ABSTRACT

SHOCK-INDUCED SEPARATION OF ADIABATIC TURBULENT BOUNDARY LAYERS IN SUPERSONIC AXIALLY SYMMETRIC INTERNAL FLOW

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INTRODUCTION

This paper reports the results of an experimental investigation at $M \sim 4$ of shock-induced turbulent boundary layer separation at the walls of axially symmetric flow passages, with particular emphasis placed on determining the shock strengths required for incipient separation. The shock waves were produced by interchangeable sting-mounted cones placed on the axes of the flow passages and aligned with the freestream flow. The interactions under study simulate those encountered in axially symmetric engine inlets of supersonic aircraft. Knowledge of the shock strengths required for boundary layer separation in inlets is important since for shocks of somewhat greater strength rather drastic alterations in the inlet flow field may occur.

Many studies of turbulent supersonic boundary layer separation due to shock impingement, compression corners and steps have been conducted over

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the past twenty years. See, for example, References 1-3 for some of the early studies. More recent studies include those reported in References 4-8. In most of the previous investigations two-dimensional configurations have been employed to produce the interactions under study. In some instances flows over axially symmetric cylinder-flare arrangements have been examined. The present study differs from those cited above in that the interactions are produced at the walls of cylindrical wind tunnels. Such interactions are of interest in their own right because of their similarity to those encountered in axially symmetric engine inlets. In addition, questions which may arise with two-dimensional configurations about the influence of end effects on the interaction are avoided.

DETECTION OF INCIPIENT SEPARATION

Incipient separation is defined as that condition for which, in the region under consideration, the wall shear stress is zero at one point but everywhere else positive. Unfortunately, direct measurement of very low values of shear stress is very difficult. As a consequence most methods of detecting incipient separation are based on the first appearance of certain flow field phenomena which are taken to indicate that separation has occurred. Many such methods have been, and continue to be, used, and it is unfortunate that the results obtained seem to vary both with the method used and the facility in which the testing has been done.

In obtaining the results reported here some of the standard methods such as liquid flow patterns at the wall in the interaction region, the orifice dam technique, the wall static pressure distributions and pitot pressure profiles have been used. In addition, however, hot-wire anemometer probes have been used to examine changes in the flow characteristics as the shock strength was varied, the hope being that the resulting signals could be used as indicators of the onset of separation.

The results obtained indicate that separation occurs at considerably lower disturbance strength (as characterized, for example, by the inviscid wall static pressure rise across the incident-reflected shock system) than has been found in most previous studies. This finding is significant with regard to the flow patterns which might be expected to occur in axially symmetric engine inlets in which shock waves are present.

EXPERIMENTAL FACILITY

The present investigation was conducted in two different flow facilities. Both were steady-flow circular wind tunnels consisting of nozzle sections followed by instrumented straight test sections. The smaller of the tunnels had a nominal 2-inch diameter test section and a freestream Mach Number of 3.88. The second tunnel, for which the freestream Mach Number was 4.06, had a nominal 3-inch diameter test section. For both tunnels the boundary layers under study developed on the walls of the nozzles and straight test sections. The boundary layer thickness at the beginning of the interaction in the 2-inch tunnel was approximately 0.20 inches while that for the 3-inch tunnel was approximately 0.3 inches. Variations from these values occurred, of course, as the tunnel unit Reynolds Numbers were varied. For both tunnels rings of flat triangular trips 0.013 inches thick were located just forward of the nozzle throats.

The plenum chamber ahead of the tunnels was supplied with dry air at a nominal temperature of 540°R and a maximum pressure of 70 psia. The discharge from the tunnels was into a large tank evacuated by air ejectors so that the tunnels could be operated over a range of freestream Reynolds Numbers.

Wall static pressures in the test section were obtained at 0.013-inch diameter static pressure ports placed in a line at intervals of 0.10 inches along the test section wall. Static pressure ports were also installed around the periphery of the tunnel so that flow symmetry could be checked.

The conical shock generator could be traversed along the centerline of the tunnel, with one count on the traversing index corresponding to a movement of the cone tip of 0.015 inches. This permitted very detailed static pressure measurements to be made at a given static pressure port as the interaction region was moved with respect to the port.

UPSTREAM BOUNDARY LAYER CHARACTERISTICS

One of the first indications that boundary layers at the walls of axially symmetric passages would separate at lower shock strengths than had been observed in studies of two-dimensional interactions was found by Seebaugh[9] in his study of shock wave boundary layers at $M = 2.82$ and $M = 3.78$. Subsequently, Rose[10] found in a study of a $M = 3.88$ flow that the shock strength required was even lower than that reported by Seebaugh. Rose, Page and Childs[11] in a further study at $M = 3.88$ confirmed the earlier findings of Rose. In view of the low shock strengths required for separation a question naturally arises about the nature of the boundary layer ahead of the interaction. Both hot-wire anemometer and pitot tube traverses of the boundary layers have been made. The results for the 3-inch diameter tunnel are shown in Figures 1-4. Comparable results have been obtained for the 2-inch diameter tunnel.

Figures 1 and 2 indicate that the velocity profiles agree well with the wall-wake representation of turbulent boundary layers as proposed in Reference 12 for both extremes of the Reynolds Numbers used in the study. Figure

3 shows the normalized fluctuating quantity $\sqrt{\overline{(\rho u)'^2}}/\rho u$ and Figure 4 shows the turbulent shear stress $\overline{\rho}\ \overline{u'v'}$. Both of these quantities were obtained directly from constant temperature hot-wire anemometer measurements. The $(\rho u)'$ distribution agrees with that reported by Kistler[13]. While there is some scatter in the $\overline{\rho}\ \overline{u'w'}$ distribution it agrees reasonably well with one reported earlier by Rose[10] and it appears to be consistent with the value of the wall shear stress as determined by a least squares fit of a wall-wake profile to the velocity profile.

In view of the measurements discussed above the boundary layer appeared to be fully turbulent and typical of those which were being investigated in many of the previously reported separation studies.

INCIPIENT SEPARATION RESULTS

Some of the criteria for defining incipient separation which have been used by various investigations are:

1. The first appearance of three points of inflection in the wall static pressure distribution as the disturbance strength (whether from an impinging shock or a compression corner) is increased.
2. A comparison of wall static pressure and the pressure measured by a pitot tube placed close to the wall.
3. A comparison of the wall static pressures upstream and downstream of a small orifice dam. The boundary layer is taken to be separated when the downstream pressure reads higher than the upstream.
4. The introduction of a minute low-speed stream of alcohol into the boundary layer and observing the onset of flow reversal

of the alcohol as the interaction is moved with respect to the port through which the alcohol is introduced. The accumulation of a line of alcohol forward of the point of introducing the alcohol is presumed to indicate the separation location.

5. Observation of oil flow patterns beneath a region of separation.

6. Observation of the first appearance of a separation shock by means of Schlieren photographs or pitot pressure readings.

In the present investigation, the first four methods were employed. In addition, two new possible methods involving the use of the hot-wire anemometer were tried. A summary of the results is given below.

a. The introduction of alcohol into the tunnels indicated that separation occurred when a 10° shock generator was used, but not when a 9° was used. This was true for both the 2-inch diameter $M = 3.88$ and the 3-inch diameter $M = 4.06$ tunnels. Examination of the separation lengths caused by shocks generated by 10°, 11°, 12° and 13° half-angle cones indicated that they were of roughly the same magnitude in both tunnels when scaled with Re_δ, indicating that for a given shock strength the extent of separation scales with upstream boundary layer thickness. Figure 5 shows the incipient separation shock strength, in terms of the inviscid wall pressure rise across the shock wave reflection as a function of Re_δ. The results apply to both tunnels. Although the dependence of disturbance strength required for separation on Re_δ is small, it does exhibit the same trend as reported by Law[8] in his recent study of separation at a compression corner.

b. In the 2-inch diameter tunnel, measurements were made of the static pressure upstream and downstream of a small (0.002" high by 0.005" long by 0.5" wide) orifice dam and compared with undisturbed wall static pressures over a range of shock strengths and Reynolds Numbers. Similar data were also taken by Rose[10] using a larger (0.005" high by 0.010" long by 0.5" wide) orifice dam in a 2-inch diameter $M = 3.8$ tunnel. The separation lengths agreed well with those of the alcohol injection method at the higher Reynolds Numbers. At low values of Re_{δ}, the orifice dam showed consistently larger regions of separation. It is possible that, small though the orifice dam is (height .01 y/δ), it can disturb the flow sufficiently to influence the results at low Re_{δ}. At the higher values of Re_{δ}, the separation lengths measured by the two orifice dams agree well.

c. A comparison of undisturbed wall static pressures with pitot pressures when the pitot tube was positioned against the tunnel wall did not indicate a region of separation when a 10° shock generator was used. (This is consistent with results which are obtained with shocks of much higher strength where, based on other detection methods, large separation regions are known to exist. As has been shown by Norris[13], and undoubtedly by others, probe interference effects cause this method to be quite unreliable.)

d. Detailed static pressure distributions through the interaction over a range of Reynolds Numbers and for shock generators of

10° and 11° half-angle cones are shown in Figs. 6 and 7. The static pressures were measured as the cone was traversed in approximately 0.015-inch intervals along the tunnel axis. The data shown are for the 3-inch tunnel. Superimposed on the plots are the corresponding separation and reattachment points as determined by alcohol patterns on the tunnel walls. There is no apparent sign of the pressure "hump" first used by Kuehn (1959) to indicate separation, even when the 11° shock generator is used. Reducing the Reynolds Number causes the interaction pressure rise to feed farther forward and the separation length to increase. The indicated separation pressure ratio shows only a moderate change with changing Re_δ. On the other hand, the reattachment pressure increases substantially with decreasing Re_δ, especially for the 11° cone.

e. A possible method for detecting separation is based on the fact that the mean response of a hot-wire anemometer $(\bar{e})$ in a supersonic flow is sensitive to changes in mass flux $(\overline{\rho u})$. Thus, a hot-wire anemometer probe traversed in the primary flow direction through an interaction should record the change in mass flux as compression of the flow occurs in the interaction. (For the essentially adiabatic flow under consideration the effects of total temperature on the hot-wire signal should be small.) Data were taken in the 3-inch diameter tunnel at high Re_δ with the probe traversed at distances of .01", .02" and .03" from the wall ($y/\delta \sim .036$, .072 and .107). Shock generators of 8°, 9°, 10° and 11° were used. The results are shown in Figs. 8-11. With the probe at y = 0.01", the first appearance of an appreciable change in $\overline{e}$ occurs for the 9° shock generator. For stronger shocks, the effect becomes progressively stronger but the rate of change of the maximum voltage reduction, $\Delta\overline{e}$, with shock strength decreases, and rather abruptly, for a cone angle of about 9°. This rather abrupt change for the flow near the wall is what one might expect at the onset of flow separation since once separation has occurred neither the velocity nor the density sensed by the wire should change much. The work with this technique is very preliminary at this point but if rather abrupt changes in flow field characteristics occur at or near the onset of separation then the results obtained suggest once again that separation occurs at quite low shock strengths.

f. Based on the findings of Green[5] that the onset of separation is accompanied by a sudden increase in the strength of the leading reflected shock, and those of Grande[14] that shock strength could be measured qualitatively by the hot-wire response $e'/\overline{e}$, it would appear that horizontal traverses of a hot-wire probe outside the boundary layer would indicate the onset of separation. Hot-wire studies just outside the boundary layer have been made in the present investigation. Only a few results are available at this time, these for the 2-inch tunnel. The results are shown in Fig. 12 and if separation is taken to occur where an abrupt increase occurs in the signal produced by the first reflected shock, then indications are that separation occurs when a shock generator between 10° and 11° is used. This is higher than the other results presented here but still indicates that a considerably lower shock strength is required for separation than reported in previous investigations for other configurations.

Additional studies of the type described here are being conducted for both Mach 3 and Mach 4 flows. Preliminary results for flow at the walls of Mach 3 wind tunnels also indicate separation at considerably lower shock strengths than have been reported in previous studies.

CONCLUSIONS

1. The results obtained in this investigation indicate that turbulent boundary layers at the walls of axially symmetric flow passages, when subjected to the adverse pressure gradient imposed by the impingement of an oblique (conical) shock wave, can separate at lower shock strengths than has been reported for interactions involving planar geometry and involving the use of other detection techniques. The conclusion is based mainly on observations of alcohol flow patterns on the wall beneath the interaction region but is reinforced by results obtained with three other methods each of which is based on a different criterion.
2. The shock strength for incipient separation increases slightly as Re_δ is increased.
3. The pressure rise to separation is relatively insensitive to changes of Re_δ and of shock strength as well. The pressure rise to reattachment is sensitive to both shock strength and Re_δ. It increases with increasing strength and decreases with increasing Re_δ.
4. The length of separation, at a given shock strength and Mach Number, scales with Re_δ.
5. The interaction pressure rise feeds progressively farther forward as Re_δ is decreased.
6. Some of the classic methods of determining separation, e.g., the "hump" in the wall static pressure distribution and a comparison of wall static pressures with pressures measured

with a pitot tube placed in contact with the wall surface, did not indicate separation at the shock strengths examined in this study even though the other methods employed in the [illegible] study indicated sizable regions of separation.

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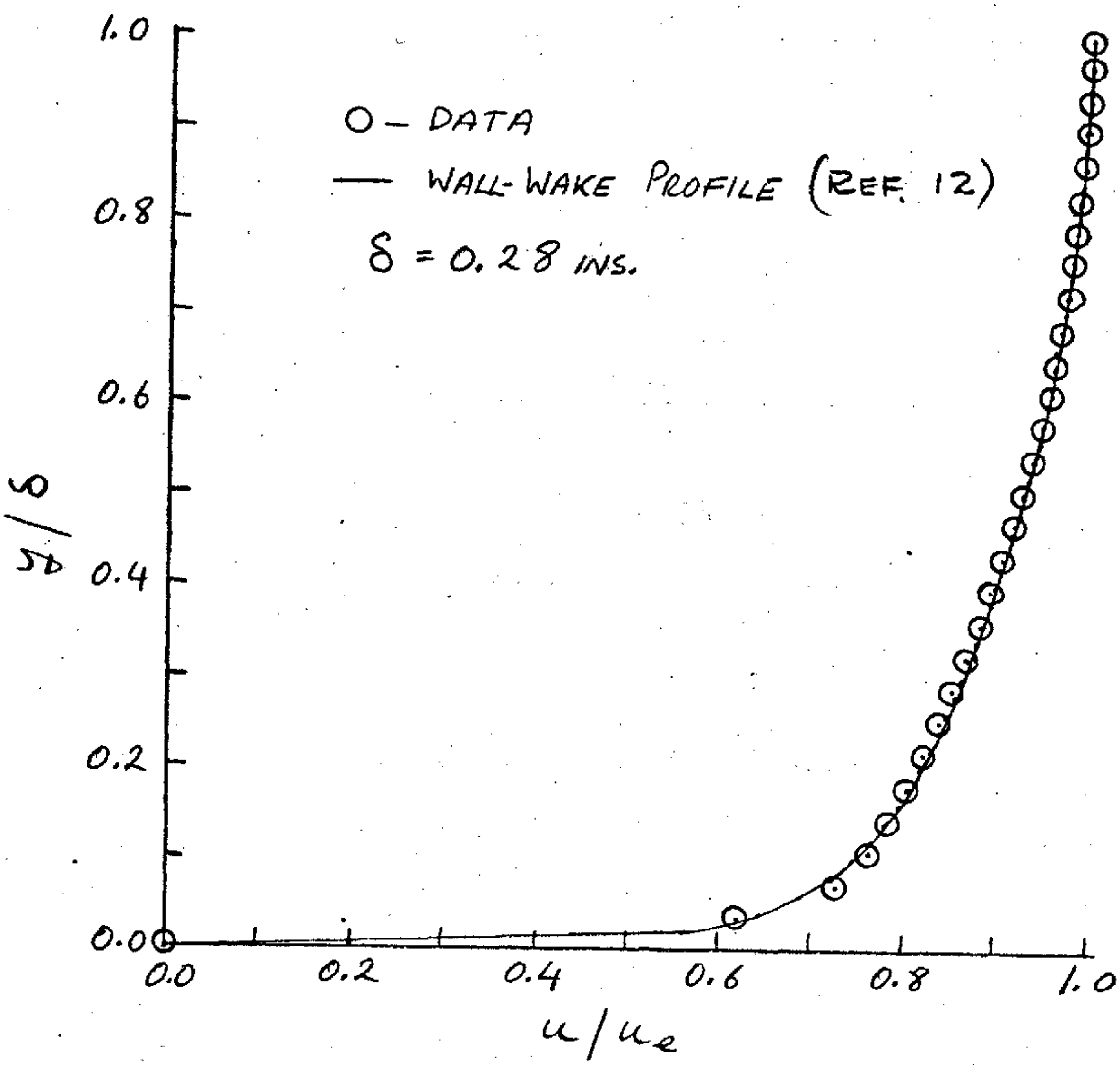

FIG. 1 – VELOCITY PROFILE – 3-IN TUNNEL
$Re_\delta = 1.1 \times 10^5$

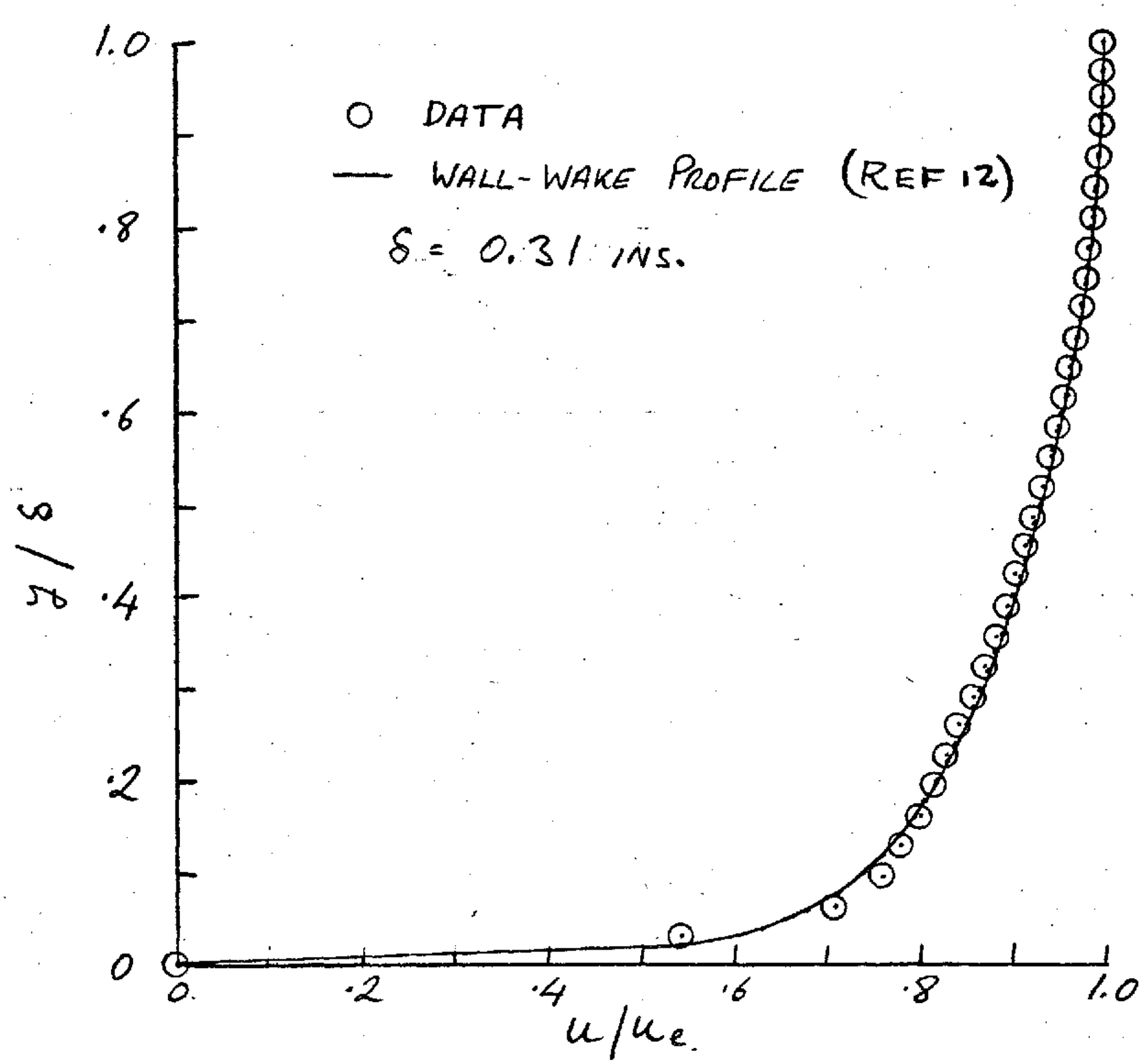

FIG. 2 — VELOCITY PROFILE — 3-IN TUNNEL

$Re_\delta = 5.5 \times 10^4$

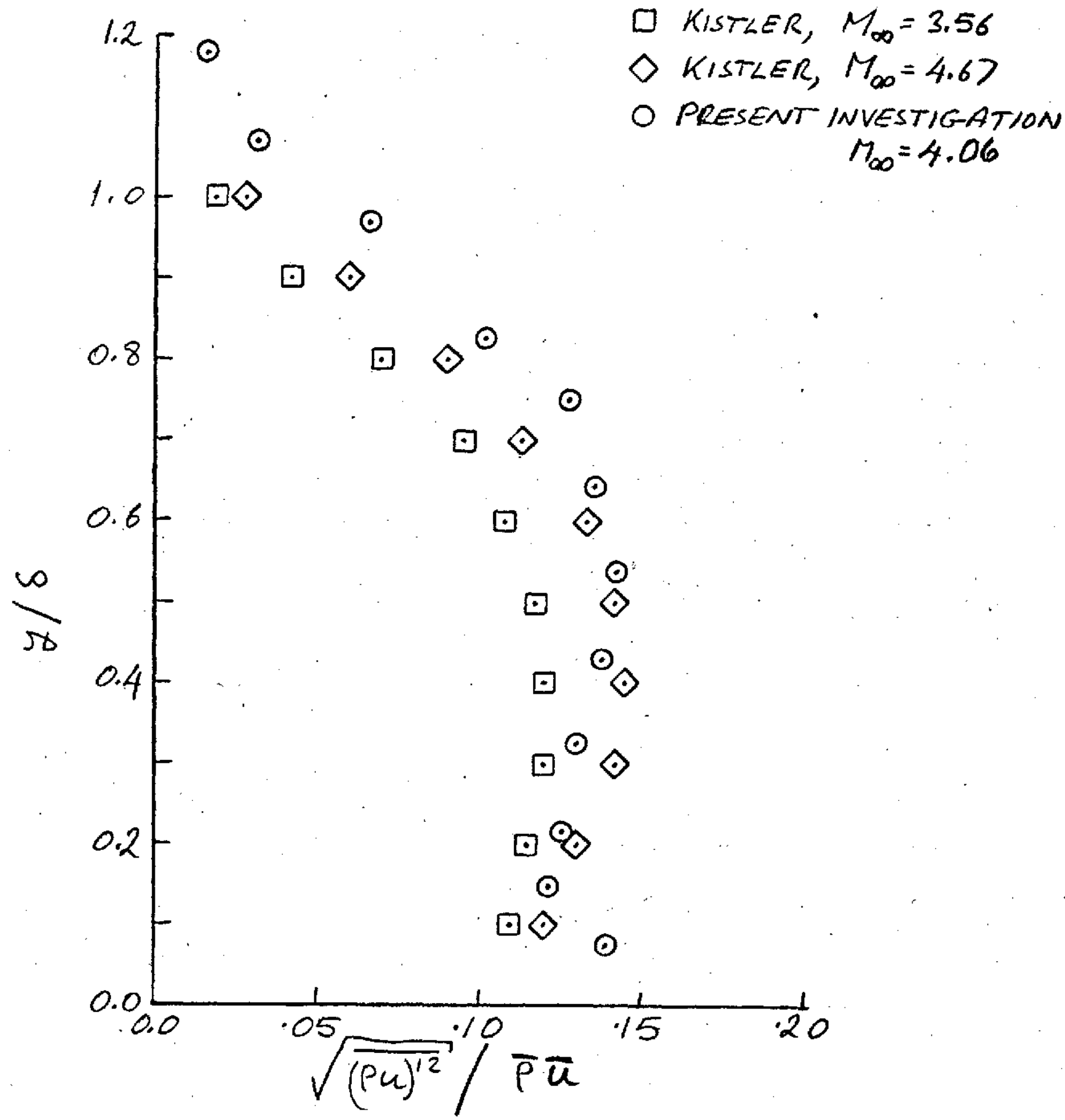

FIG 3 - FLUCTUATING MASS FLUX - 3-IN TUNNEL
$Re_\delta = 1.1 \times 10^5$

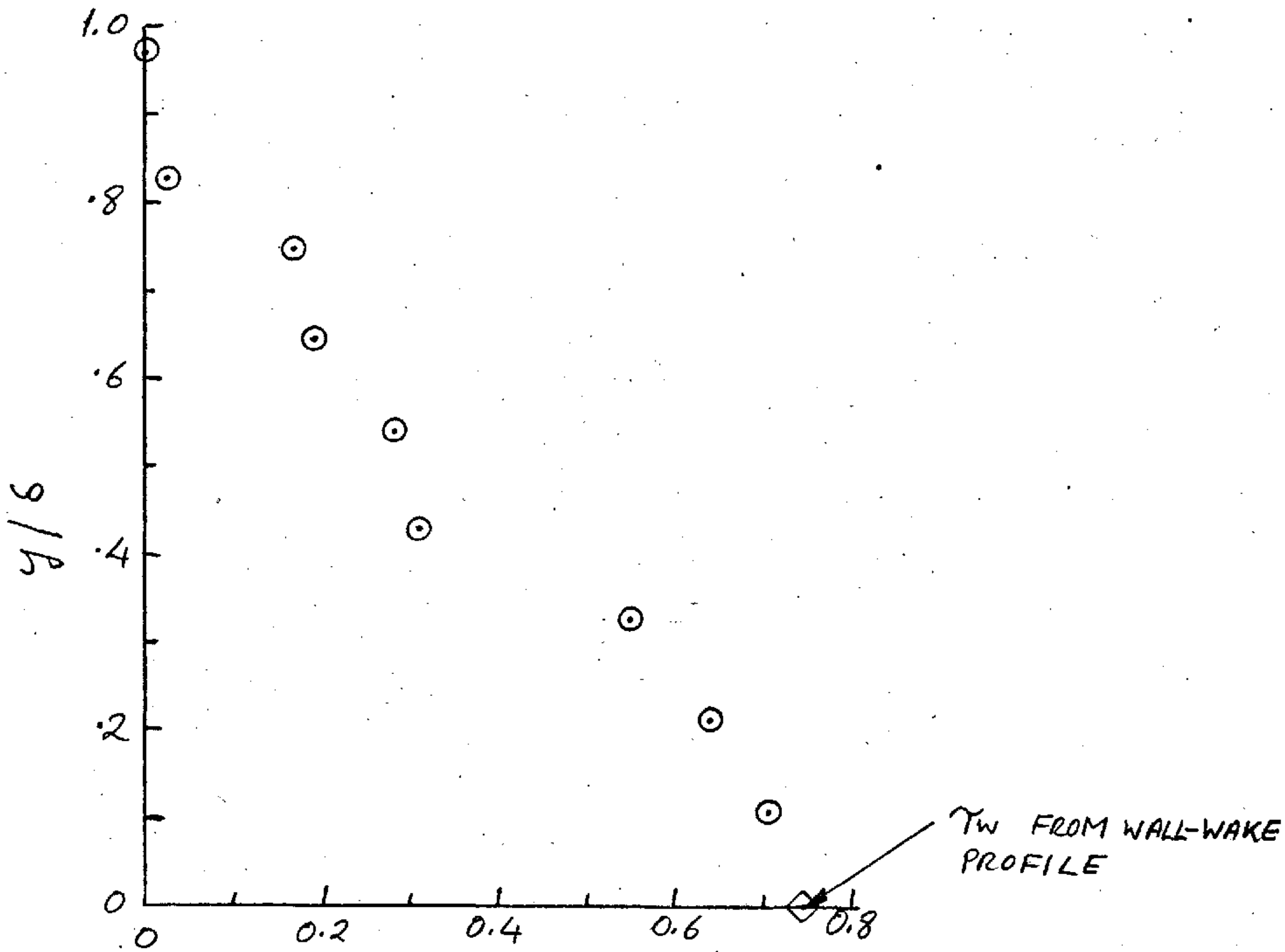

FIG 4. TURBULENT SHEAR STRESS – 3-IN. TUNNEL $Re_\delta = 1.1 \times 10^5$

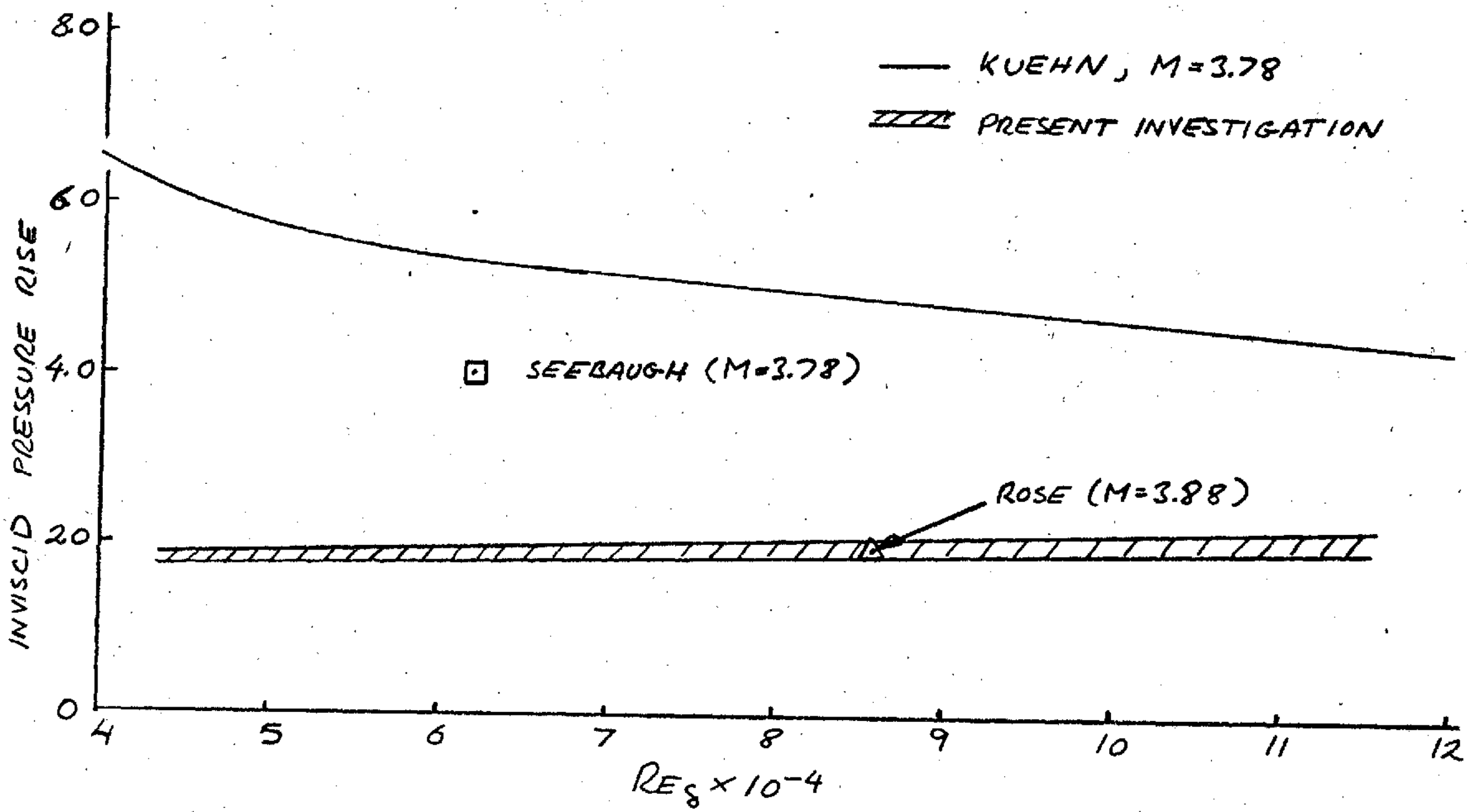

FIG. 5 INCIPIENT SEPARATION DATA
2 INS. AND 3 INS. TUNNELS

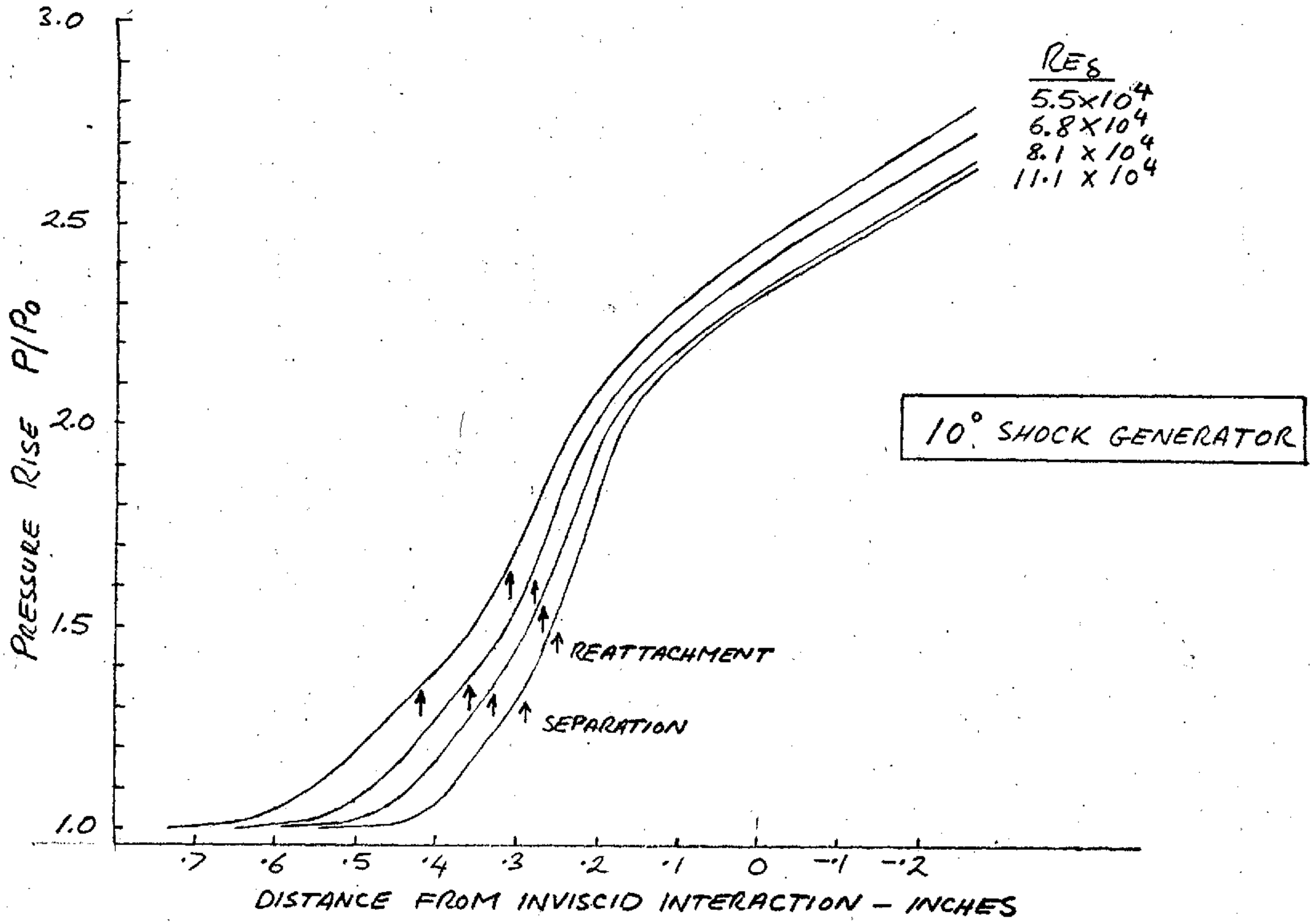

FIG. 6 – STATIC PRESSURE DISTRIBUTION THROUGH INTERACTION
3-IN. TUNNEL

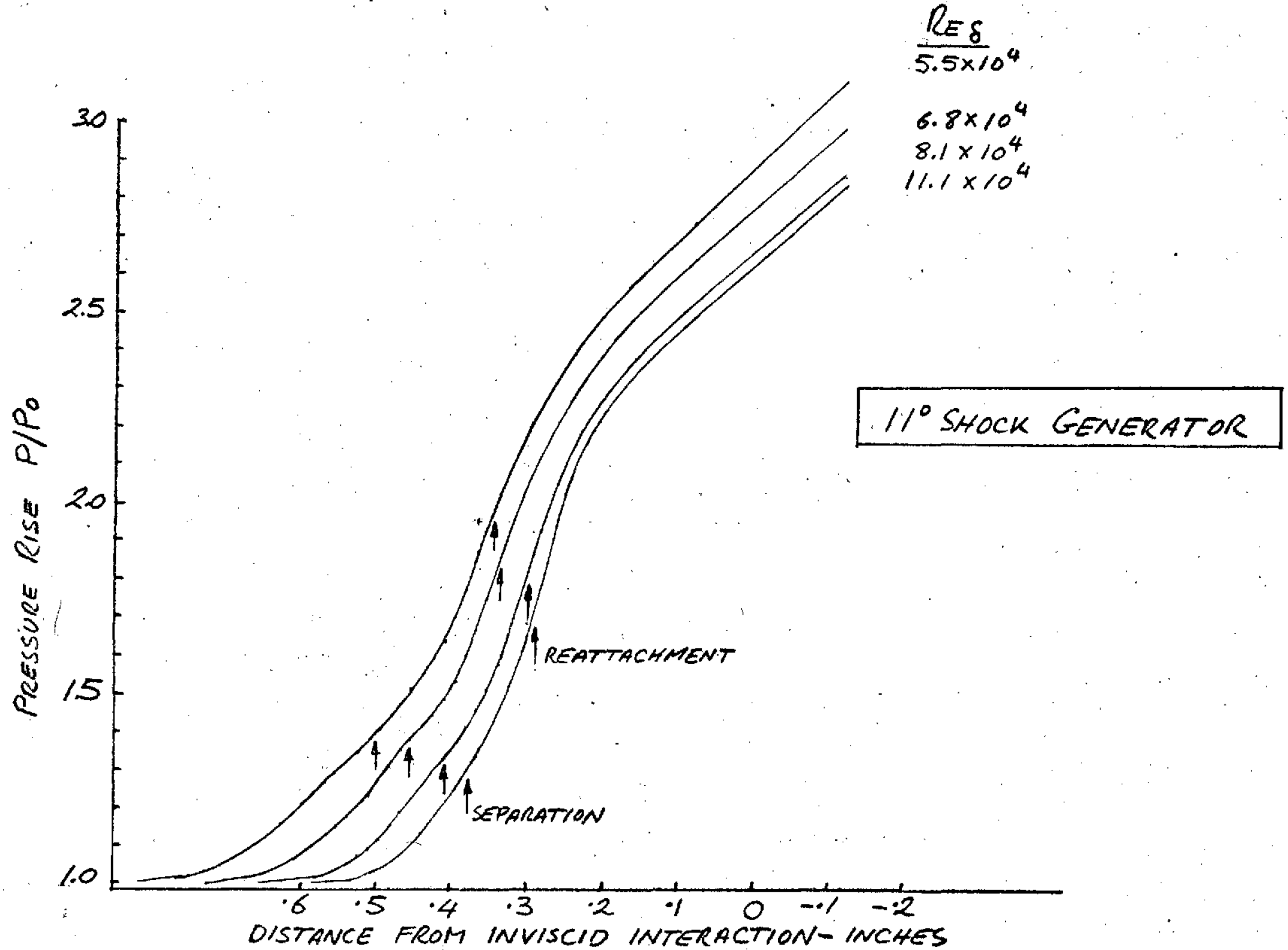

FIG. 7 STATIC PRESSURE DISTRIBUTION THROUGH INTERACTION
3-IN. TUNNEL

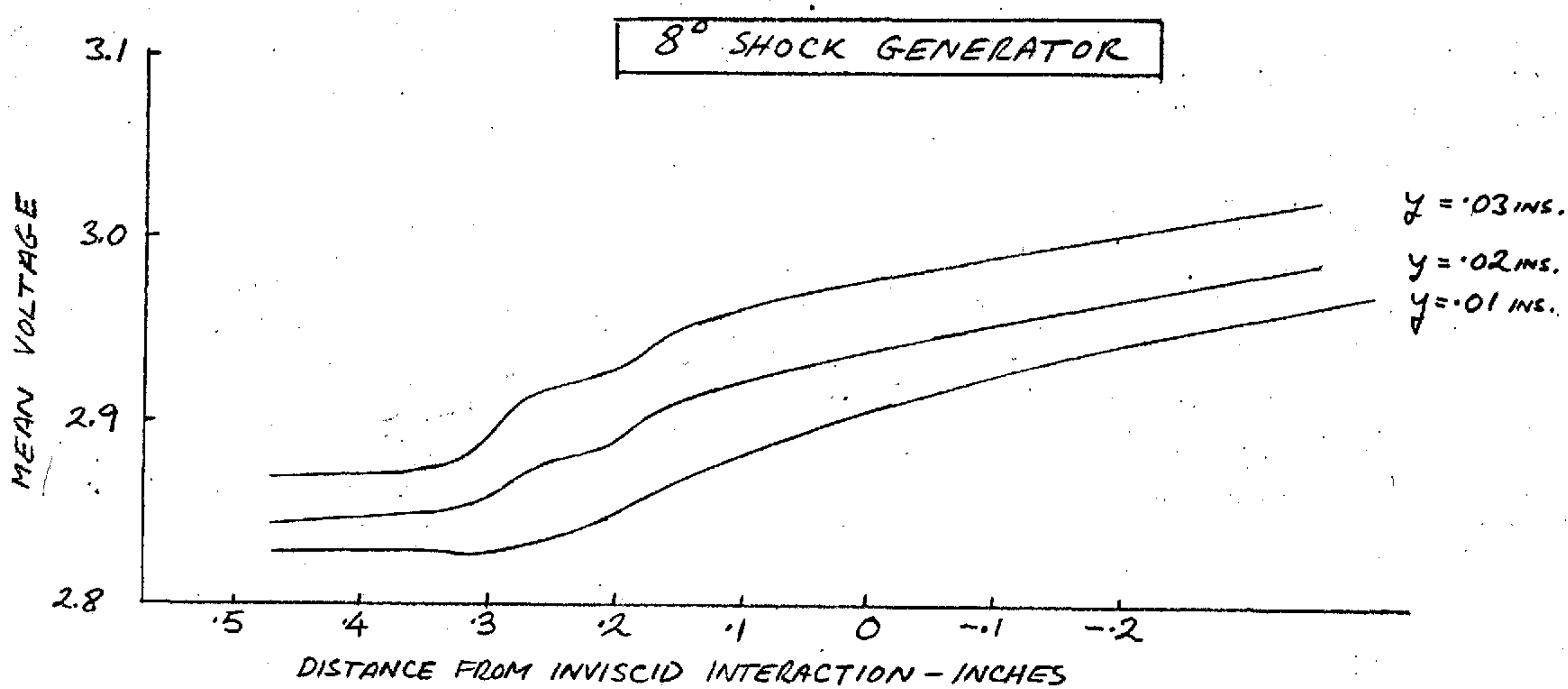

FIG. 8 - HORIZONTAL HOT-WIRE TRAVERSE THROUGH INTERACTION

3-IN. TUNNEL

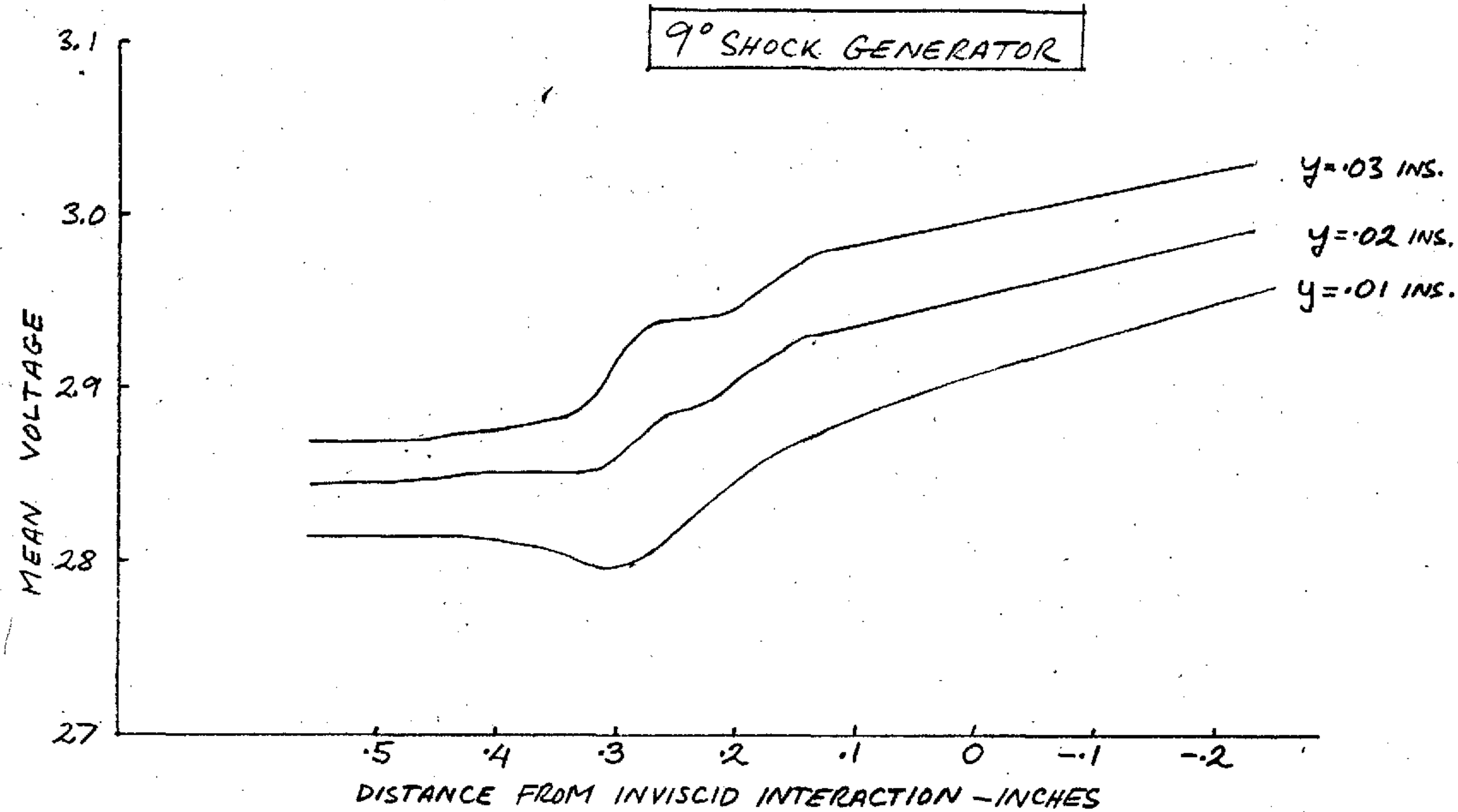

FIG. 9 – HORIZONTAL HOT-WIRE TRAVERSE THROUGH INTERACTION 3-IN. TUNNEL

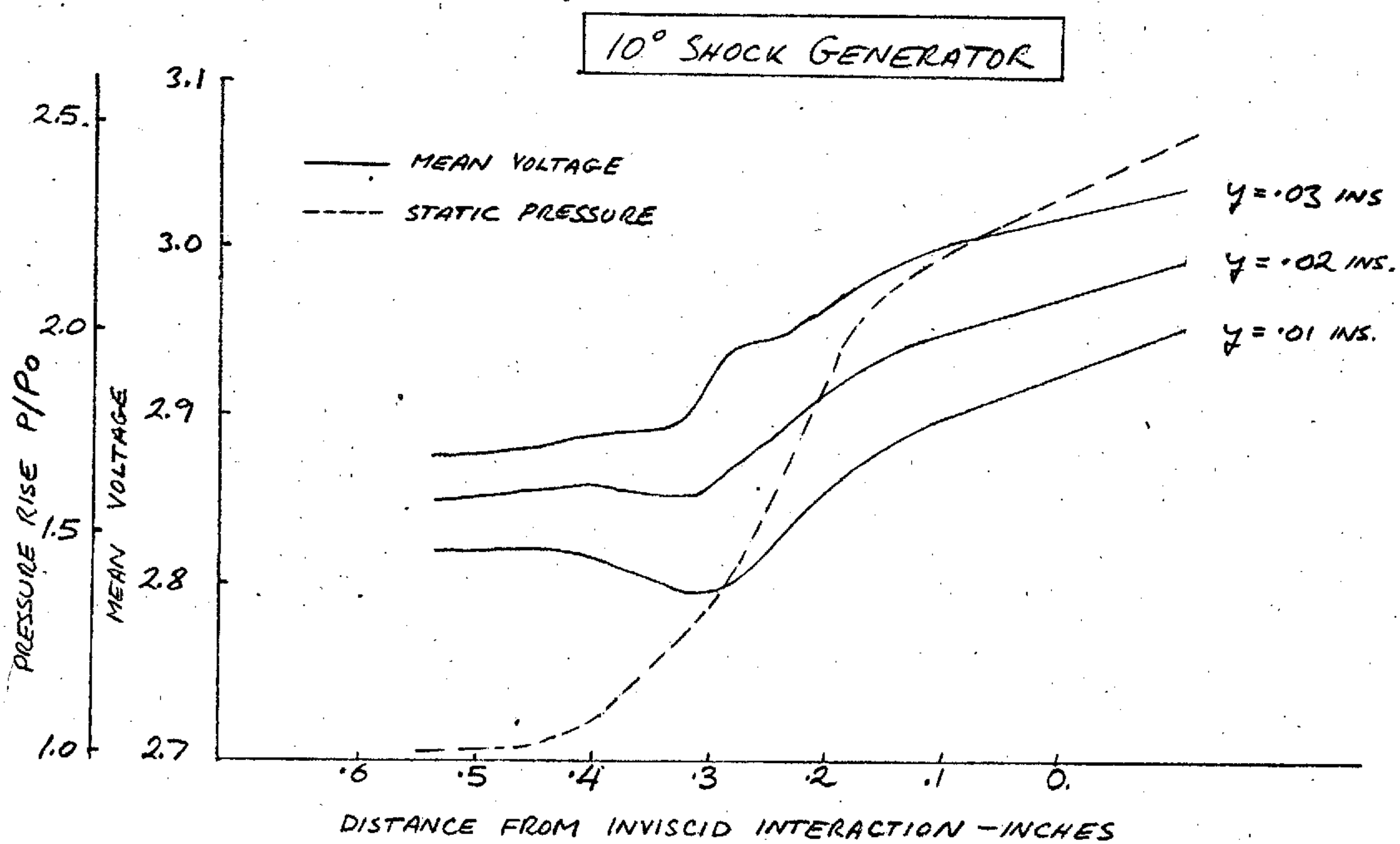

FIG. 10 HORIZONTAL HOT-WIRE TRAVERSE THROUGH INTERACTION
3-IN. TUNNEL

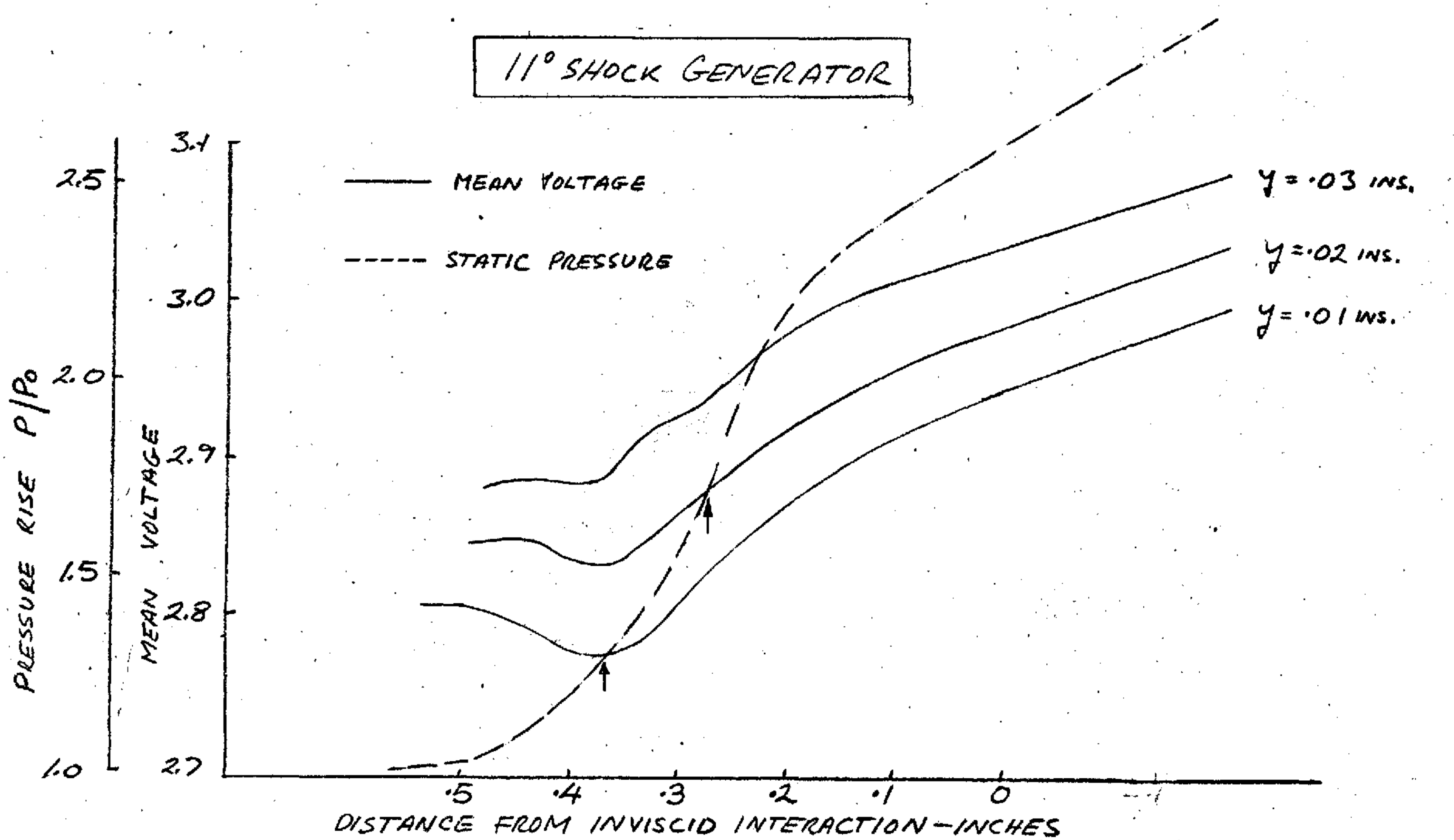

FIG. 11 – HORIZONTAL HOT-WIRE TRAVERSE THROUGH INTERACTION
3-IN. TUNNEL

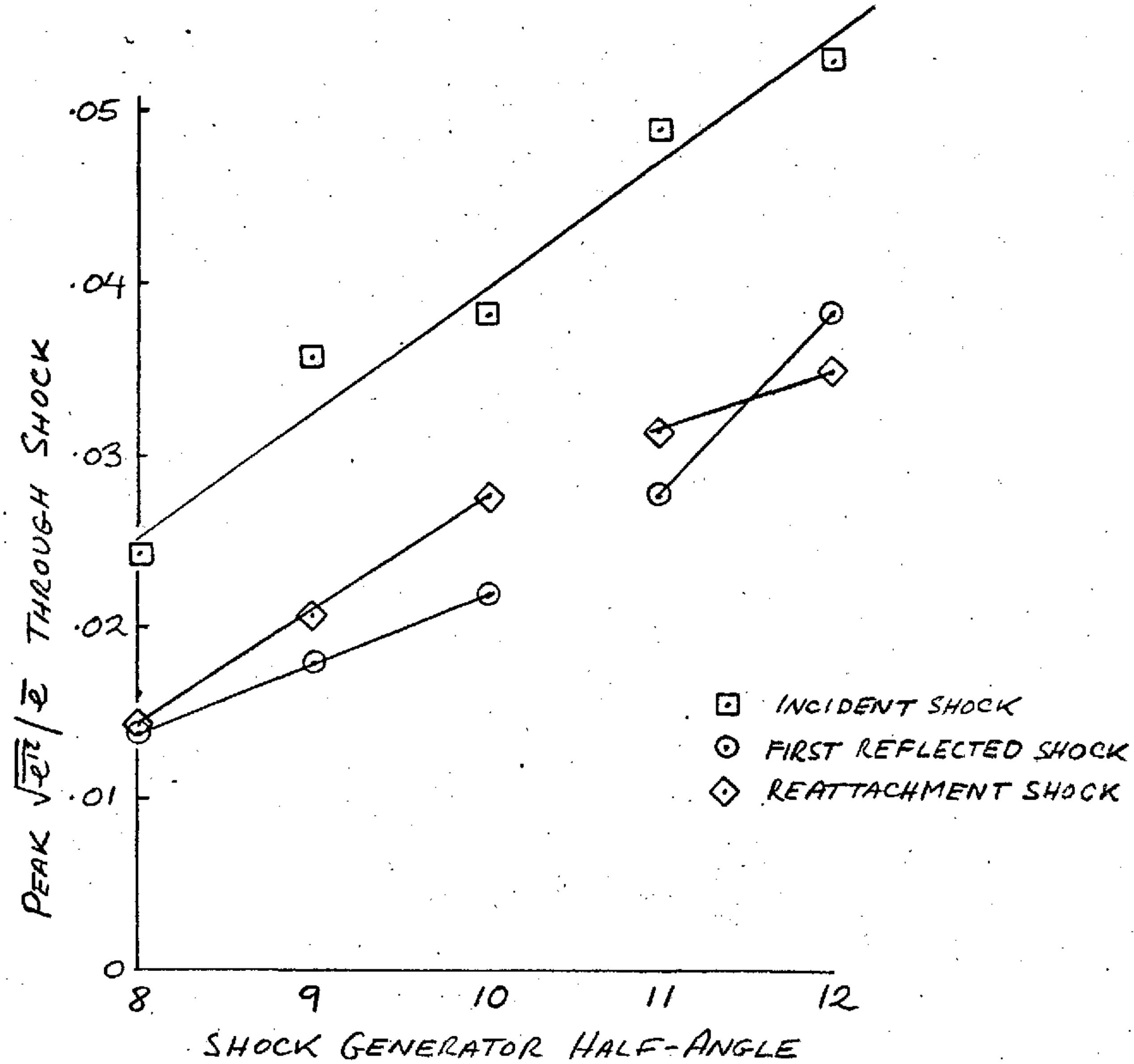

FIG. 12 - INCIDENT AND REFLECTED SHOCK STRENGTHS

2-IN. TUNNEL