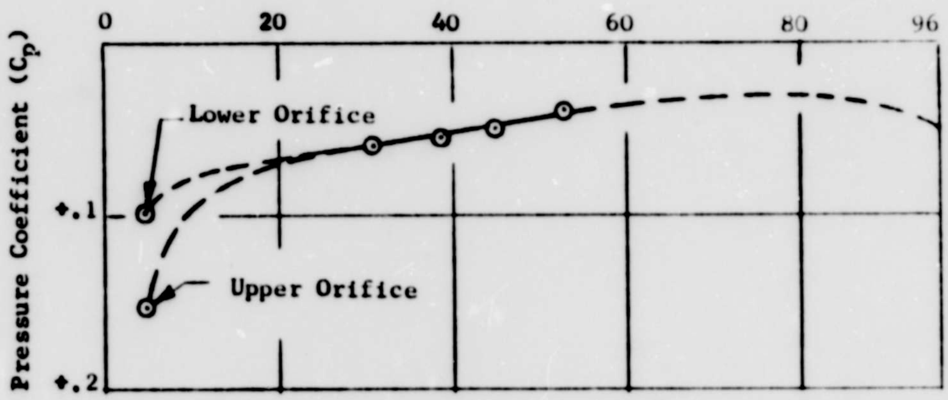


Sine Wave Reference

Frequency = 300 cps

FIGURE 2: EXPERIMENTAL SETUP AND CHORDWISE PRESSURE DISTRIBUTION





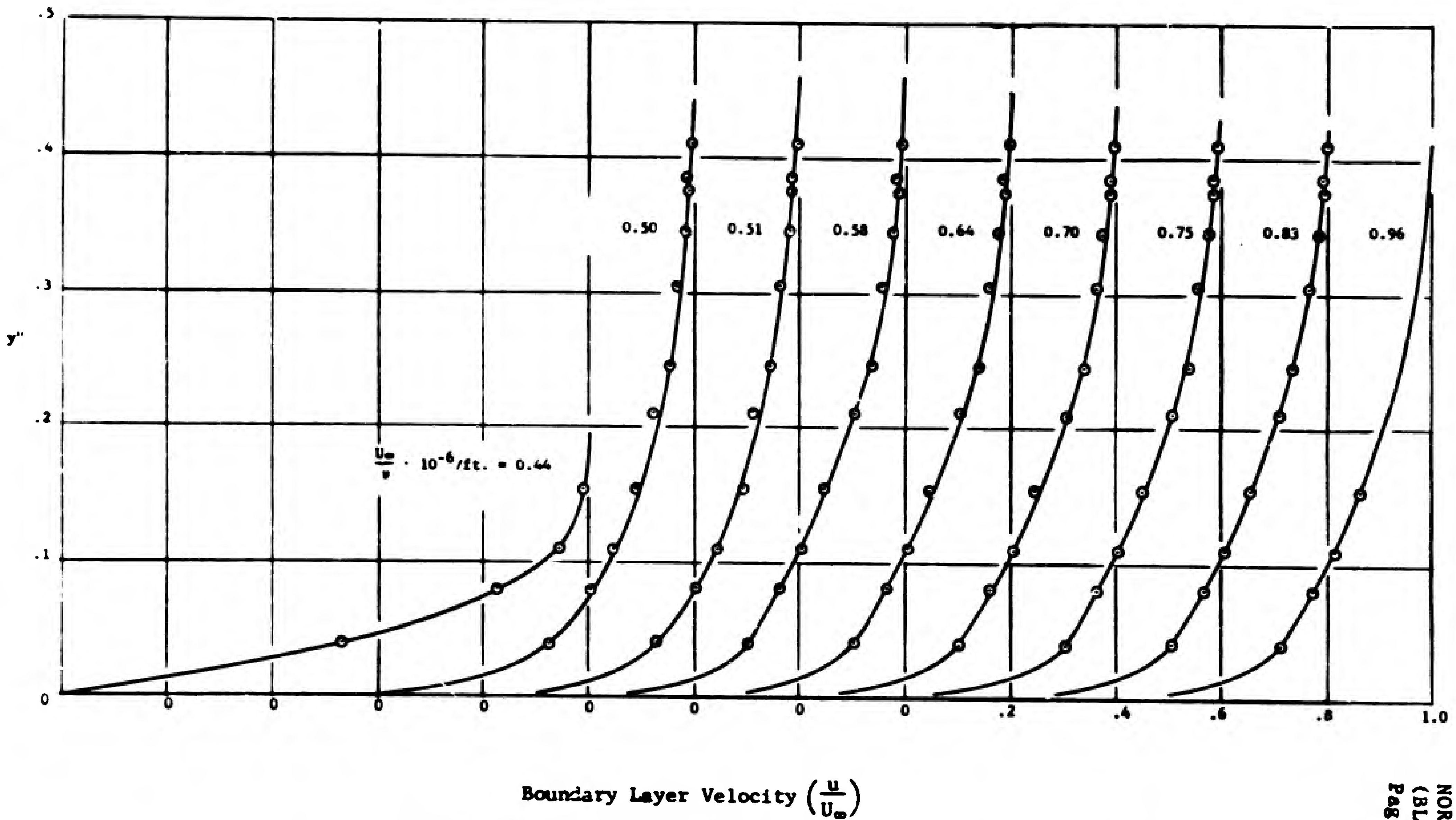
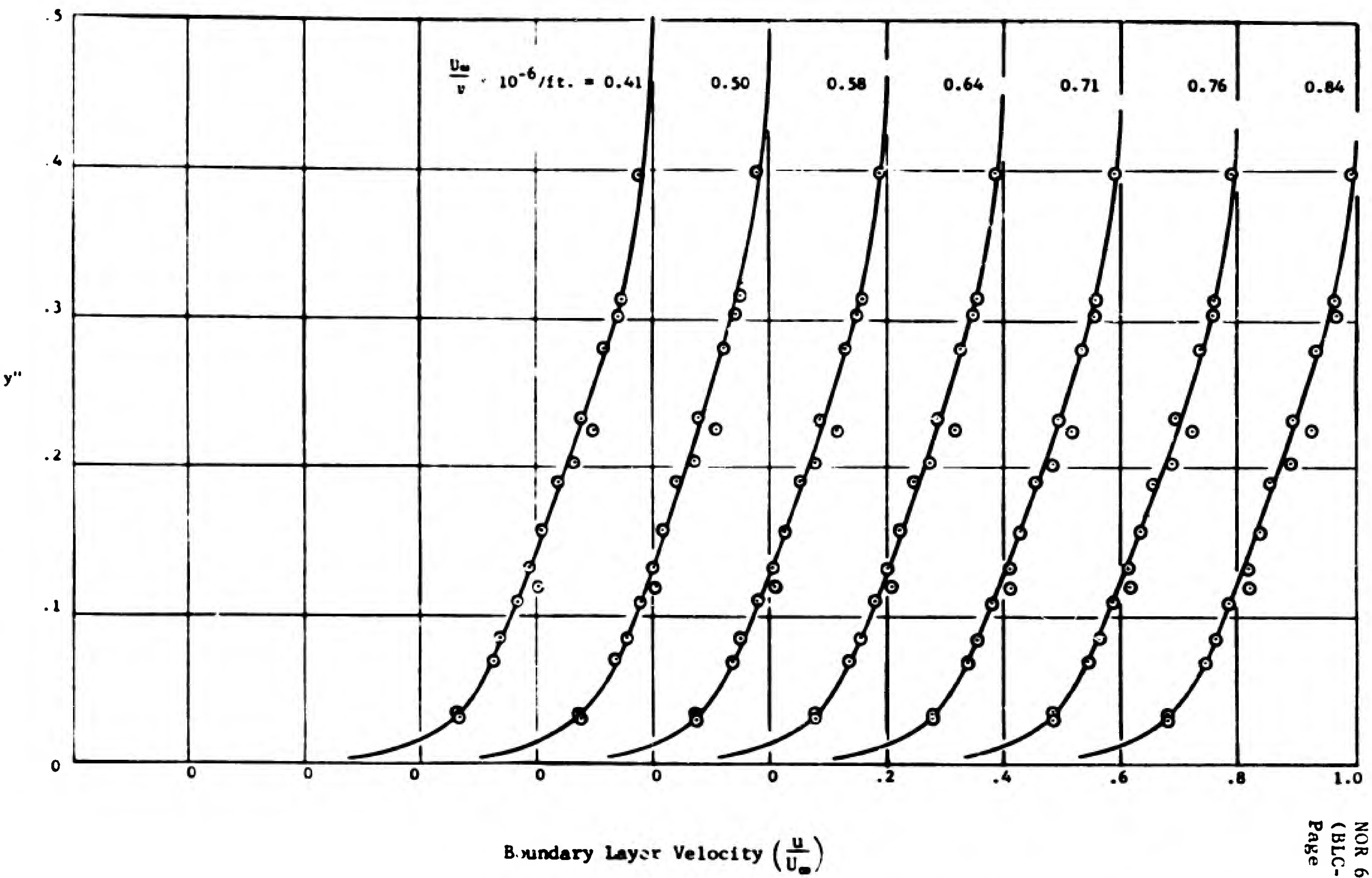


FIGURE 4: TURBULENT BOUNDARY LAYER PROFILES AT THE UPSTREAM END OF THE SUCTION AREA
TRIP 2



$\frac{U_\infty}{\nu} \cdot 10^{-6}$/ft. = 0.41
0.50
0.58
0.64
0.71
0.76
0.84
y"
.5
.4
.3
.2
.1
0
0
0
0
0
0
0
.2
.4
.6
.8
1.0
Boundary Layer Velocity $\left(\frac{u}{U_\infty}\right)$

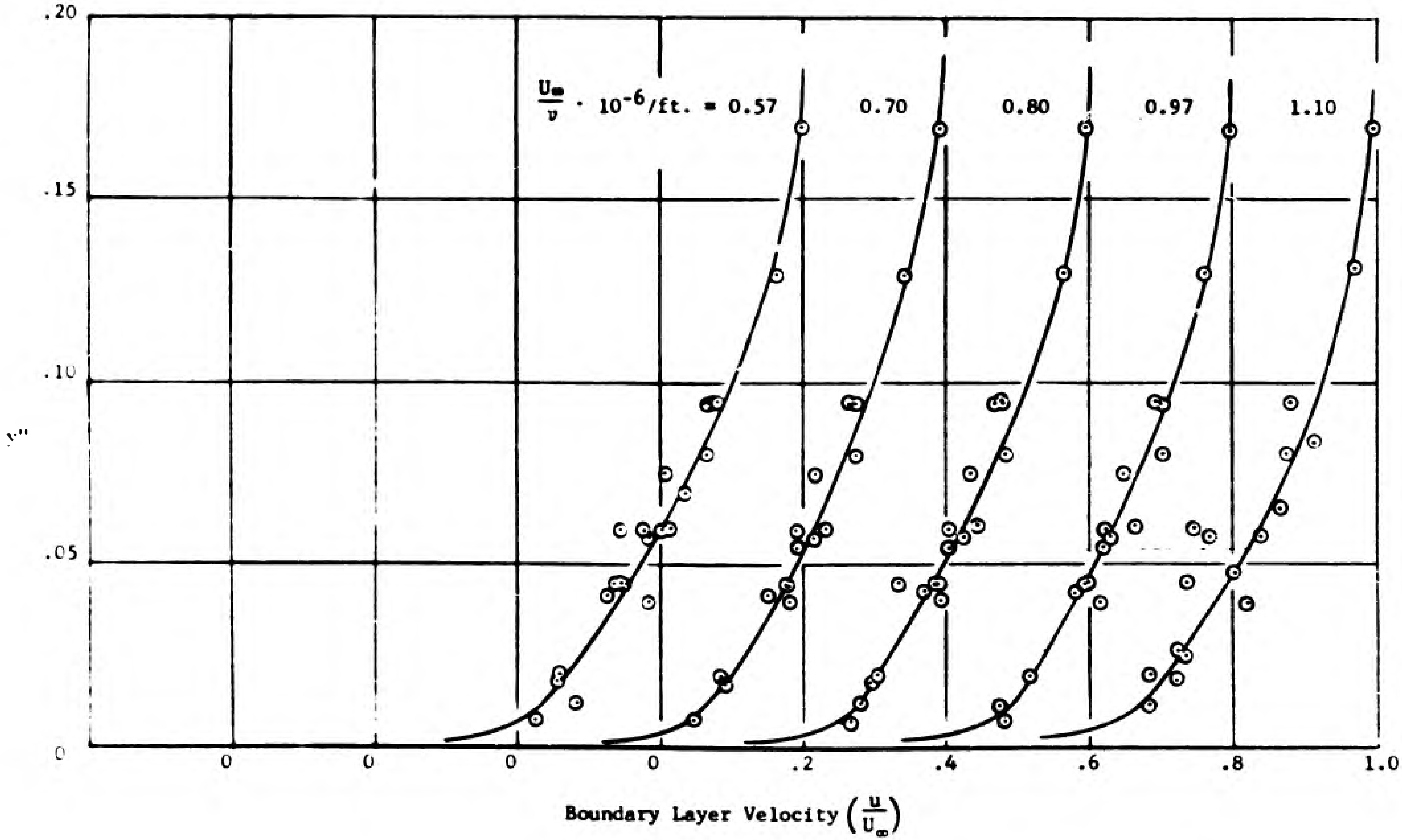
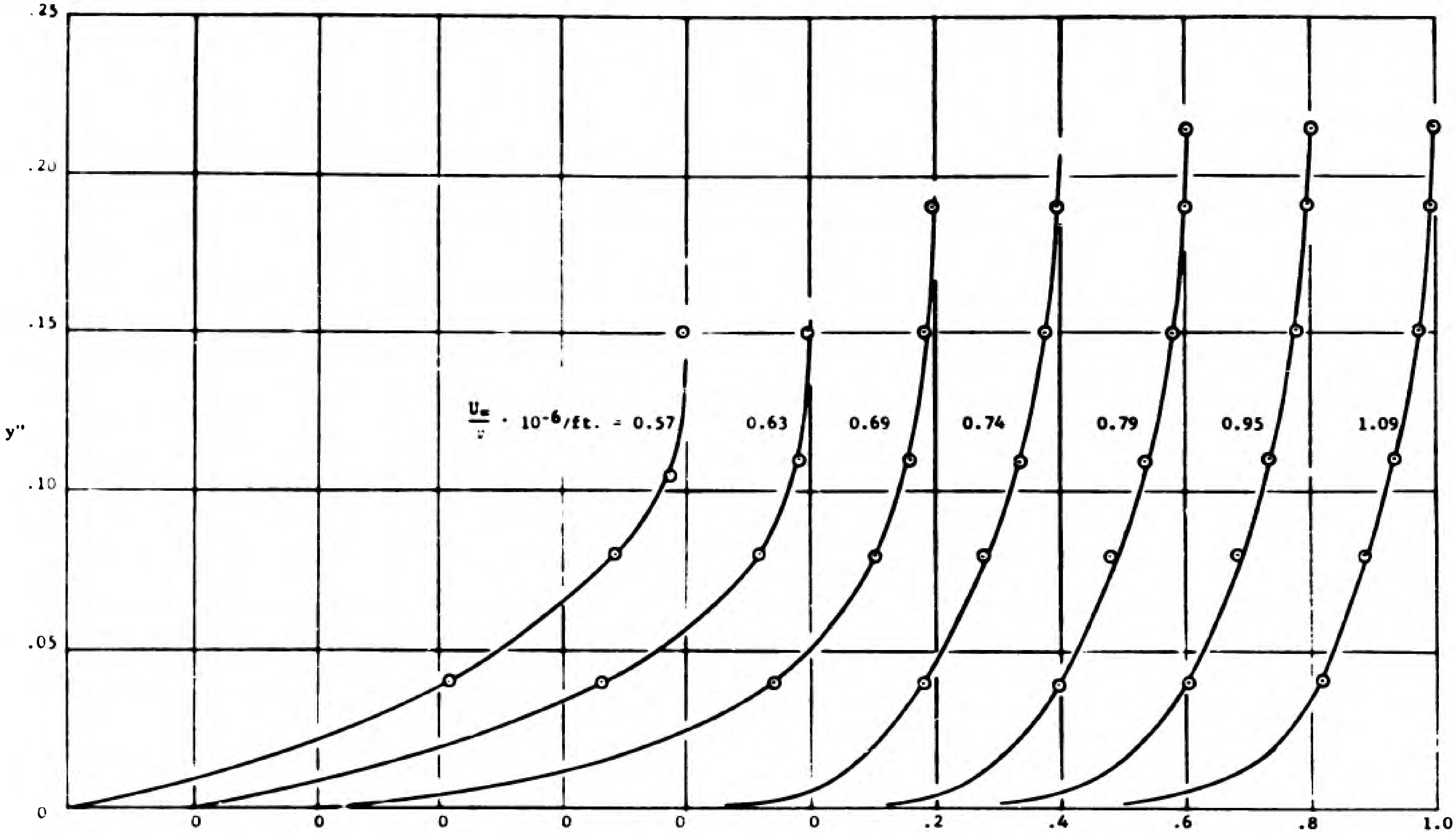


FIGURE 6: TURBULENT BOUNDARY LAYER PROFILES AT THE UPSTREAM END OF THE SUCTION AREA
TRIP 4



Boundary Layer Velocity $\left(\frac{u}{U_\infty}\right)$

FIGURE 5: TURBULENT BOUNDARY LAYER PROFILES AT THE UPSTREAM END OF THE SUCTION AREA
TRIP 3

FIGURE 7: SUCTION REQUIRED FOR RESTARTED LAYER TO CARRY 6" DOWNSTREAM VS. UNIT REYNOLDS NUMBER

MODERATE SUCTION (1 BURST/5 SECONDS)

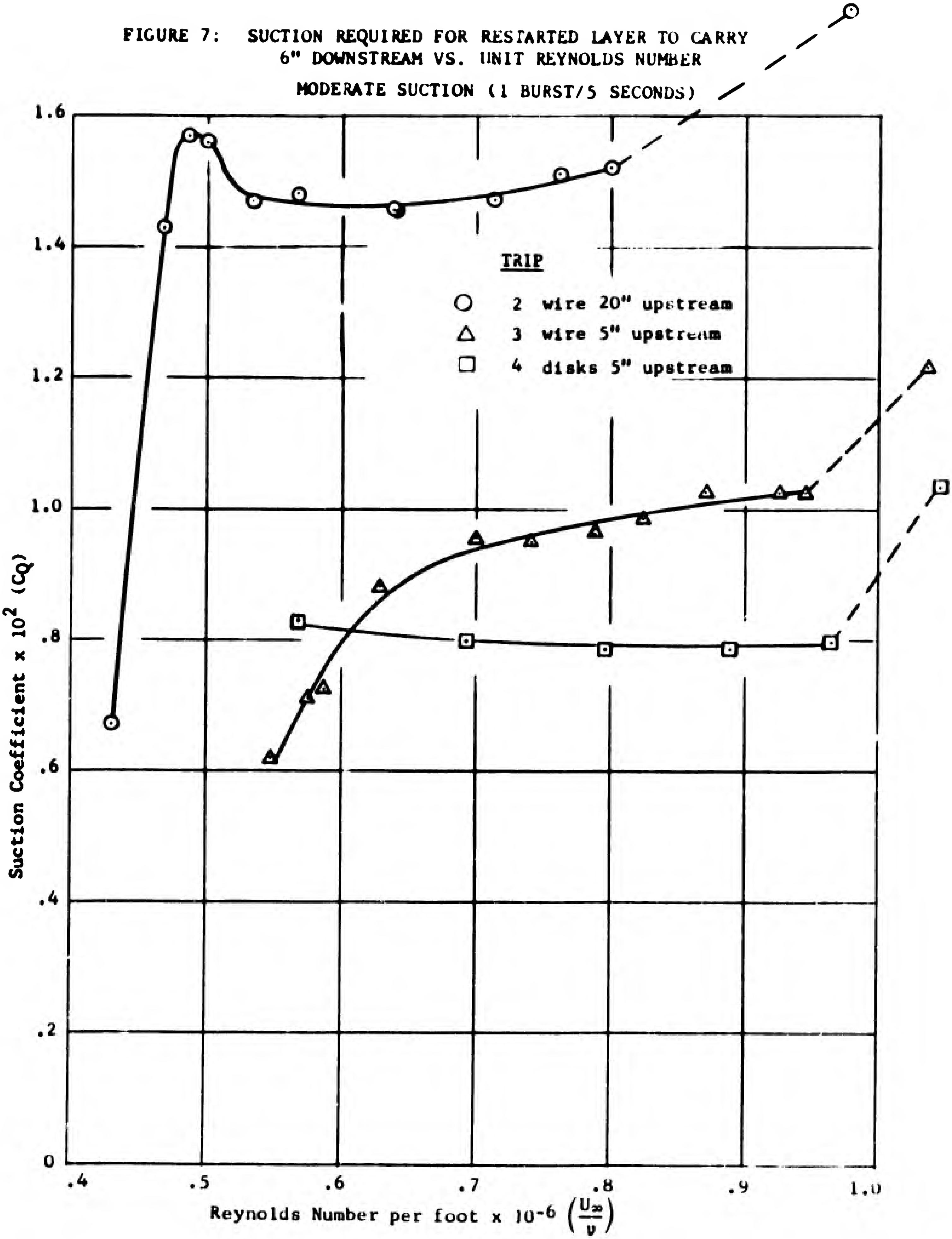


FIGURE 8: SUCTION COEFFICIENT REQUIRED FOR RESTARTED LAYER TO CARRY 12" DOWNSTREAM VS. UNIT REYNOLDS NO.

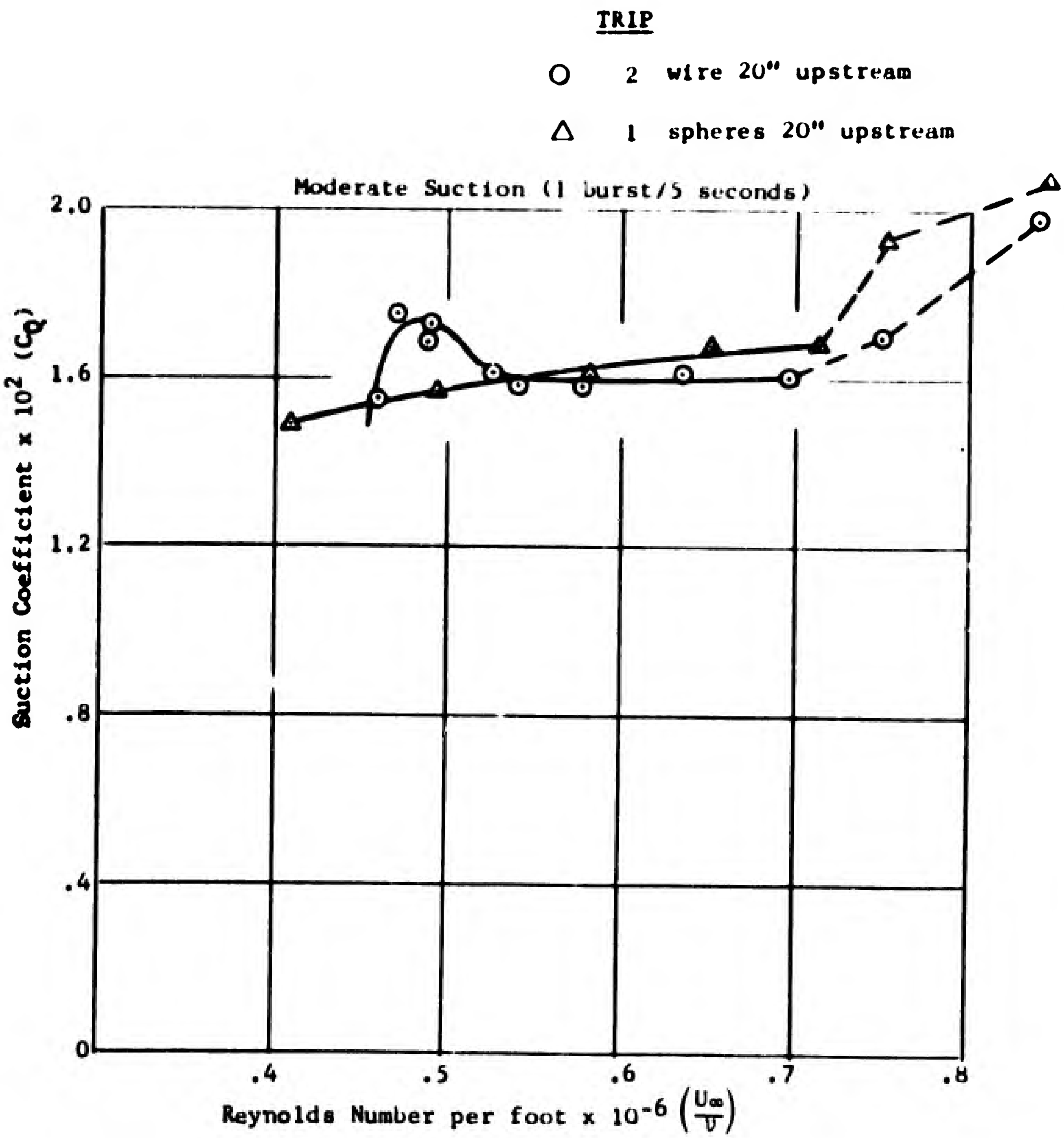


FIGURE 9: SUCTION REQUIRED FOR RESTARTED LAMINAR LAYER TO CARRY VARIOUS DISTANCES DOWNSTREAM VS. UNIT REYNOLDS NUMBER

	Probe Location		Suction
○	Aft Edge of Suction Insert	Strong	No turbulent bursts
△	3" Downstream of Insert	Moderate	1 burst/5 seconds
⊡	6" Downstream of Insert	Moderate	1 burst/5 seconds
▽	12" Downstream of Insert	Moderate	1 burst/5 seconds
◇	24" Downstream of Insert	Moderate	1 burst/5 seconds

Trip 2

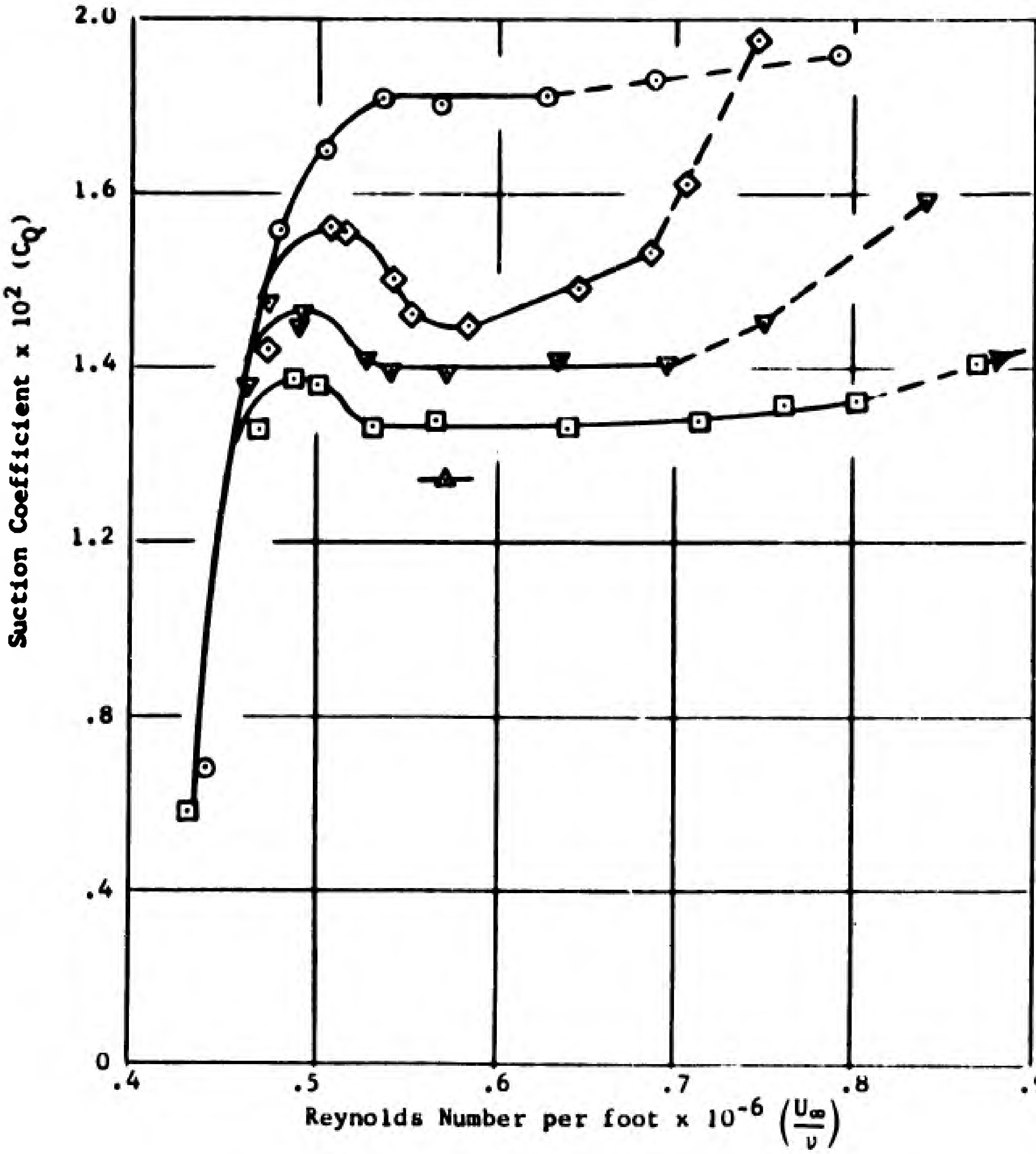


FIGURE 10: HEIGHT OF SUCKED LAYER REQUIRED FOR LAMINAR RESTART VS. UNIT REYNOLDS NUMBER

Trip	Probe Location
1	12" Downstream of Insert
2	12" Downstream of Insert
3	6" Downstream of Insert
4	6" Downstream of Insert

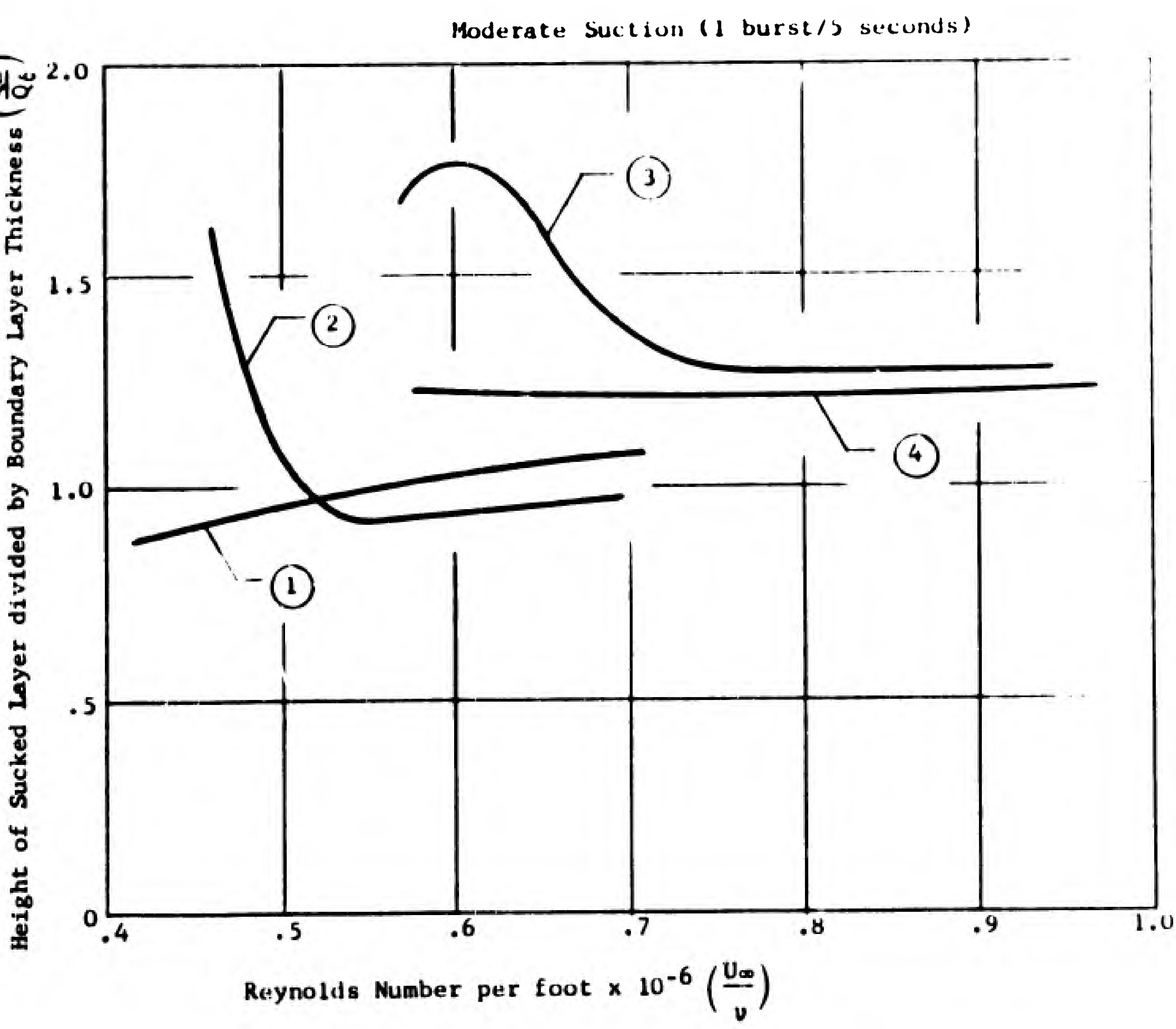


FIGURE 11

TRIP 4 - 100 TO 5000 CPS
MODERATE (1 BURST/5 SECONDS) SUCTION

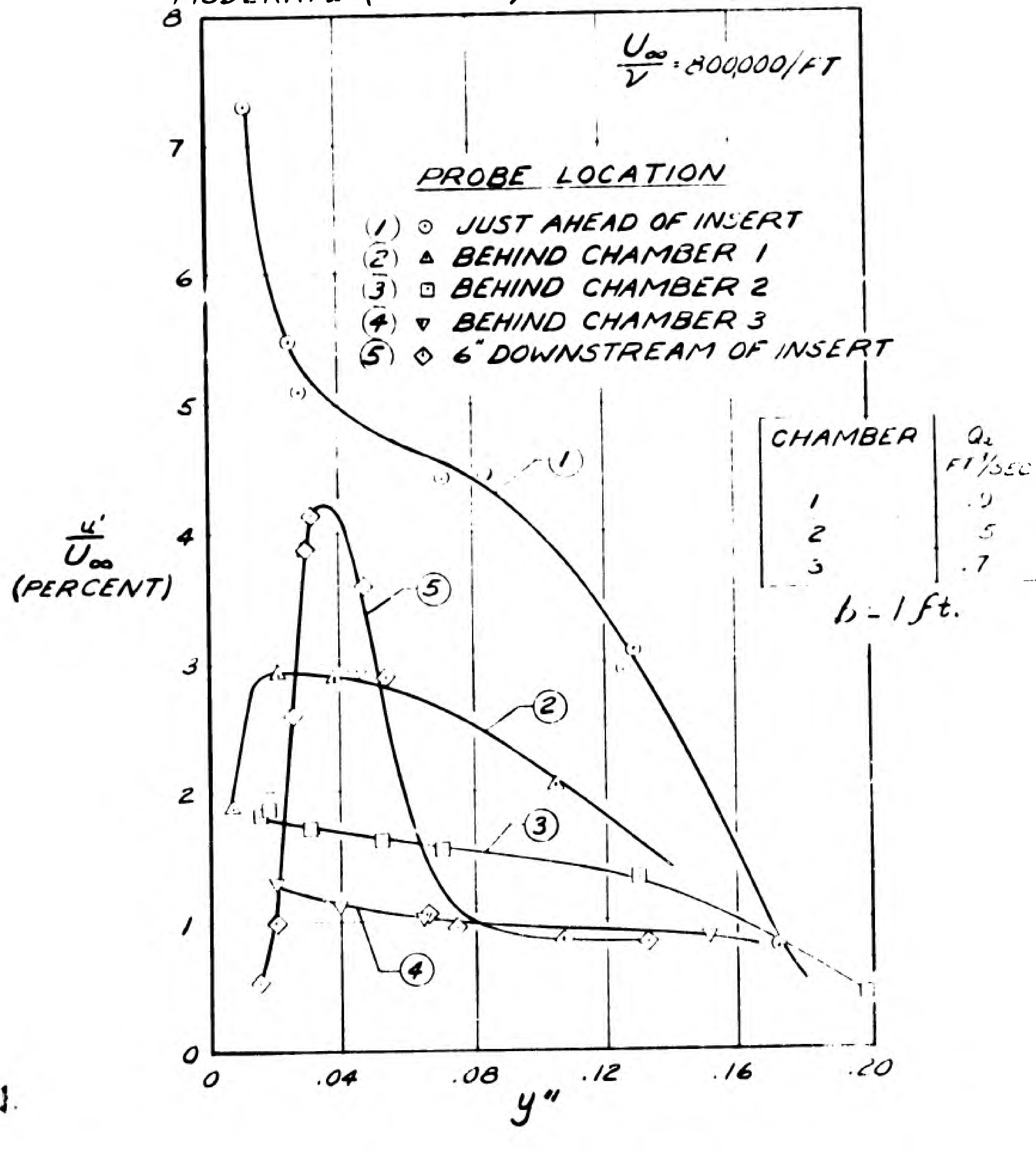
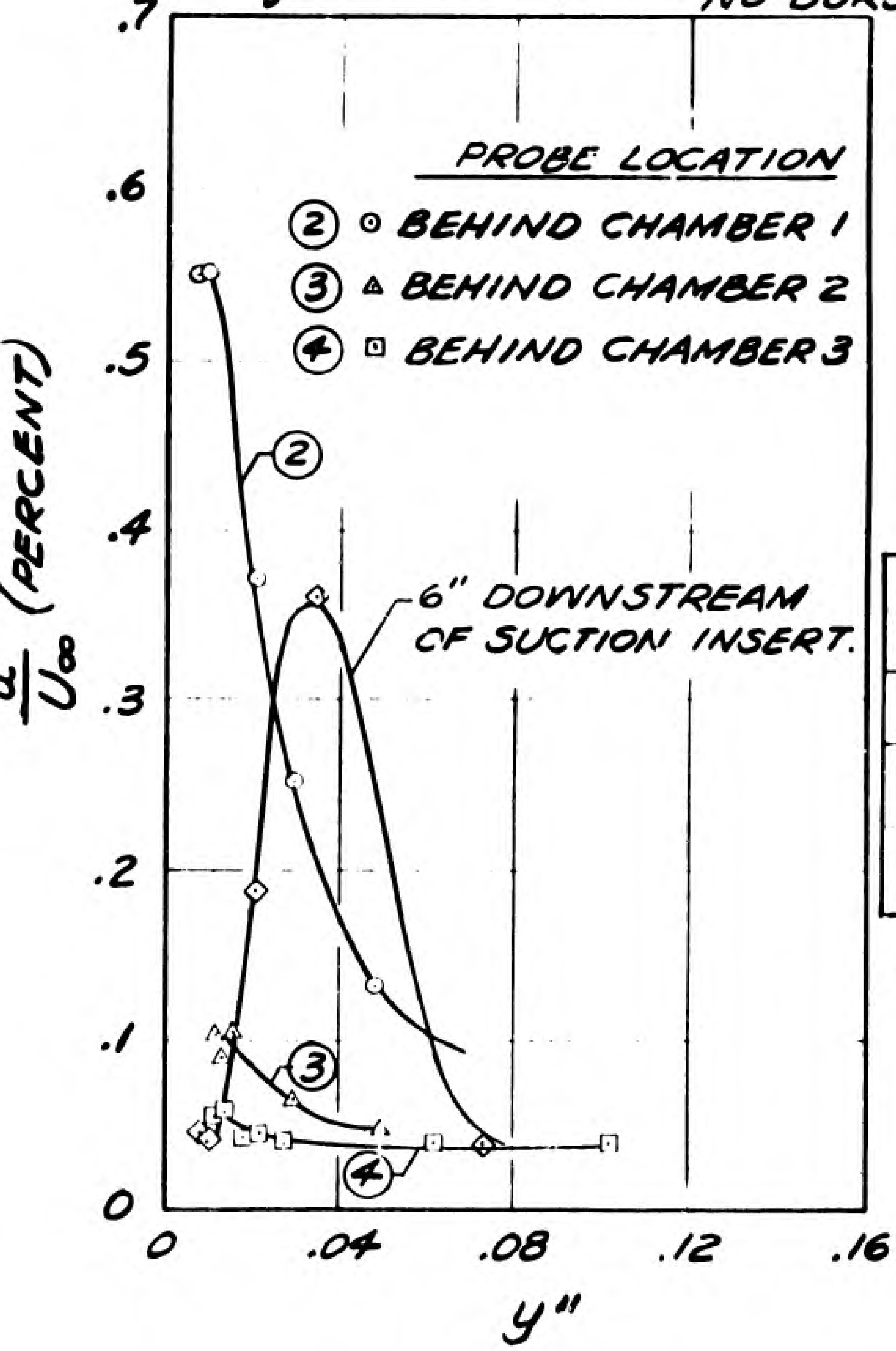


FIGURE 12
VELOCITY FLUCTUATIONS IN BOUNDARY LAYER

TRIP 4, 100 TO 5000 CPS

$\frac{U_\infty}{V} = 800{,}000$ / FT. STRONG SUCTION
NO BURSTS



CHAMBER	Q_a FT³/SEC
1	2.1
2	.9
3	1.3

b = 1 ft

FIGURE 13: HOT WIRE OSCILLOSCOPE TRACES IN RESTARTED LAMINAR BOUNDARY LAYER 6" DOWNSTREAM OF SUCTION INSERT

$.80 \cdot 10^6$ Per Foot Unit Reynolds Number

Moderate Suction (1 burst/5 seconds)

Trip 4

$y = 0.025''$

$\frac{u'}{U_\infty} = 2.61\%$

$\frac{U_\infty}{\nu} = 800{,}000/\text{ft.}$

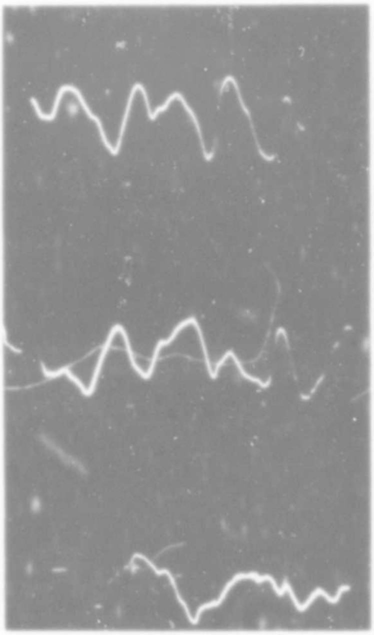


FIGURE 14: HOT WIRE OSCILLOSCOPE TRACES IN RESTARTED LAMINAR BOUNDARY LAYER 6" DOWNSTREAM OF SUCTION INSERT

$.80 \cdot 10^6$ Per Foot Unit Reynolds Number

Moderate Suction (1 burst/5 seconds)

Trip 4

$y = 0.107''$

$\frac{u'}{U_\infty} = .83\%$

$\frac{U_\infty}{\nu} = 800{,}000/\text{ft.}$

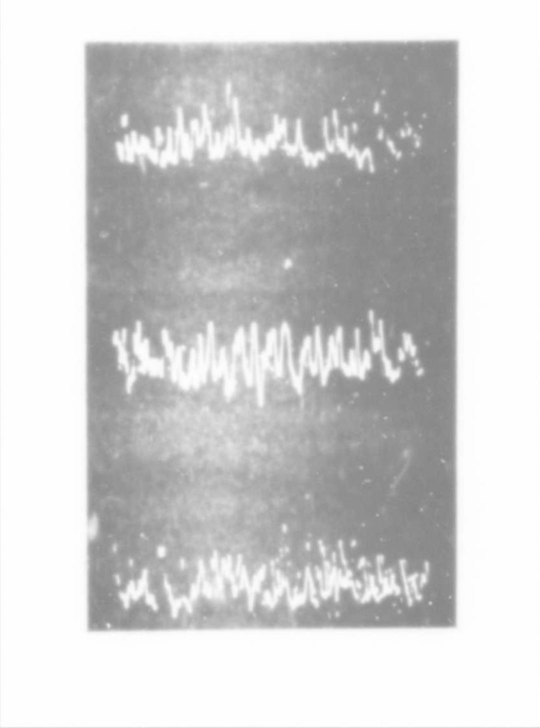


FIGURE 15: LAMINAR BOUNDARY LAYER VELOCITY FLUCTUATIONS 20" DOWNSTREAM FROM THE PLATE LEADING EDGE

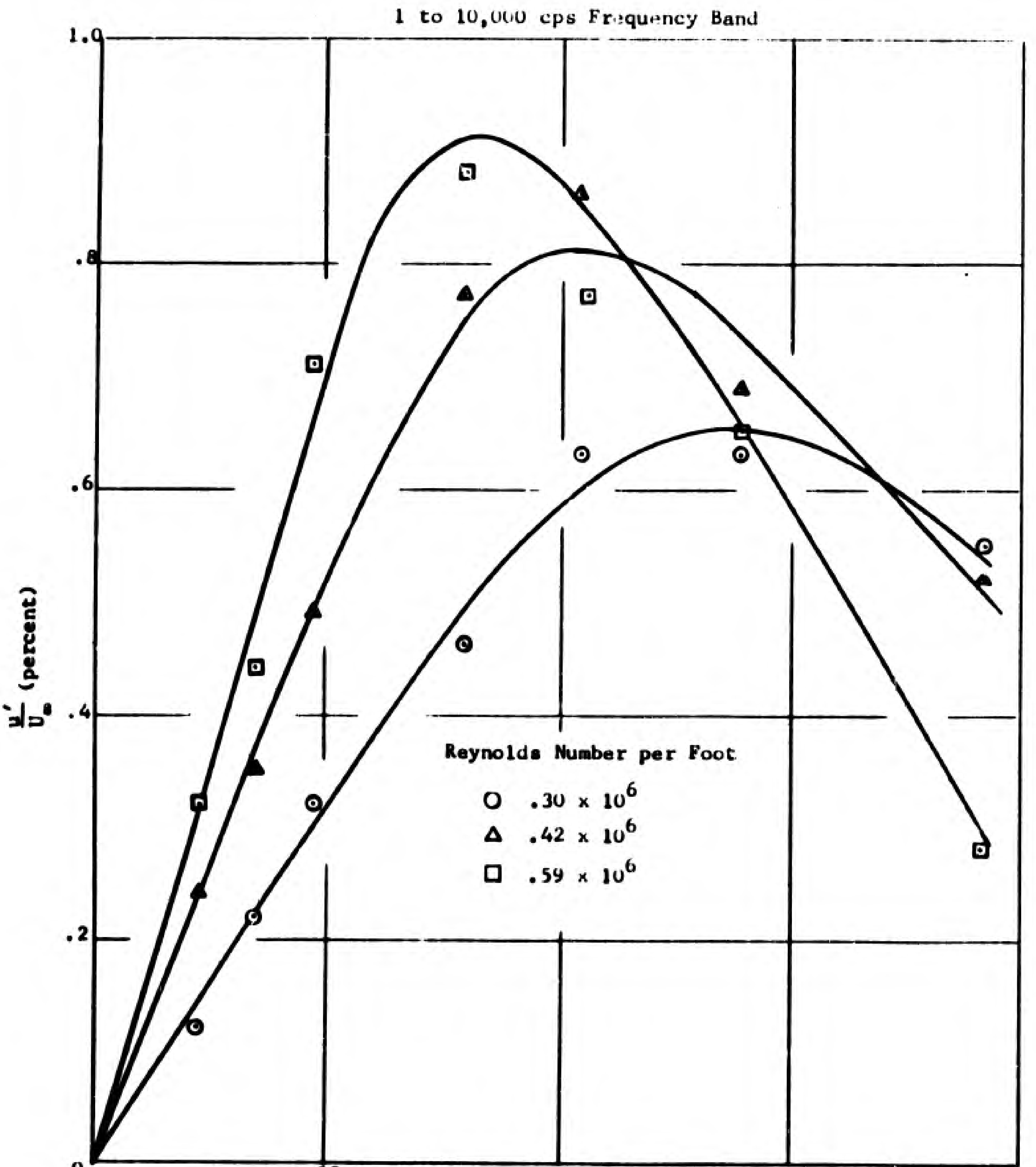
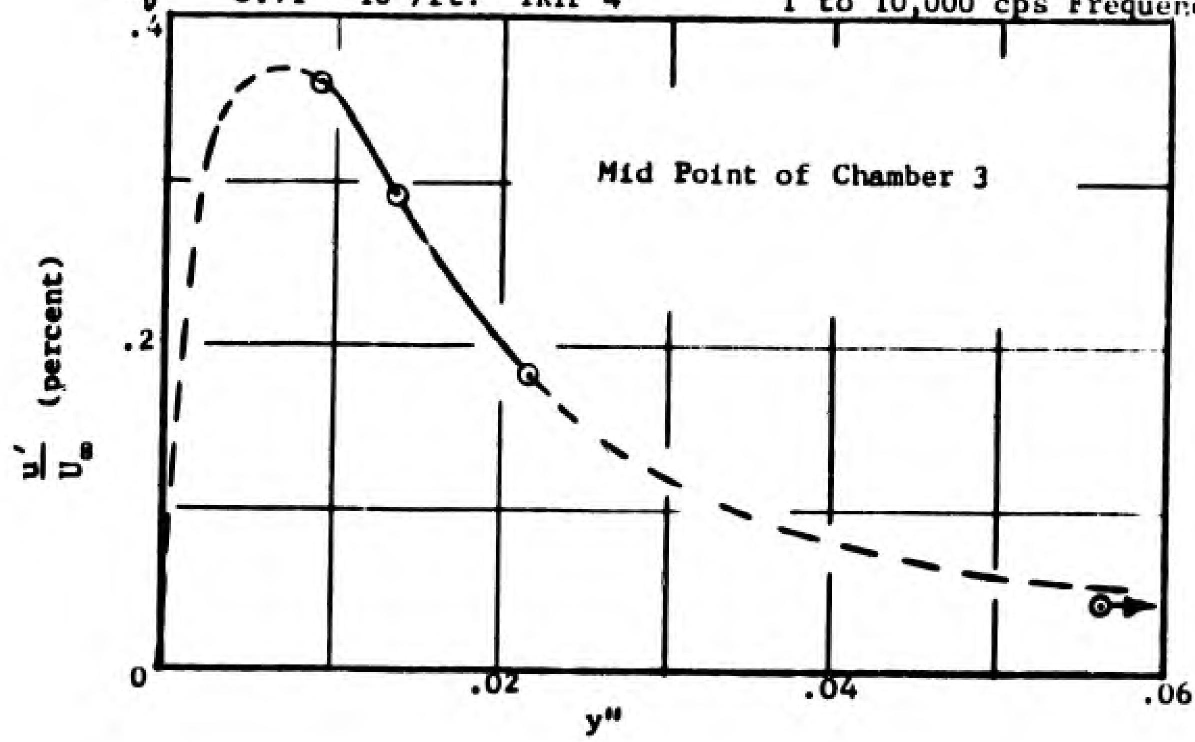


FIGURE 16: BOUNDARY LAYER VELOCITY FLUCTUATIONS WITH $\frac{u'_{max}}{U_\infty}$ IN THE REGION OF THE THIRD CHAMBER HELD CONSTANT TO 0.36%

$\frac{-vo_1}{U_\infty} = .048$, $\frac{-vo_2}{U_\infty} = .012$, $\frac{-vo_3}{U_\infty} = .001$

$\frac{U_\infty}{\nu} = 0.71 \cdot 10^6/ft.$ TRIP 4 1 to 10,000 cps Frequency Band



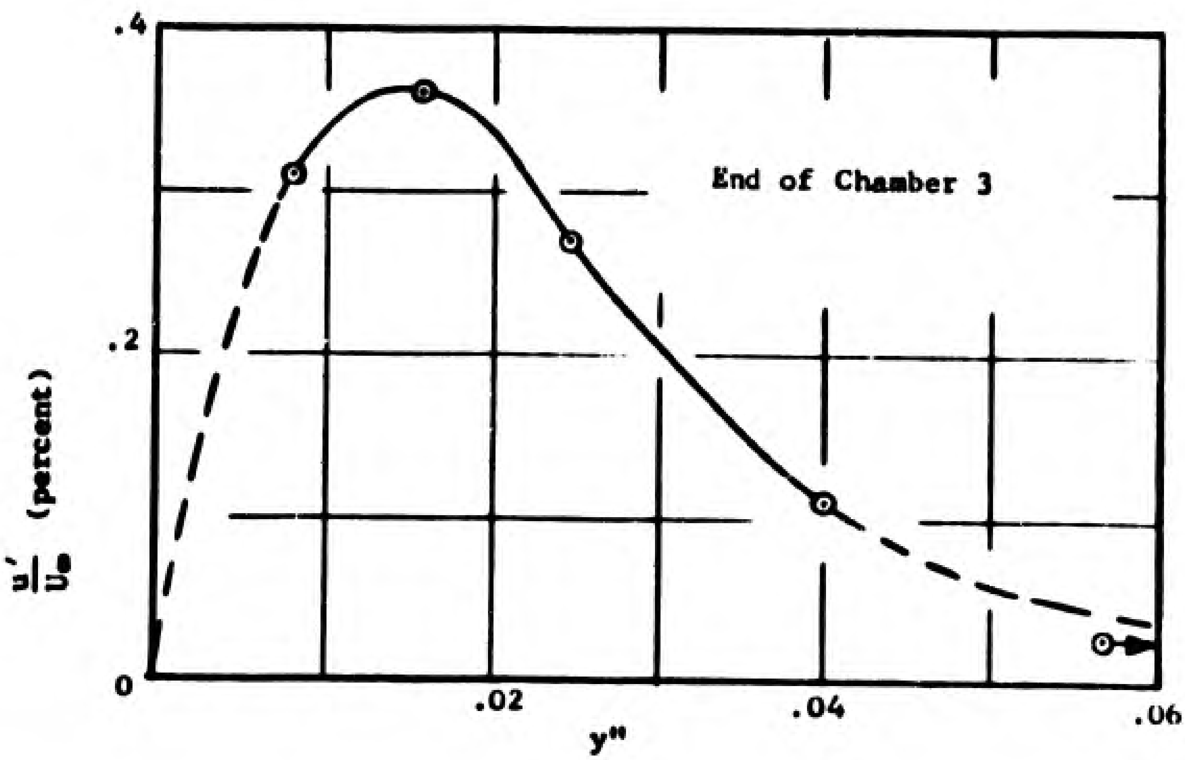


FIGURE 17: BOUNDARY LAYER VELOCITY FLUCTUATIONS AT VARIOUS CHORDWISE STATIONS IN AND DOWNSTREAM OF THE SUCTION AREA AND "INTERMEDIATE" SUCTION

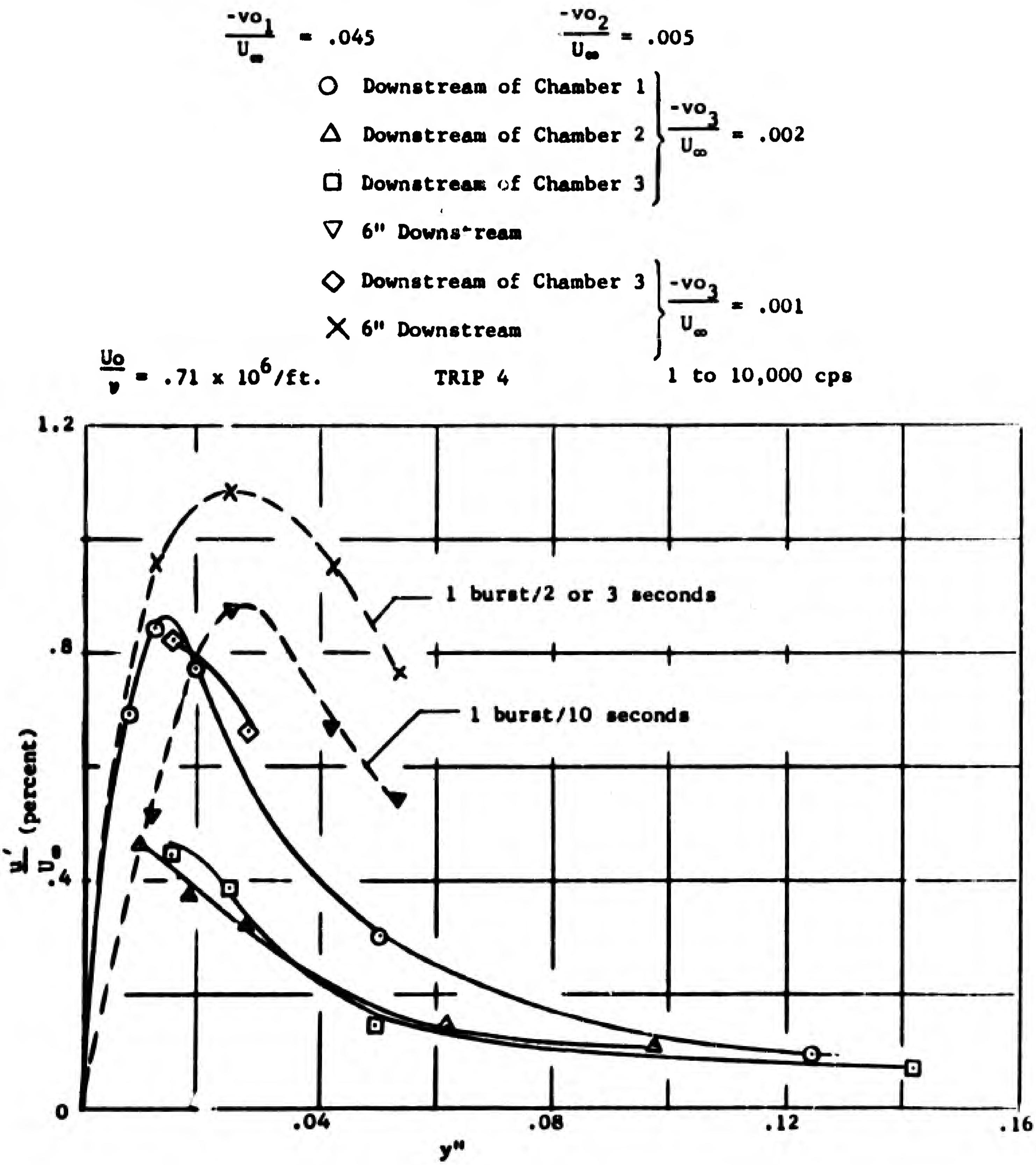


FIGURE 18: HOT WIRE OSCILLOSCOPE TRACES WITH INTERMEDIATE SUCTION AT VARIOUS CHORDWISE LOCATIONS

1 to 10,000 cps, $\frac{-vo_3}{U_\infty} = .002$

$\frac{U_\infty}{\nu} = .71 \times 10^{-6}/\text{ft.}$

TRIP 4

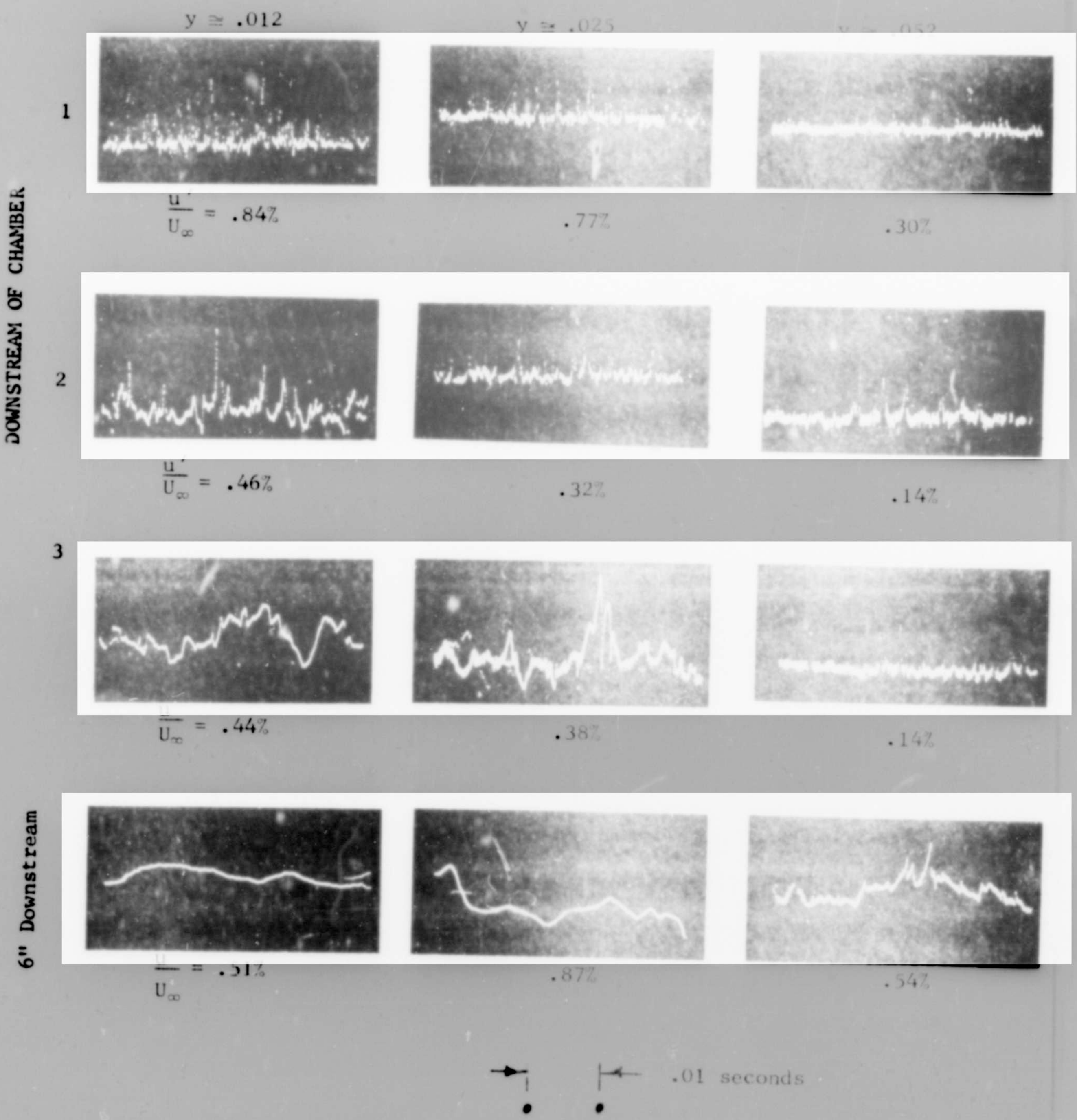


FIGURE 19: VARIATION OF THE MAXIMUM BOUNDARY LAYER VELOCITY FLUCTUATION AT VARIOUS CHORDWISE LOCATIONS VS. C_Q AND Q_a/Q_δ

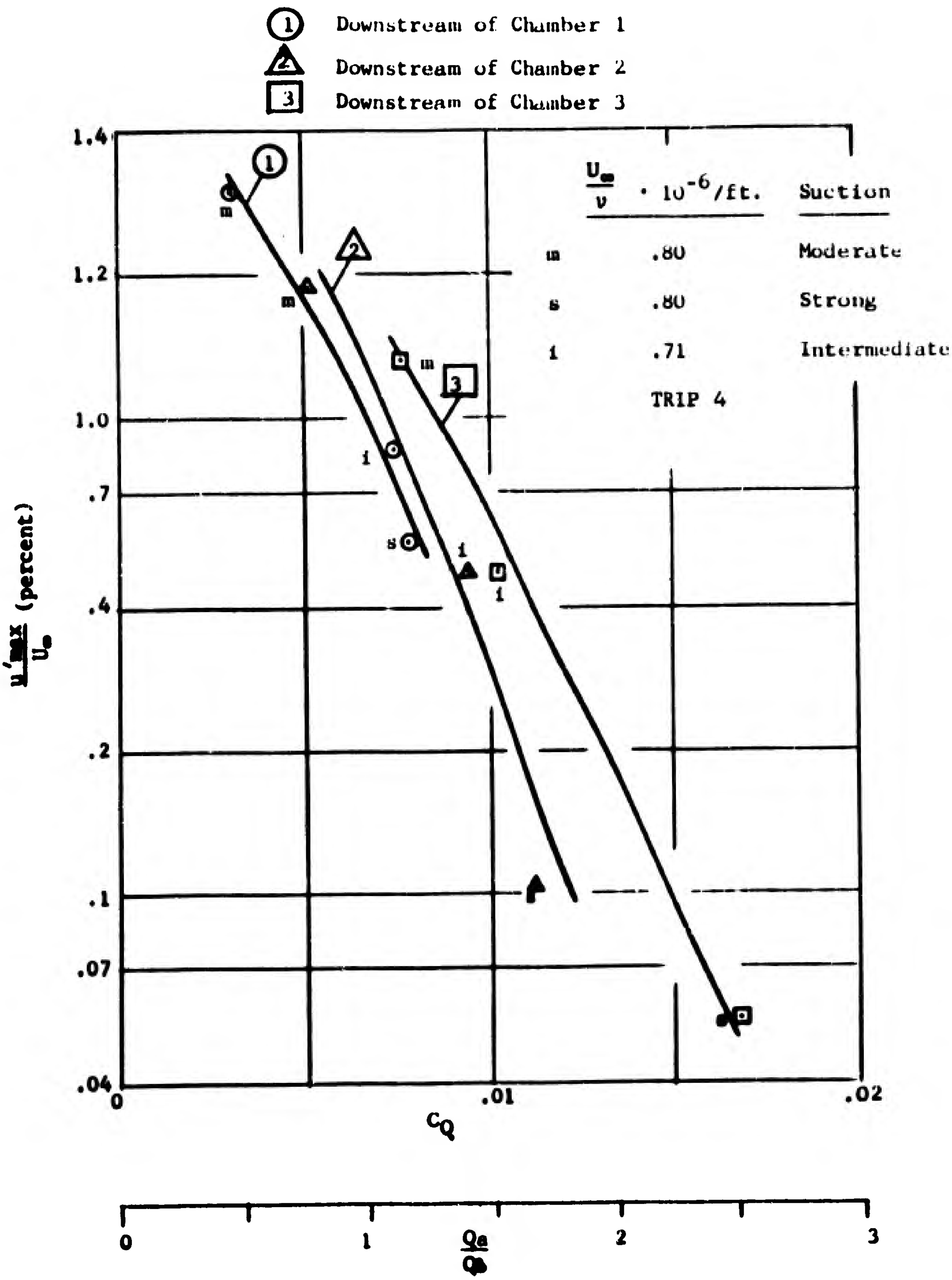


FIGURE 20: BOUNDARY LAYER PROFILES WITH INTERMEDIATE SUCTION

$$\frac{U_\infty}{\nu} \simeq .72 \times 10^{-6}/ft.$$

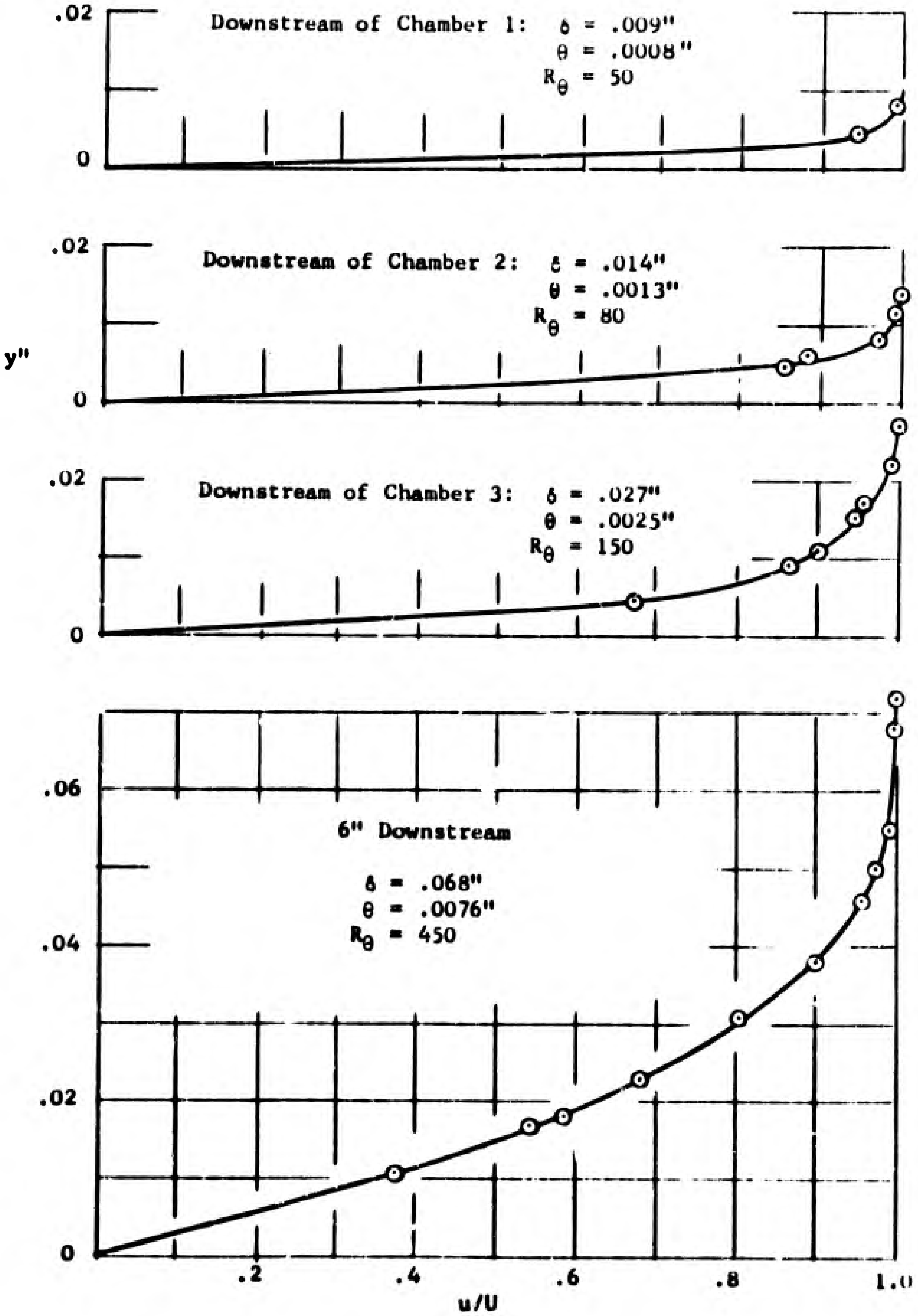


FIGURE 21: CHORDWISE GROWTH OF THE MAXIMUM BOUNDARY LAYER VELOCITY FLUCTUATION u'_{max} UPSTREAM AND DOWNSTREAM OF THE SUCTION REGION