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A PRELIMINARY EVALUATION OF NOISE REDUCTION POTENTIAL FOR THE UPPER SURFACE BLOWN FLAP

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SUMMARY

The upper surface blown flap has been suggested as a feasible alternative to the under-the-wing externally blown flap (EBF) for powered-lift STOL aircraft. Since noise may be a controlling factor in the commercial implementation of any new aircraft concept, it is essential to assess the noise reduction possibilities of various lift augmentation systems prior to extensive development. This study is a preliminary assessment of the basic acoustic characteristics and noise reduction potential of an upper surface blown flap consisting of a rectangular nozzle and a single turning flap which was designed to approximate a typical takeoff setting. Noise reduction concepts studied were (1) replacing a section of the flap trailing edge with a porous material and (2) active modification of the flow field using blowing near the trailing edge.

The basic findings of this study are summarized below:

(1) The upper surface blown flap (USB) configuration exhibited significantly different far field noise characteristics than an under-the-wing EBF with comparable thrust (same exit velocity and area). The chief differences in the radiated noise were that the USB spectrum peaked at lower frequencies than the EBF and the overall levels of the USB were somewhat lower than the EBF (for the conditions stated above).

(2) The source of broad band noise on the USB flap was identified to be the interaction of the wall jet flow with the trailing edge of the turning flap.

(3) Replacing part of the trailing edge with a porous insert reduced the rediated noise over a broad frequency range by as much as 10 dB.

(4) Injection of secondary air through a spanwise blowing slot near the trailing edge reduced radiated noise over a broad frequency range by 3-6 dB.

I. Study of Basic Upper Surface Blowing Configuration

Geometry and Layout

A turning flap was constructed with a contour which represented a smooth curve over upper surfaces of the EBF flaps in the takeoff flap setting. The turning angle (tangent to the upper surface at the trailing edge) was 45°. A slot nozzle having the same exit area as the 1.75 inch round nozzle used in a previous study* of the 3-flap EBF was fabricated with an aspect ratio of 10:1 (5" wide × 0.5" high). The nozzle was initially located in two positions as shown in Fig. 1. The position selected for detailed study was "Position 2", after a qualitative evaluation of the flow turning performance of the flap. A removable section of the turning flap near the trailing edge allowed evaluation of insertable porous edges.

The exit velocities were varied between 315 fps and 976 fps. Acoustic (and aerodynamic) characteristics of the flap system were evaluated in an anechoic space. High pressure air was provided by a 600 hp diesel engine and air compressor. (See Fig. 2.) The wing and flap span was about 15 inches. Figure 3 shows the view of the wing/flap/nozzle system from "above the wing".

Aerodynamic Studies

Flow Visualization and Mean Velocity Profiles: To quickly assess the nature of the "wall jet" flow over the turning flap, a flow visualization study using a brush-on pigmented oil mixture was conducted. The results are shown in Figs. 4a and 4b.

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*Hayden, R.E., Kadman, Y. and Chanaud, R.C., NASA CR 112166 (August 1972).

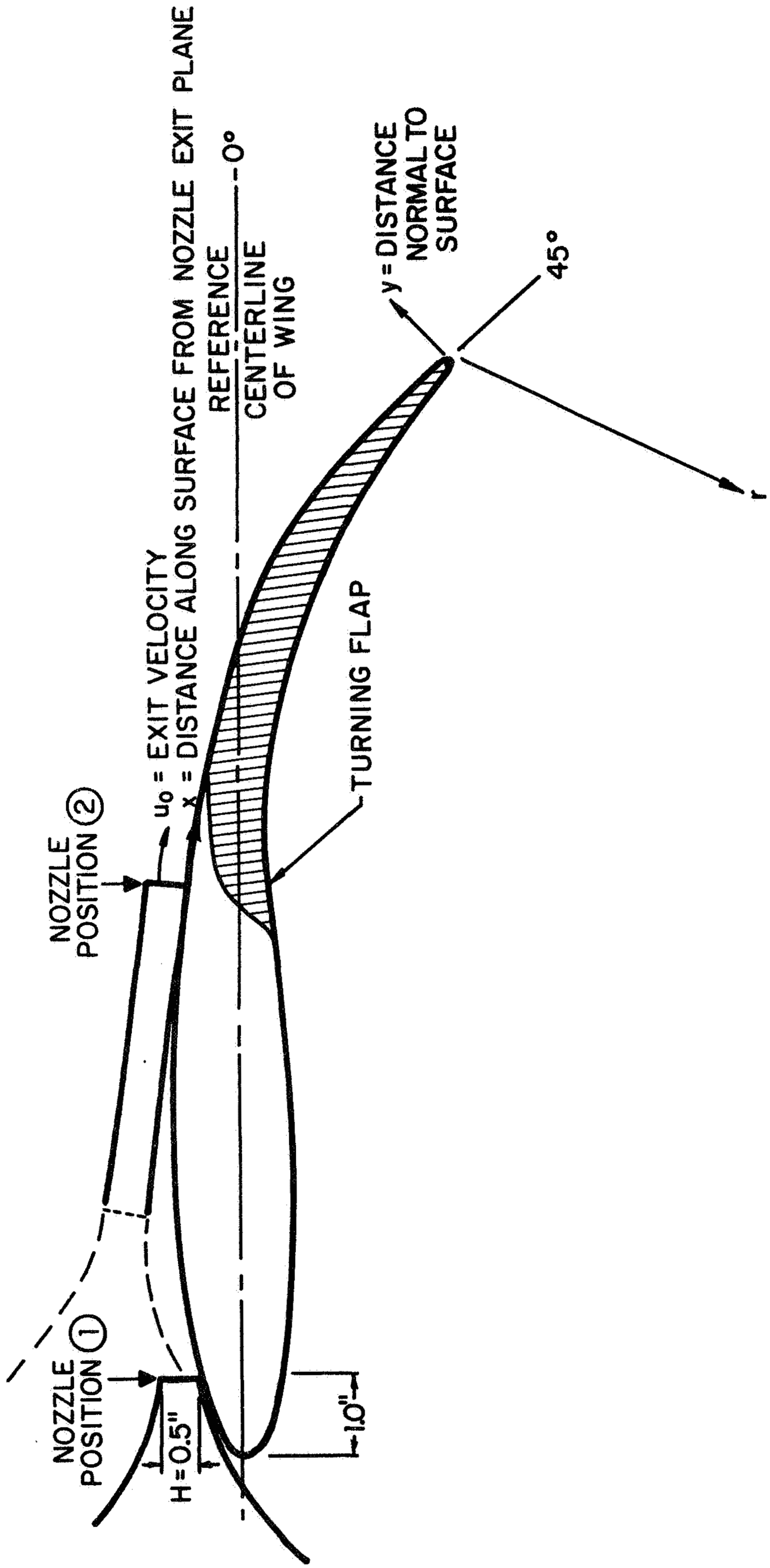

FIG. 1 MODEL CONFIGURATION TESTED.

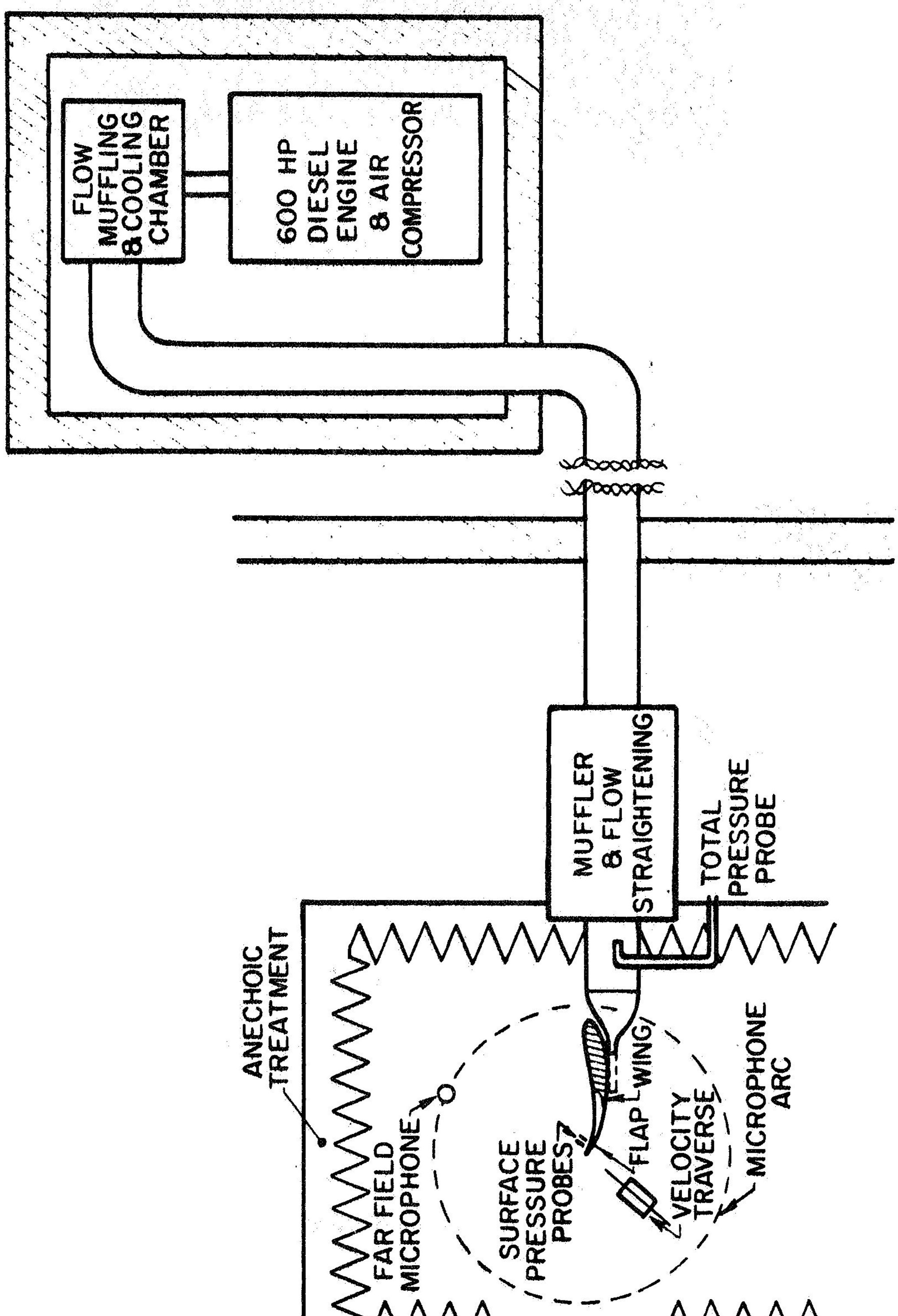

FIG. 2 TEST LAYOUT.

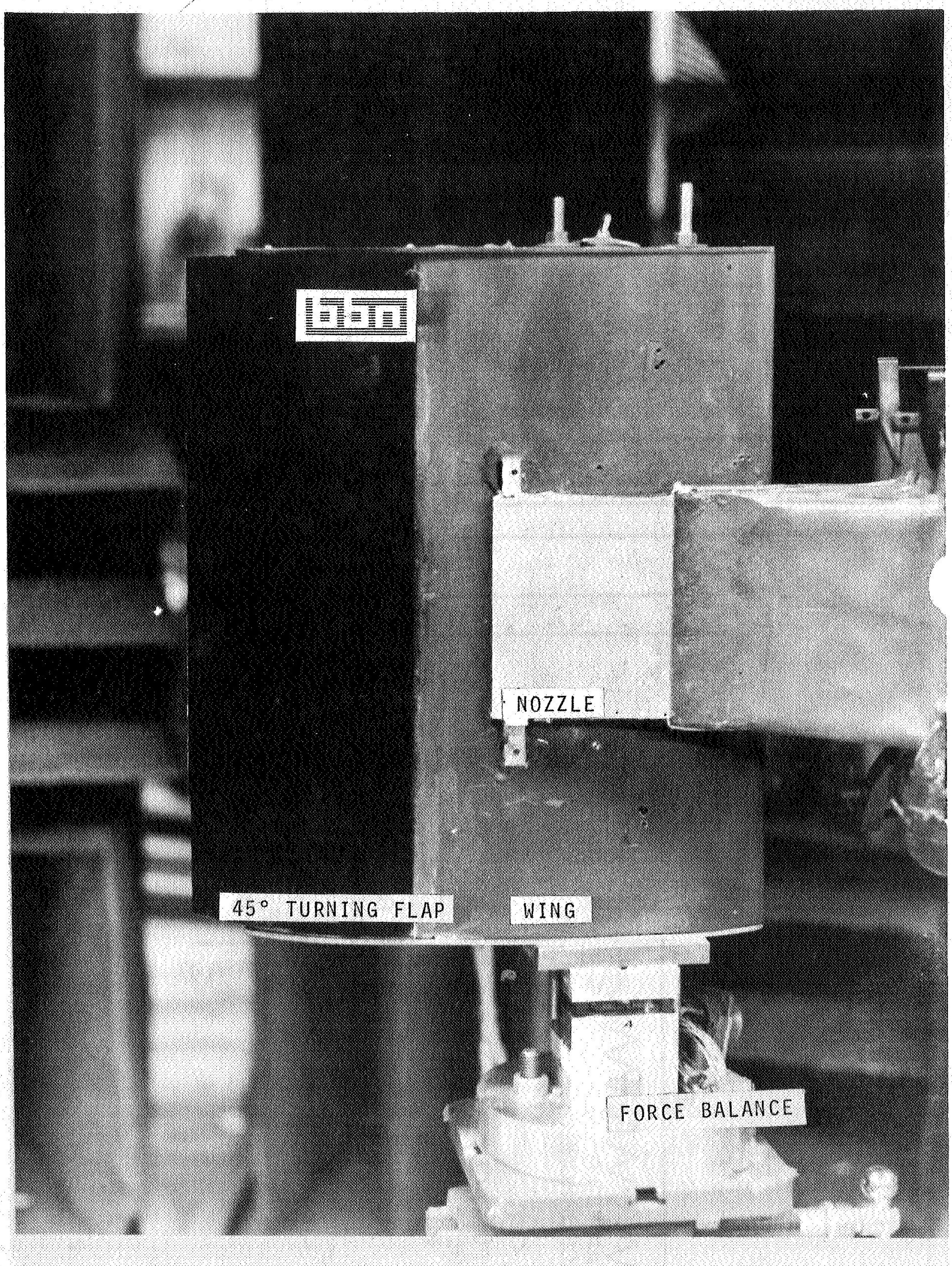

FIG. 3 LAYOUT OF UPPER SURFACE BLOWING EXPERIMENT

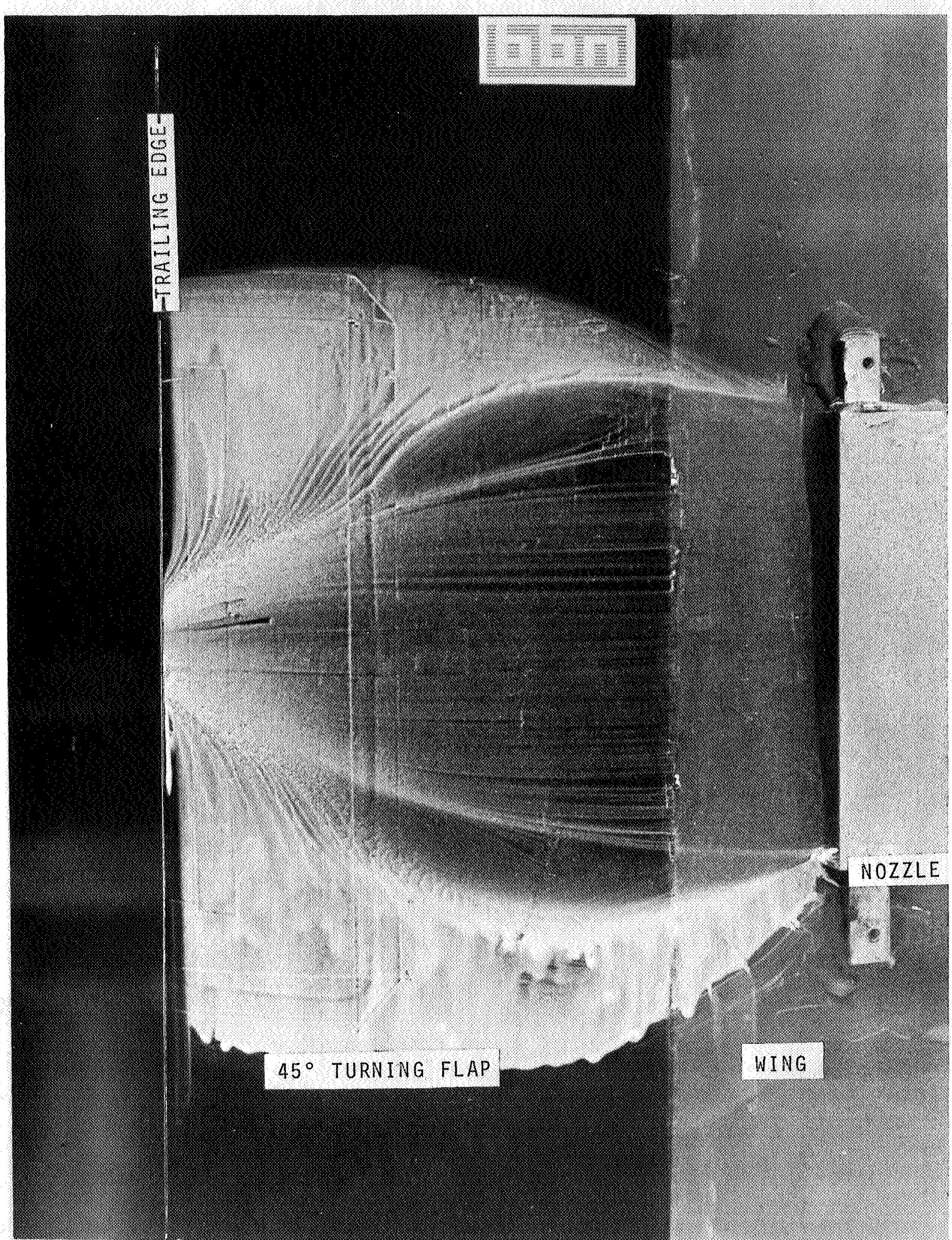

FIG. 4a SURFACE OIL FLOW VISUALIZATION ON UPPER SURFACE BLOWN FLAP
(OBSERVER ABOVE WING)

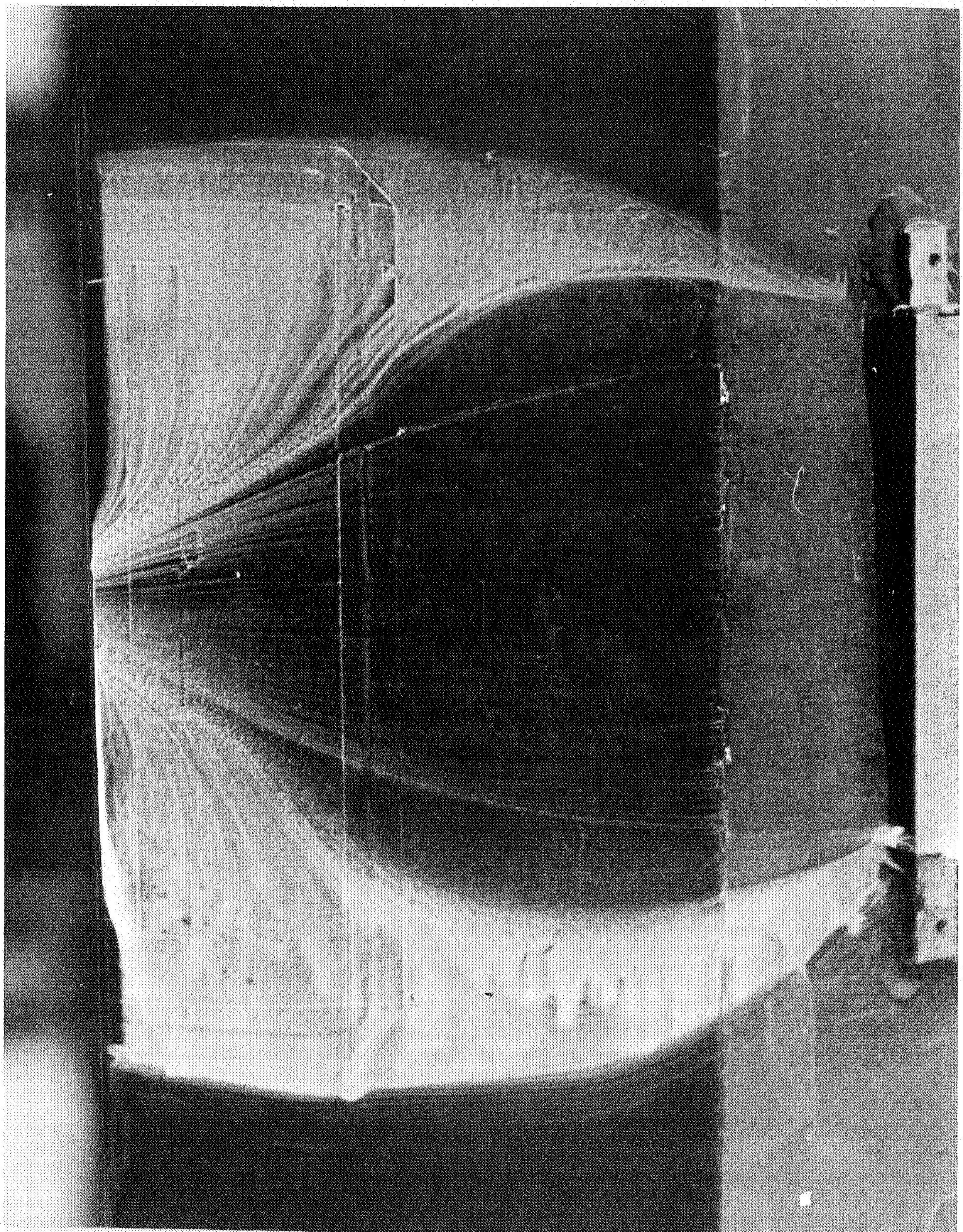

FIG. 4b CLOSE-UP OF FLOW VISUALIZATION ON UPPER SURFACE BLOWN FLAP

The wall jet flow remained attached along the entire centerline of the jet. The free shear regions along the edges of the jet were observed to "roll up" and move toward the centerline with increasing downstream distance over the convex surface. This intense pair of "stream-wise" vortices existed along the outer edges of the flow and well above the surface, although this high energy flow followed the turning angle of the flap. Figure 5 shows steady-state velocity profiles along the centerline of the flow. (Curves are also shown for the case where a section of the flap was replaced with a porous insert of about 0.2 ρc flow resistance.) Figure 6 supports the concept that in a symmetric pair of high velocity regions exist well away from the centerline and above the surface in the vicinity of the trailing edge. No attempt was made to correct these measurements for non-axial velocity components; thus the relative magnitudes of the velocities reported should be regarded only as indicative of trends.

Turbulence Measurements: Profiles of rms turbulence intensity were obtained using a single hot wire probe and a traversing mechanism. The results are shown for a number of streamwise and spanwise locations (Figs. 7 and 8 respectively). The turbulence levels are normalized with respect to local maximum mean velocity (U_{Lm}). In Fig. 7, the intense velocity fluctuations are most evident in the surface shear layer as well as relatively intense fluctuations in the free shear region of the wall jet. In Fig. 8, it is apparent that such intense near-wall fluctuations exist primarily at spanwise locations relatively close to the centerline. At distances further from the surface, high intensity velocity fluctuations exist in the off-centerline regions with variations between different positions occurring in a very complex manner. Very intense fluctuations were observed at those vertical heights (y/h) and spanwise distances roughly corresponding to

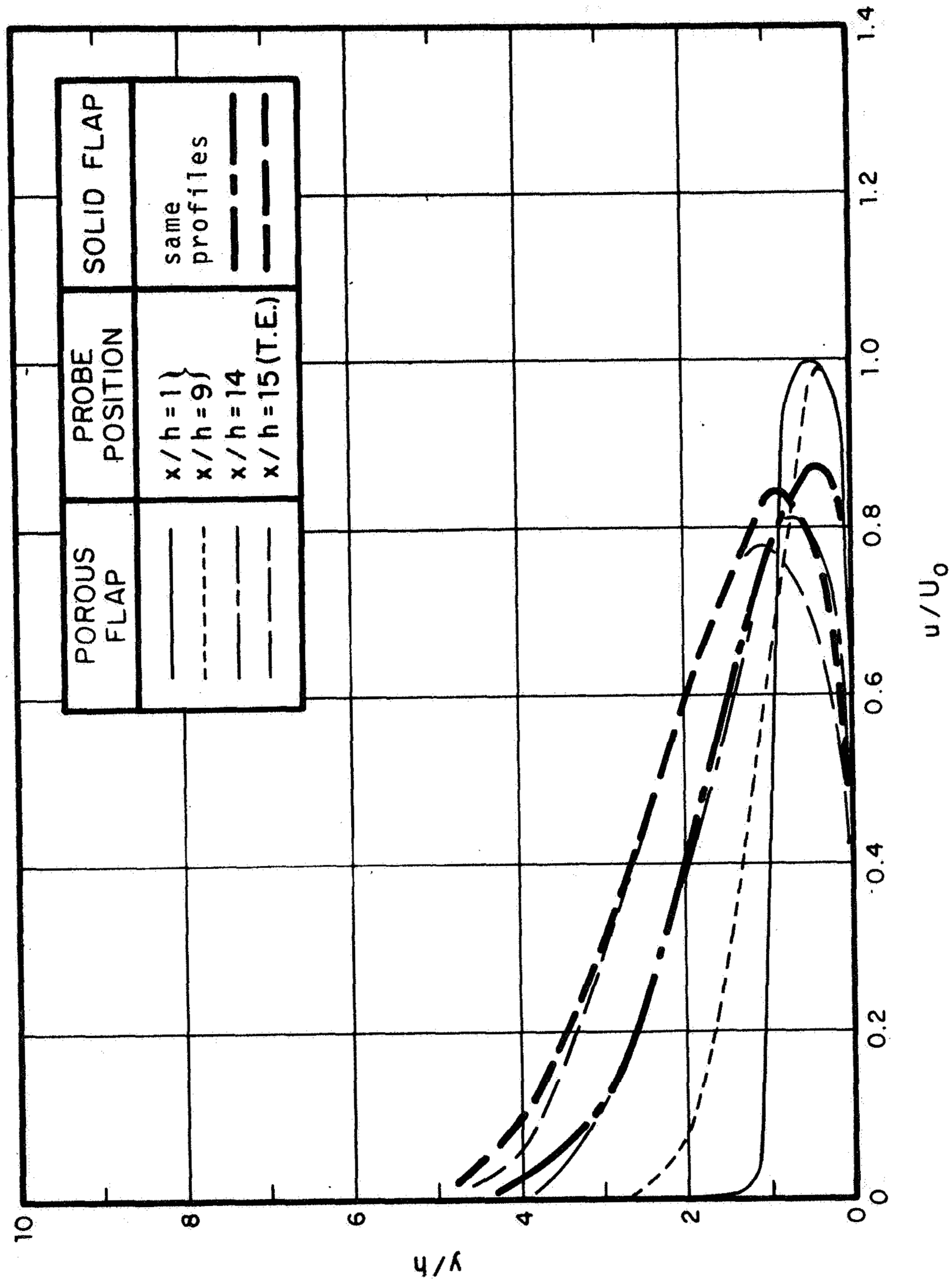

FIG. 5 STEADY-STATE VELOCITY PROFILES ALONG FLAP CENTERLINE MEASURED IN A PLANE NORMAL TO THE FLAP SURFACE.

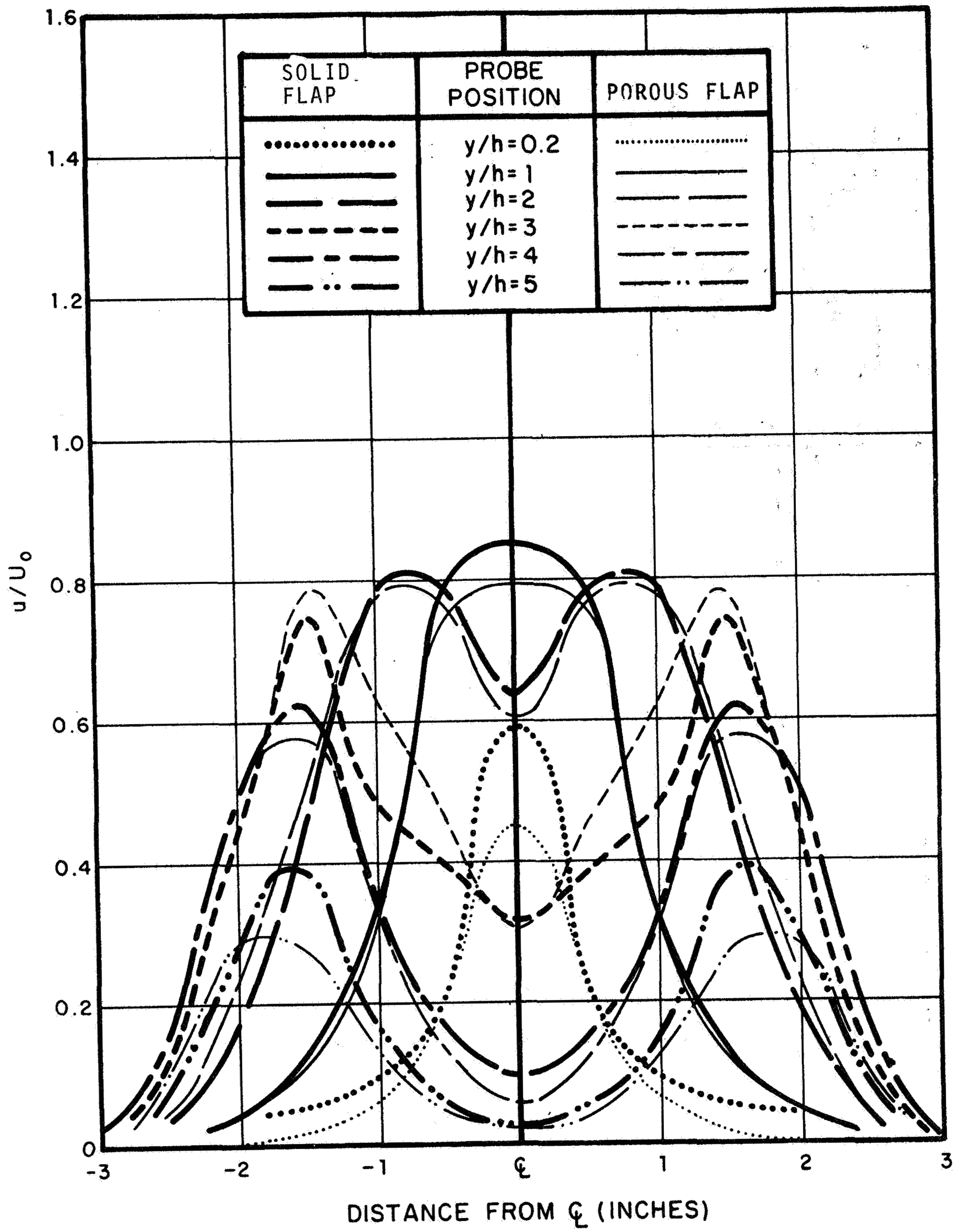

FIG. 6. SPANWISE PROFILES OF MEAN VELOCITY MEASURED AT TRAILING EDGE AT VARIOUS DISTANCES FROM SURFACE.

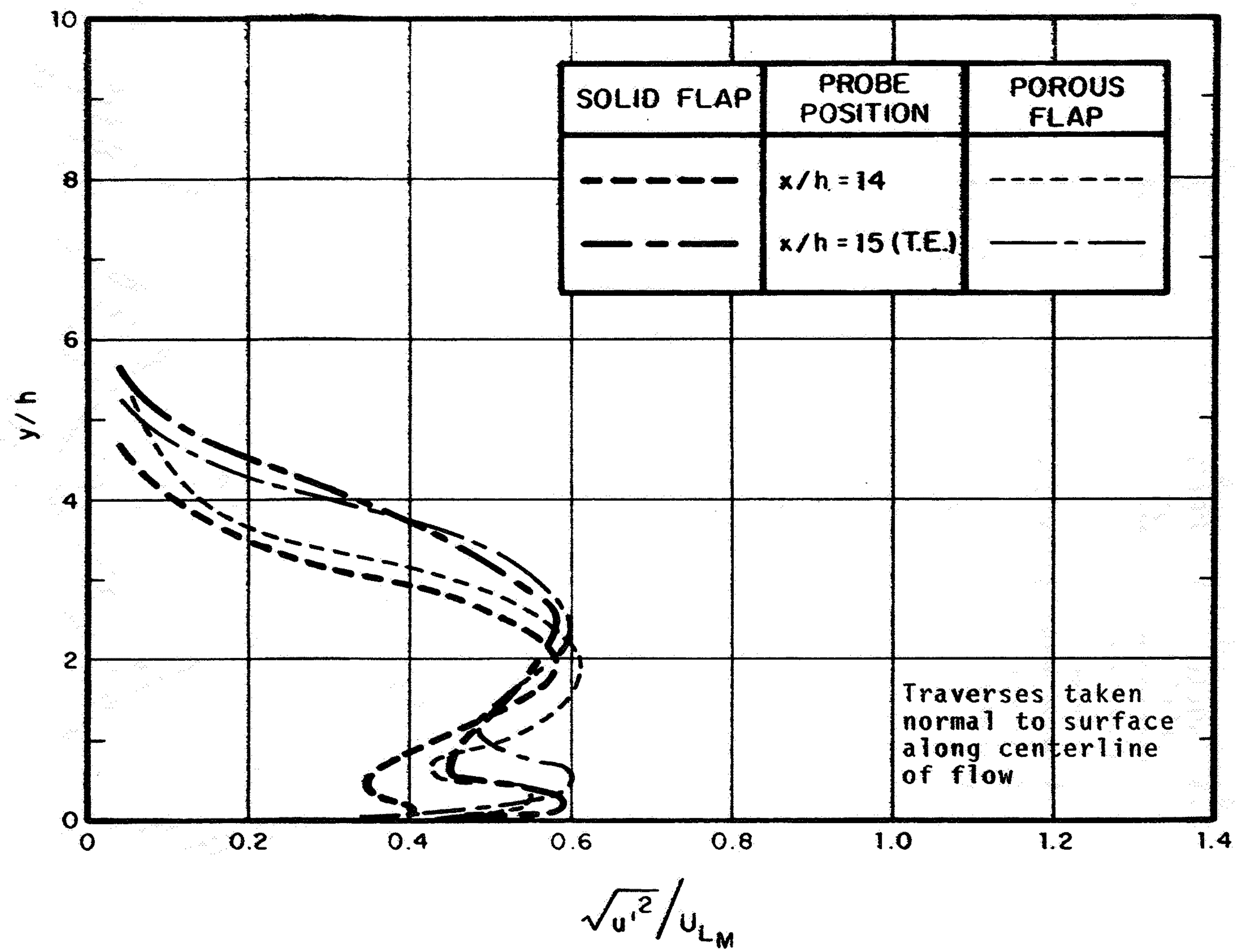

FIG. 7 PROFILES OF RMS TURBULENCE LEVEL MEASURED IN PLANE NORMAL TO SURFACE AT TWO CHORDWISE POSITIONS.

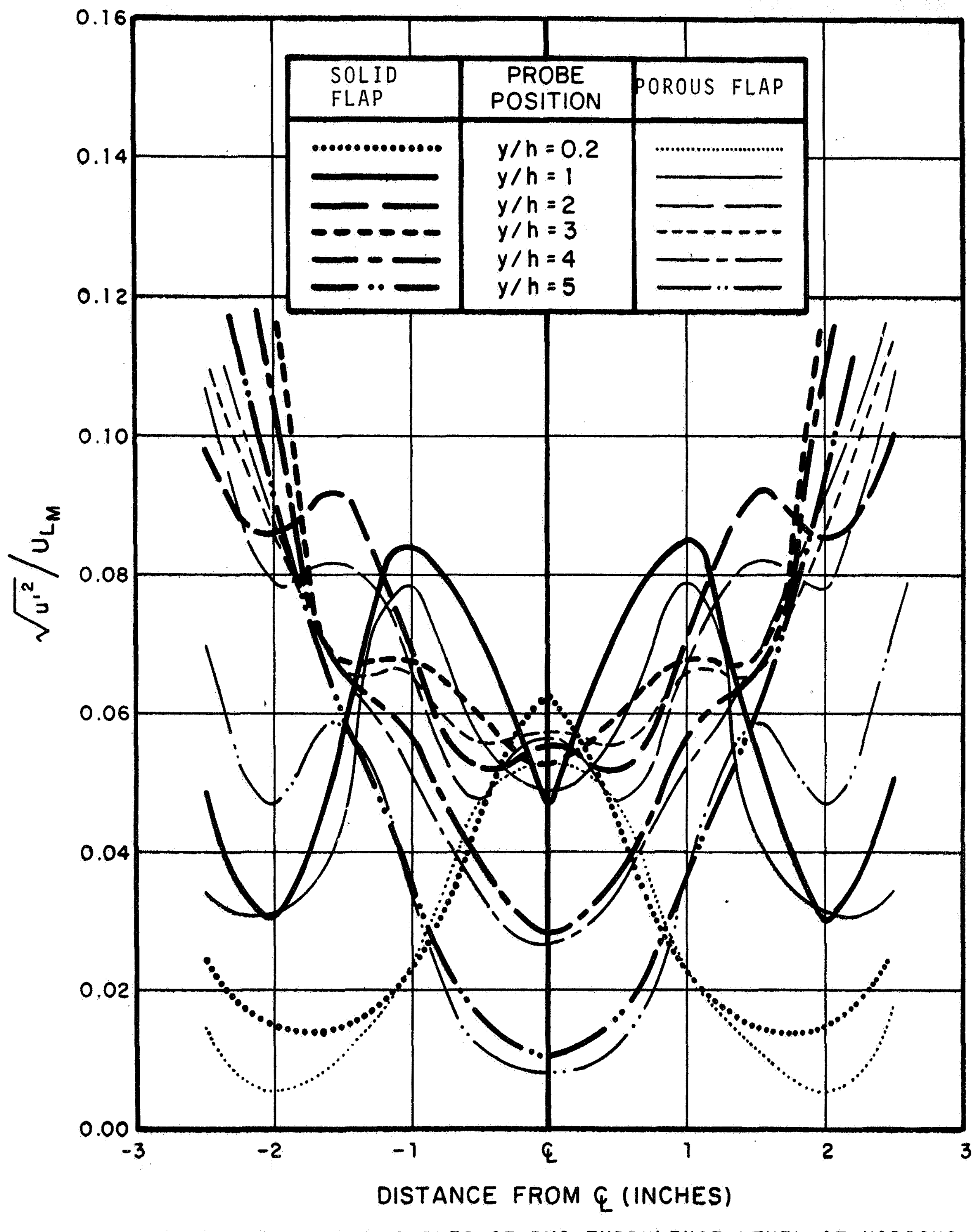

FIG. 8 SPANWISE PROFILES OF RMS TURBULENCE LEVEL AT VARIOUS HEIGHTS ABOVE TRAILING EDGE.

those positions in Fig. 6 where high steady state velocities were found off the centerline.

Acoustic Characteristics

The far field sound characteristics of the unmodified nozzle/flap system are summarized in Figs. 9 and 10. Figure 9 shows the speed dependence of the spectrum levels and frequency content. The overall levels shift from a U^6 dependence at very low speeds to a U^4 dependence at intermediate speeds and then toward a U^6 dependence at highest speeds. No detailed investigation of this phenomena has been made; however, it is evident that the low frequency peak dominates the overall levels at low speeds and shifts to a U^4 dependence at $U_0 > 400$ fps. The other broader-band part of the spectrum at high frequencies rises at U^6 throughout the speed range. Due to the complexity of the flow field and brief nature of the current study, it is impossible at this stage to fully explain the various components of the total spectrum.

The directivity from the basic flap is of the cardioid-like pattern with the null aligned with flap plane at the trailing edge, as shown in Fig. 9. It is thought that considerable high frequency noise arises from the lip of the slot nozzle and radiates like a trailing edge source, although primarily into the space above the wing.

The sound spectra for the upper surface blown flap (USB) is compared with the under-the-wing EBF (3-flap version) - both in the takeoff flap setting - in Fig. 11. The exit velocities and observation points were identical in both cases, as were the exit areas. It is evident that the radiated sound from the USB flap system is lower in amplitude than the EBF at high frequencies and, since the spectrum is shifted toward low frequencies, higher in amplitude at low frequencies. The effect of these factors on

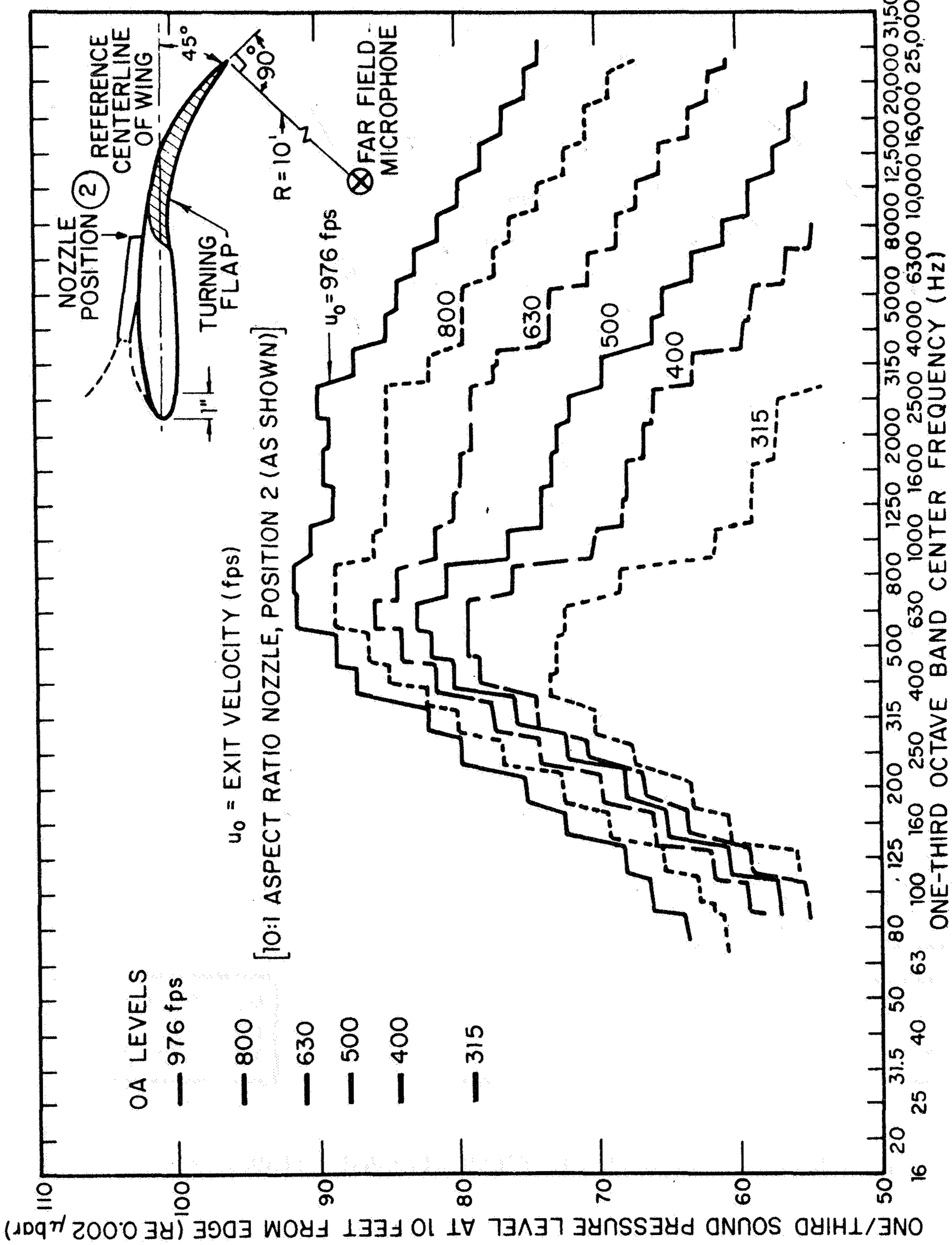

FIG. 9 TYPICAL SOUND SPECTRA AT VARIOUS EXIT VELOCITIES (UNMODIFIED FLAP).

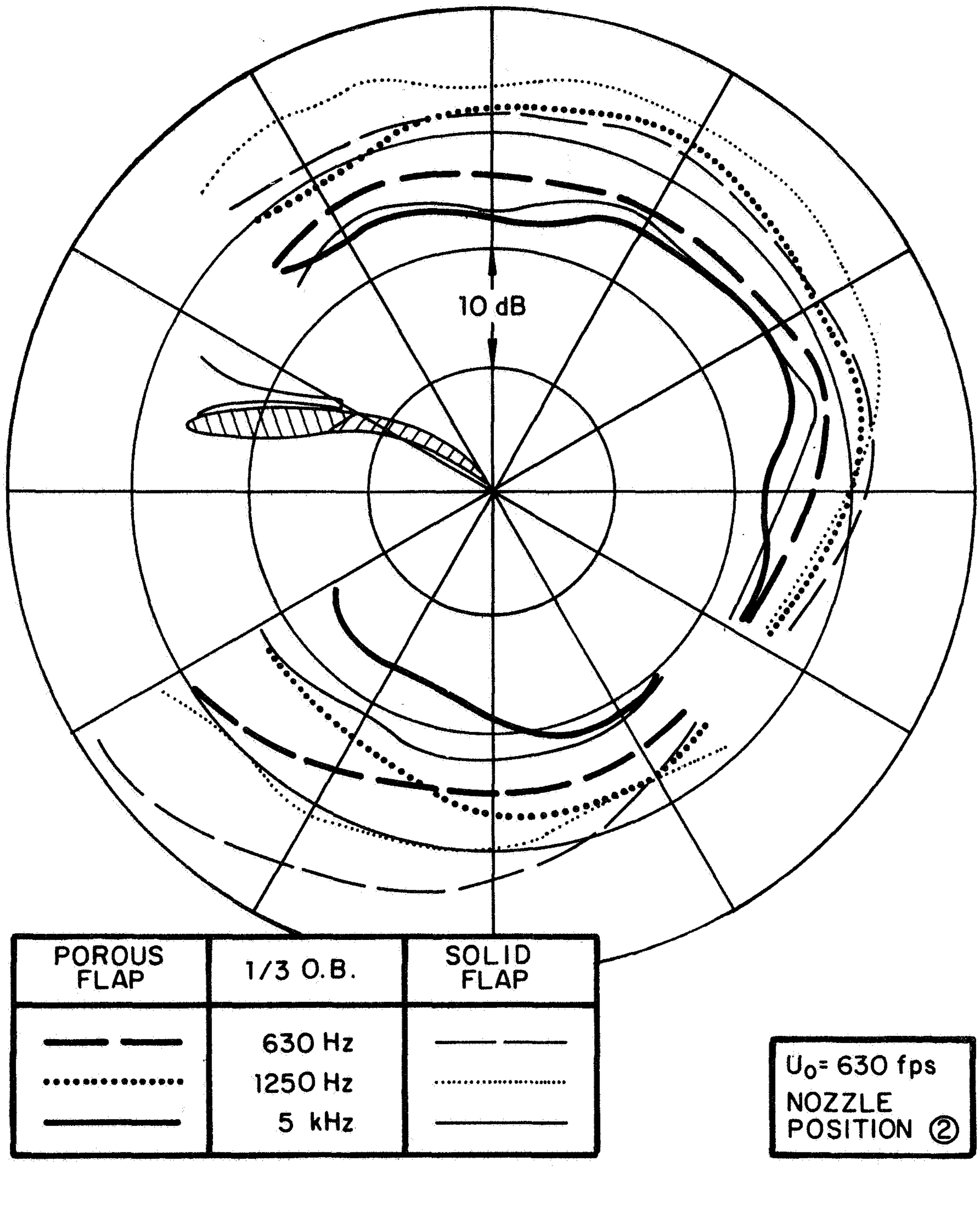

FIG. 10 DIRECTIVITY OF SOUND FIELD WITH AND WITHOUT POROUS EDGE ON FLAP.

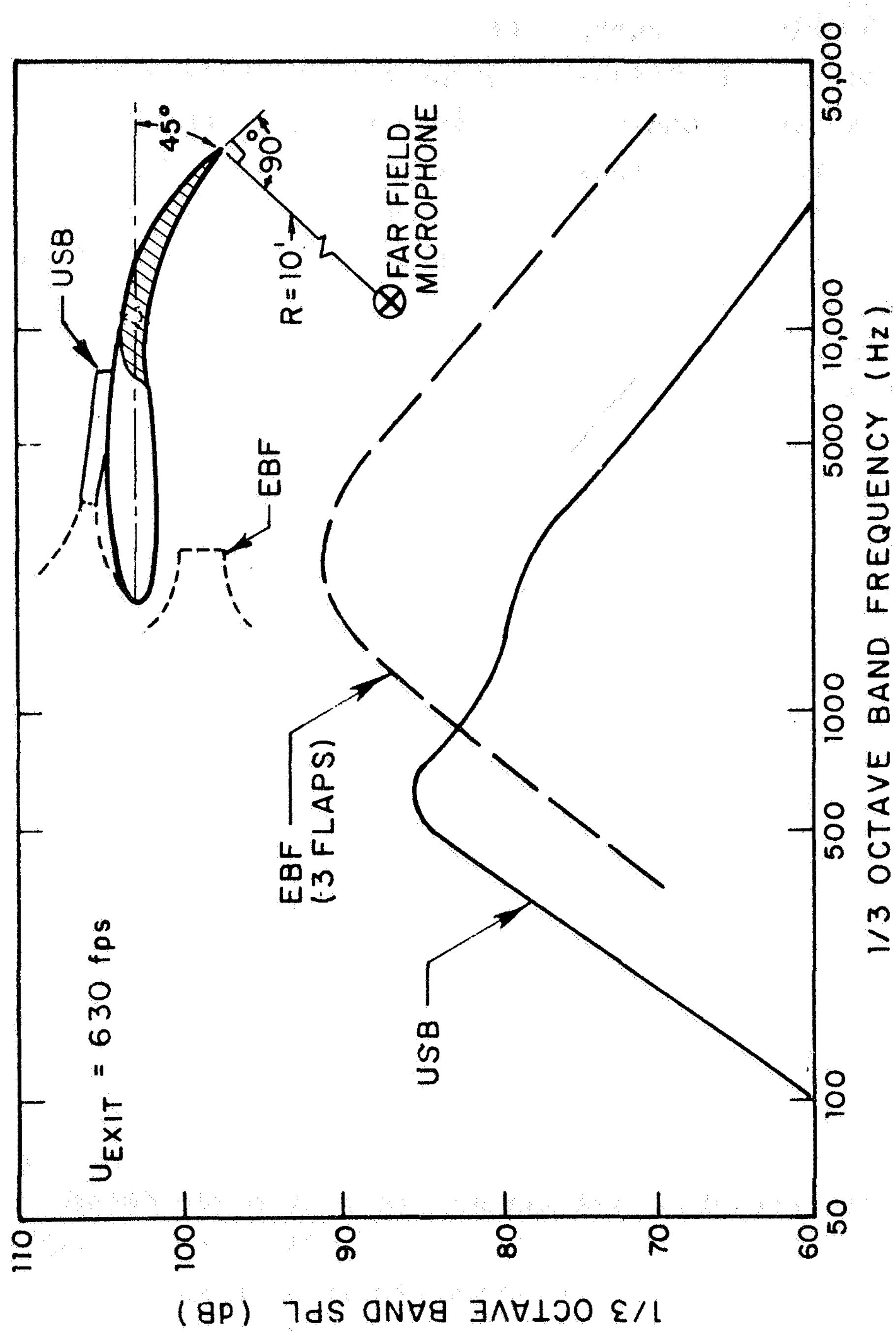

FIG. 11 COMPARISON OF FAR FIELD SOUND SPECTRA FROM 3-FLAP EBF AND UPPER SURFACE BLOWN FLAP (USB)

community noise criteria (such as PNL or dBA) will favor the USB flap concept if velocities do not have to be raised significantly to achieve aerodynamic performance equal to the EBF. However, the low frequency peak associated with the USB will produce substantial interior noise problems and possibly objectionable sound-induced structural vibration of both the aircraft and buildings near the flyover path.

Surface Pressure Correlations and Location of Sound Sources

Pressure cross correlation measurements were performed to evaluate the eddy length scales and to isolate the predominate sound producing area of the flap. The former task involves correlation of two surface-mounted pressure sensors and the latter correlation between a surface mounted pressure sensor (moved to various positions on the flap) and a free field microphone.

Eddy Scales

Two BBN 0.1 inch diameter flush mountable piezoelectric pressure sensors were mounted at various positions in the flap to determine eddy scales and, when correlated with the far field sound, to locate the sound sources along the flap chord and span.

The sensor array is shown in Fig. 12 (hole diameters not to scale). The spanwise eddy scales were determined by moving the sensors with respect to the centerline at two chordwise locations ("M" Row and "T" Row in Fig. 12). Figures 13A and 13B show the results of these measurements in a normalized

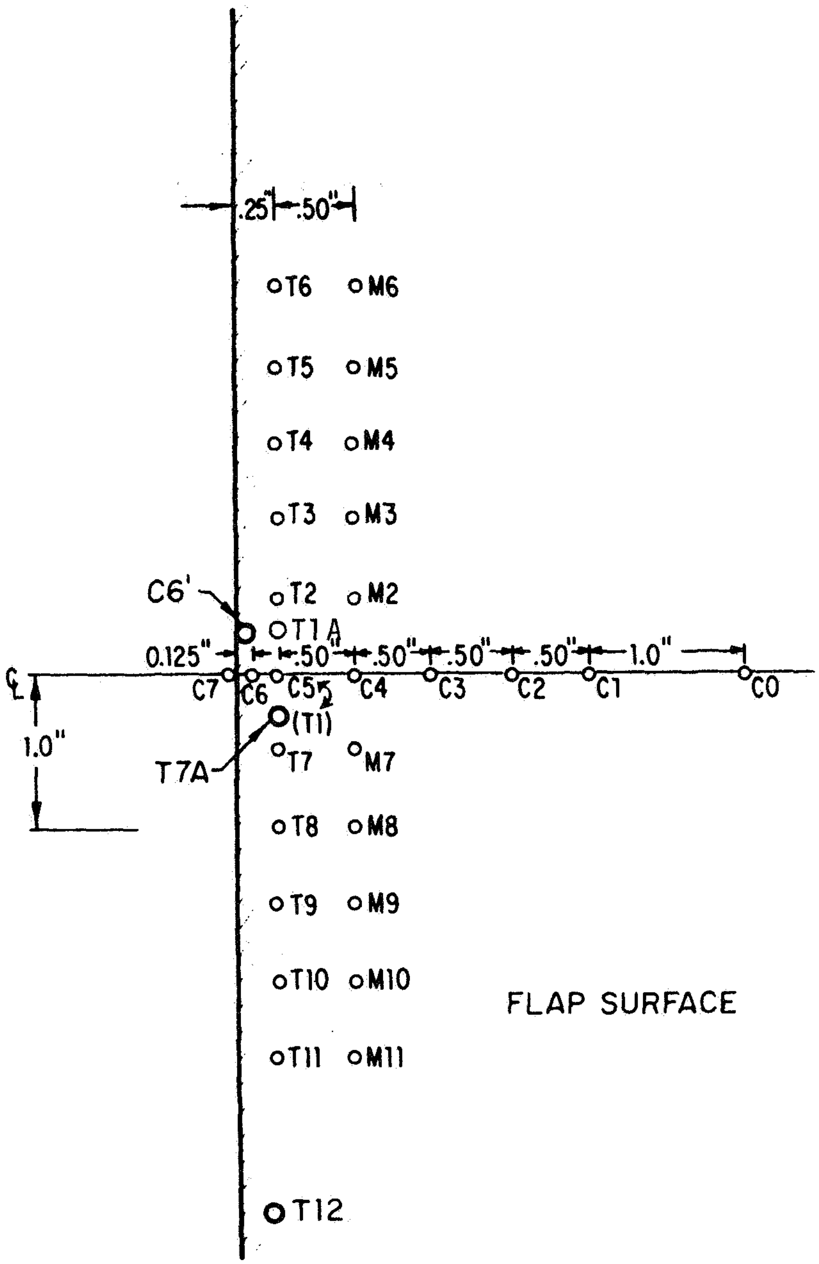

FIG. 12 LAYOUT OF SURFACE PRESSURE SENSOR ARRAY

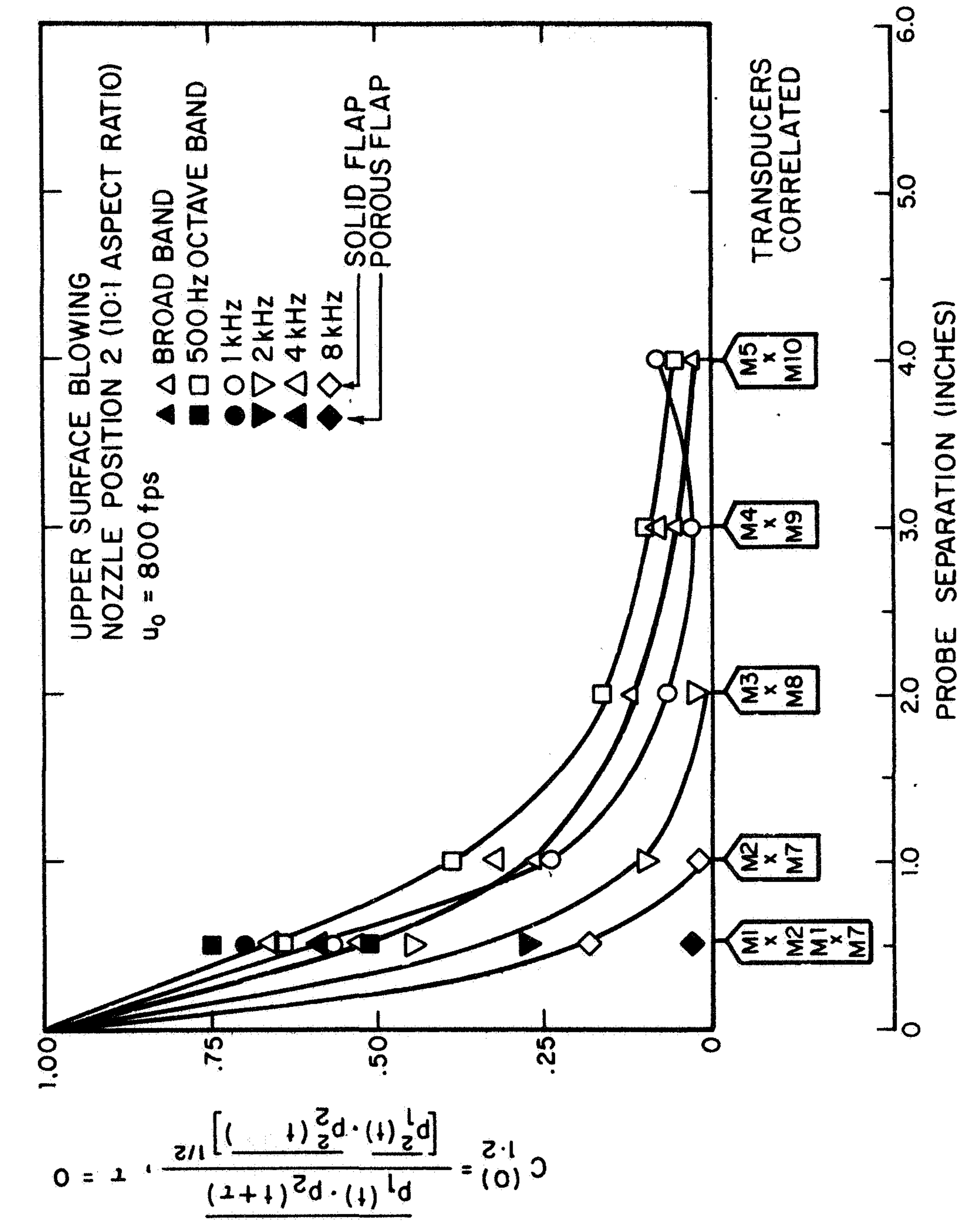

FIG. 13a SPANWISE CORRELATION OF SURFACE PRESSURES UPSTREAM OF EDGE

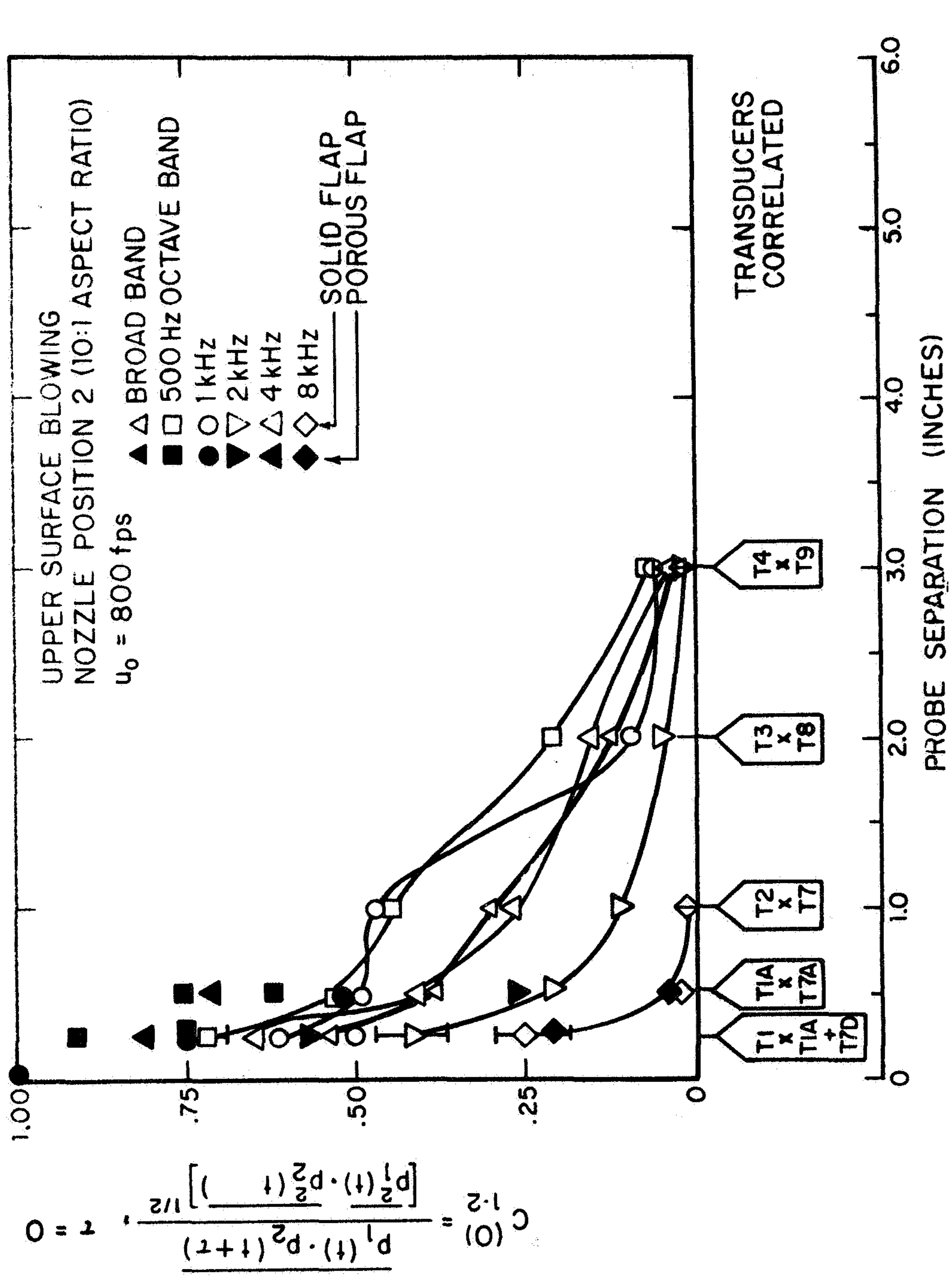

FIG. 13b SPANWISE CORRELATION OF SURFACE PRESSURES ALONG TRAILING EDGE

fashion for various frequencies.* As expected, higher frequencies are characterized by smaller integral eddy correlation lengths. The correlation curves for the "T" Row (i.e., near the trailing edge) are somewhat different than for the "M" Row which is further upstream. A partial explanation for this may be found in previous data on the flow field characteristics (i.e., the "core" shrinks quickly near the trailing edge as was evident in the flow visualization photos, Figs. 4A and 4B, and the velocity profiles in Fig. 6). Furthermore, the "T" Row is in the hydrodynamic near field of the trailing edge sound source which may tend to give apparent eddy scales larger than those due to the convective field alone.

Location of Sound Sources

The dominant sound-producing of the flap was located using cross-correlation between flap surface pressure (p_F) and far field sound pressure (p_S) at a time delay (τ_M) corresponding to the acoustic propagation time over the far field microphone distance, r ($\tau_M \approx r/c_0$ where c_0 is the sound speed). The correlations are normalized with respect to the product of the r.m.s. surface and far field pressures. Thus, magnitude of the normalized cross-correlation is a measure of how much sound originates from a particular location on the surface. When this analysis is performed in relatively narrow bandwidth (octaves were chosen here), one may locate the source of the various components of the far field sound spectrum.

---

*
p_2 = surface pressure at sensor 1
p_2 = surface pressure at sensor 2
t = time
τ = time delay
C = normalized cross correlation coefficient

Such an analysis was performed on the USB turning flap described earlier for an exit velocity of 800 fps. The free field microphone was located below the flap and the surface pressure sensors measured the pressure on the upper surface. The results are summarized in Figs. 14 and 15. In Fig. 14, the correlation coefficients are shown as a function of frequency and distance from the trailing edge. As expected, the high frequencies sources are located very close to the trailing edge and the low frequency components distributed over a larger area. It is interesting to note, however, that the low frequencies and broad band correlations both have maximum values near the trailing edge. Figure 15 shows correlation between surface pressure and far field sound taken at spanwise locations 0.25 inches from the trailing edge ("T" Row). The high frequencies seem to be concentrated along the centerline of the flow while lower frequencies and the broad band correlations show additional peaks at spanwise distances corresponding to the "rolled-up" vortices which were evident in the flow visualization and velocity measurements.

From these measurements, one can easily see that noise control of the USB could be accomplished by treatment of the trailing edge region - either through modifying the flow field or the acoustic transduction process through which hydrodynamic pressure fluctuations are converted into sound. The remainder of this report is devoted to a summary of the results of (1) treating the trailing edge region with a porous insert and (2) injection of secondary air near the trailing edge.

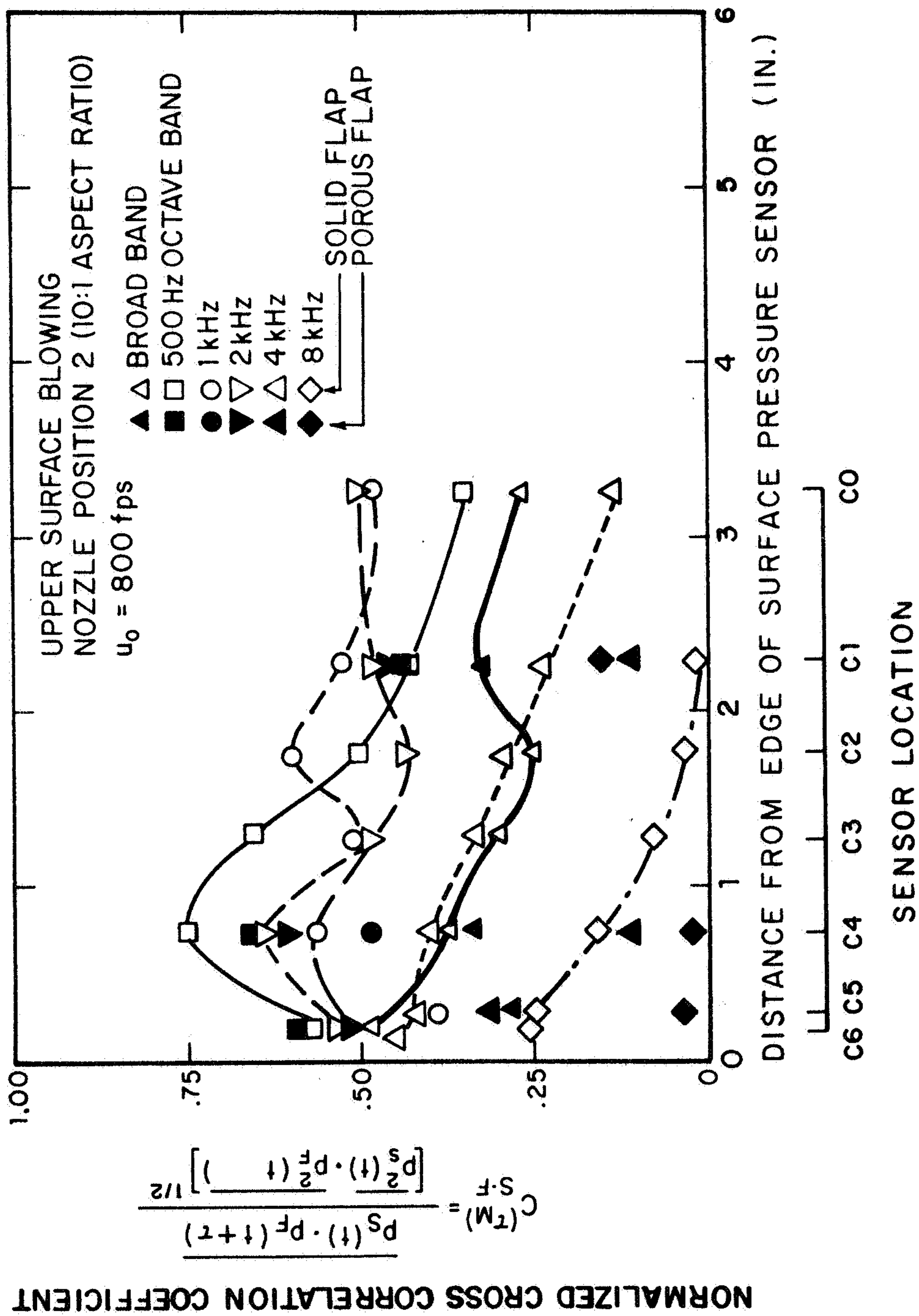

FIG. 14 CORRELATION BETWEEN SURFACE PRESSURE AND FAR FIELD SOUND VS DISTANCE FROM TRAILING EDGE ALONG CENTERLINE OF FLOW

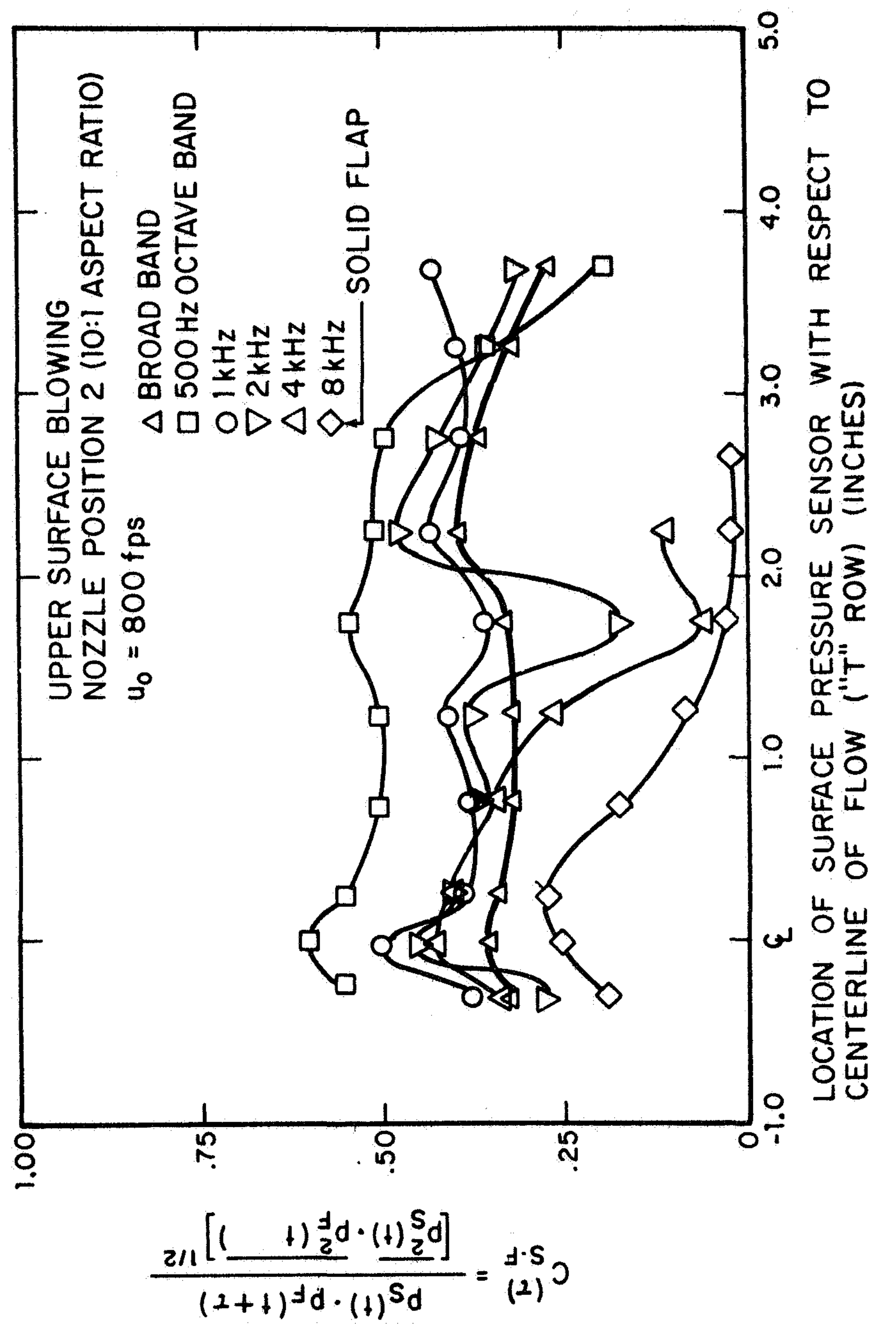

FIG. 15 CORRELATION BETWEEN SURFACE PRESSURE AND FAR FIELD SOUND VS DISTANCE ALONG SPAN OF TRAILING EDGE

II. Porous Trailing Edge Study

A section of the trailing edge of the flap (2.5 inches × 8 inches) was removed and replaced with porous inserts - one being simply a porous sheet of about 0.2 ρc flow resistance without any backing, and the other being the same porous sheet with an air cavity behind it having the shape of the original flap section. The second configuration had a solid backing plate which followed the contour of the lower flap surface up to about 0.25 in. from the trailing edge where a highly porous "spacer" connected the solid backing to the porous upper flap surface.

Noise Reduction

The noise reduction achieved with both configurations was appreciable. Figure 16 gives normalized spectra of the sound radiated below the wing and in the "forward" direction (i.e., 150° from the jet axis) for the basic flap configuration and the two porous trailing edge configurations. It is encouraging that the noise reduction is greatest below the wing for the case where a solid backing is used behind the porous insert. This configuration is thought to have very minimal aerodynamic losses since steady state through-flow is essentially blocked. Of further significance is the reduction of the low frequency noise "at the source" since this noise would otherwise be extremely troublesome in cabin interiors and on the ground.

The noise reduction was also found to be not strongly dependent upon the observation angle as shown in Fig. 10. The 5 KHz noise above the wing is not strongly influenced by the porous flap. This is thought to be partly due to lip noise from the slot nozzle and partly from radiation from the solid/porous interface where the impedance discontinuity pressure field was still large enough to cause sound radiation from that junction.

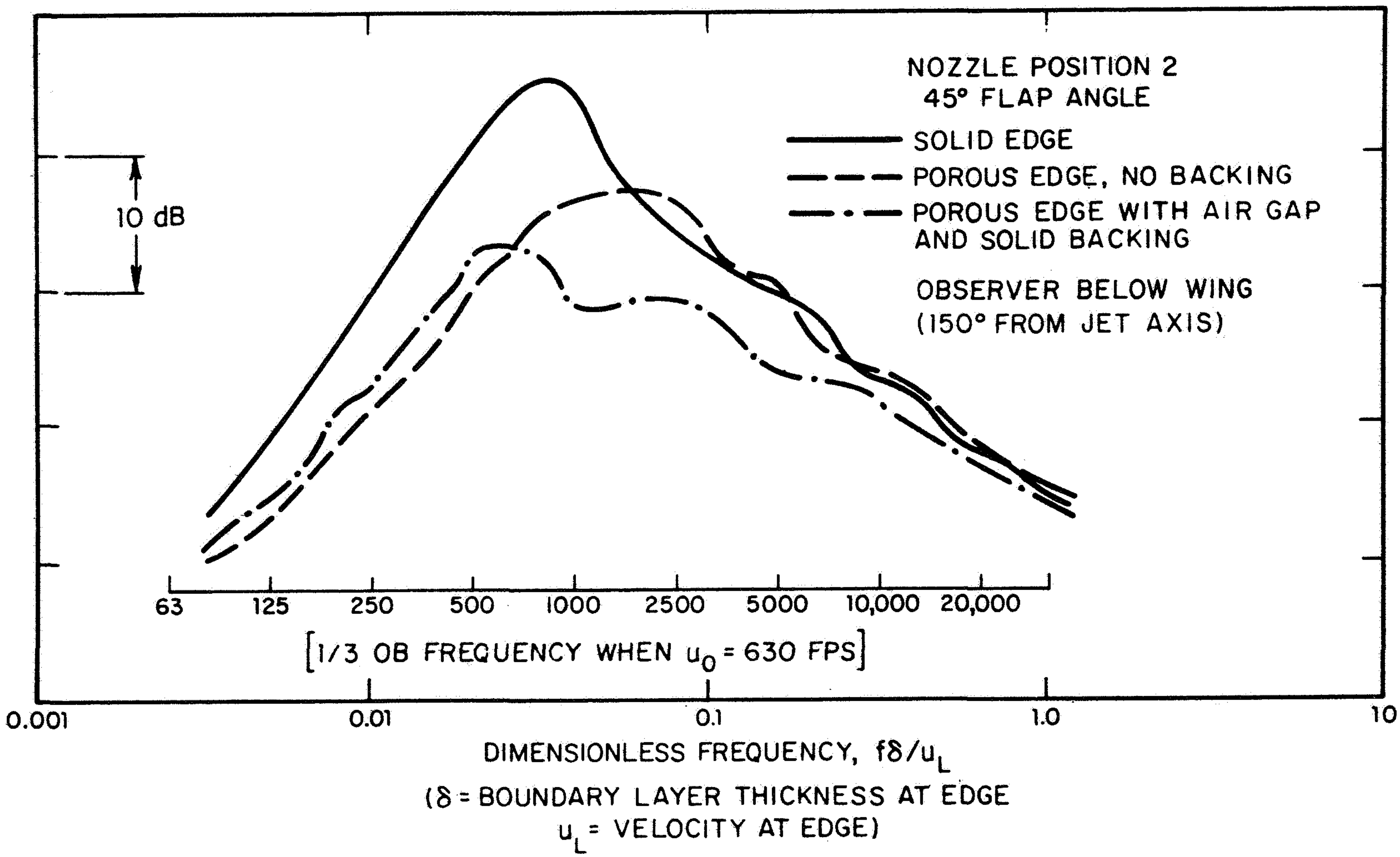

FIG. 16 NOISE REDUCTION ACHIEVED WITH TWO POROUS TRAILING EDGE CONFIGURATIONS

This hypothesis was investigated using correlation techniques, wherein a 0.1" pressure sensor was treated at several positions in the porous flap (no solid backing) and surface pressures correlated with far field sound. These results, given in Fig. 14, show that the high frequency pressures near the trailing edge are less strongly correlated with the far field than in the solid flap. In fact, the only significant correlation in the 8 KHz band comes near the solid/porous junction (which was 2.5 inches from the trailing edge). This observation suggests that some type of gradual impedance change from solid to very porous would provide minimal "scattering" such as observed in the 8 KHz band here, and thus optimize noise reduction.

Effect on Flow Field

Steady Component: The porous flap (no air gap) was studied for its influence of the steady and unsteady parts of the flow field near the trailing edge. As shown in Fig. 5, the centerline profiles of mean velocity were found to be slightly changed by the addition of the porous flap, with the maximum local velocity being reduced slightly and the distance from the surface to the point of maximum local velocity increasing slightly. This effect is also reflected in the spanwise profiles of axial velocity shown in Fig. 6 at various distances from the flap surface. However, in Fig. 6, the profile for y/h = 3.0 shows a substantial increase in axial velocity at spanwise locations between ±0.25 in. and ± 1.75 in. from the centerline of the flow. Thus, the total momentum flux through the turning angle might well be the same for the two cases.

Unsteady Flow Components: Profiles of r.m.s. turbulence intensity were measured in the plane normal to the flap surface along the flow centerline and in the spanwise direction at various distances from the flap surface near the trailing edge. Figure 7 compares the r.m.s. intensity profiles with those for the unmodified flap at two chordwise positions near the trailing edge. Upstream of the edge ($x/h = 14$), the intensity near the surface is increased by the porous flap, but only slightly. (The actual values of fluctuating velocity were almost identical when normalized to exit velocity, but the intensities shown in Fig. 7 are normalized with respect to maximum local velocity.) At the trailing edge, the solid flap had a slightly greater local turbulence intensity than the porous flap, while the location of the peak was further from the surface in the case of the porous flap. In all cases, the outer (free) shear layer turbulence intensities are roughly comparable.

Figure 8 compares spanwise profiles of r.m.s. turbulence intensities (axial component) for various heights above the surface and the two flap surface conditions described above. These traverses were all taken in the immediate vicinity of the trailing edge ($x/h \approx 15$). In general, the turbulence intensities were reduced by the porous flap, but only slightly and not enough to account directly for the noise reduction observed. Some significant reductions were observed in the "axial-vortex" region, but the pattern of change is very complex and a more detailed explanation is beyond the scope of this study.

Correlation Lengths: A brief investigation of the eddy correlation lengths on the porous portion of the flap was carried out using techniques previously described. These results are summarized in Figs. 13A and 13B and compared with comparable data for the solid flap. In Fig. 13A, the spanwise correlations in the porous flap upstream of the edge are seen to be comparable to those in the solid flap at low frequencies and smaller at high frequencies. However, at the edge (Fig. 13B), the low frequency correlations seem to be slightly larger in the porous flap than in the solid flap, with high frequencies being quite comparable for the two cases. Due to the preliminary nature of this survey, no meaningful conclusions can be drawn, but it appears that the porous insert does not significantly affect the eddy scales of the turbulent wall jet flowing over it.

III. Trailing Edge Blowing Study

Summary

A preliminary experimental study has been performed to measure the sound reduction characteristics for an upper surface blowing airfoil with secondary air blowing from a slot near the airfoil trailing edge. With secondary air pressure of up to 24 inches H_2O, far field sound reductions of 3.5 to 5.5 dB were achieved at high frequencies (e.g., 4000 Hz model scale) and 2 to 3 dB at the peak of the spectrum (approximately 630 Hz model scale). Surface pressures near the trailing edge showed greater reductions (6.5 dB at the higher frequencies) than those in the far field. This result, together with changes in the cross correlation between surface and far field pressures, indicates that sound is being generated upstream as well as downstream of the slot, perhaps at the slot lip. Hence, it is recommended that further studies be performed to explore the use of a secondary blowing system which has a chordwise distribution of secondary air through additional slots, holes, porous skin, etc.

Test Setup

A model scale airfoil was constructed to represent an upper surface blowing wing-flap system in takeoff configuration (Fig. 17). The airfoil had a span of 12 inches and a rectangular jet nozzle with dimensions 5 inch x 0.5 inch was positioned close to the upper surface of the airfoil. A hole was drilled in the airfoil, between the secondary blowing slot and the flap trailing edge, so that a transducer (B & K 1/8-inch diameter microphone) could be mounted with its diaphragm flush with the upper surface of the airfoil.

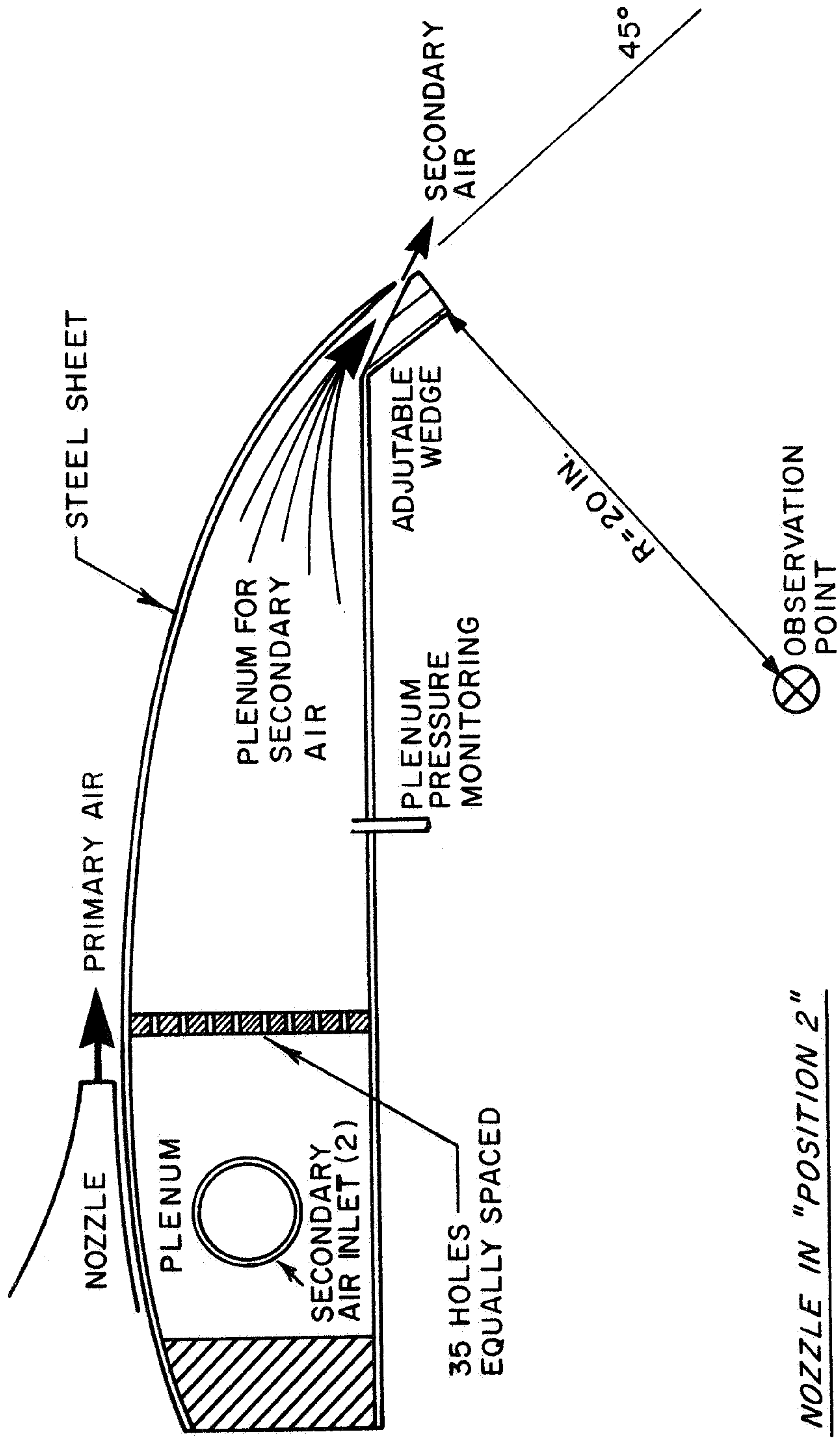

FIG. 17 EXPERIMENTAL ARRANGEMENT FOR EDGE BLOWING STUDY.

Acoustic measurements were performed in an anechoic chamber, except in the initial checkout phase when the far field acoustic radiation for the jet nozzle alone was measured in a reverberant room.

Sound from Jet and Turning Flap

The far field sound from the jet blowing over the turning flap was measured for several slot geometries, with and without secondary blowing. In some cases when there was no secondary blowing, the slot was sealed with tape but in other cases the slot remained unsealed.

Acoustic spectra for two slot geometries are shown in Figs. 18-20. In Figs. 18 and 19, the slot gap is 0.05 inch and it is located 0.3 inch upstream of the flap trailing edge. In Fig. 20 the gap is 0.10 inch and the slot is 0.75 inch upstream of the trailing edge. For both examples the microphone was located approximately 20 inches from the trailing edge, at an angle of 90°, and the exit Mach number of the primary jet was 0.5. The spectra peak at frequencies in the range 500-630 Hz, which is much lower than the corresponding range for the jet alone.

Figures 18-20 show the acoustic changes associated with the introduction of secondary air. The following observations can be made:

1) When there is no blowing, the size of the slot has little or no effect on the far field noise except at low frequencies (less than 160 Hz model scale) when the bigger slot causes an increase in the radiated sound. With the 0.05 inch slot and no secondary blowing, sealing the slot has at most a 1 dB effect on the far field sound.

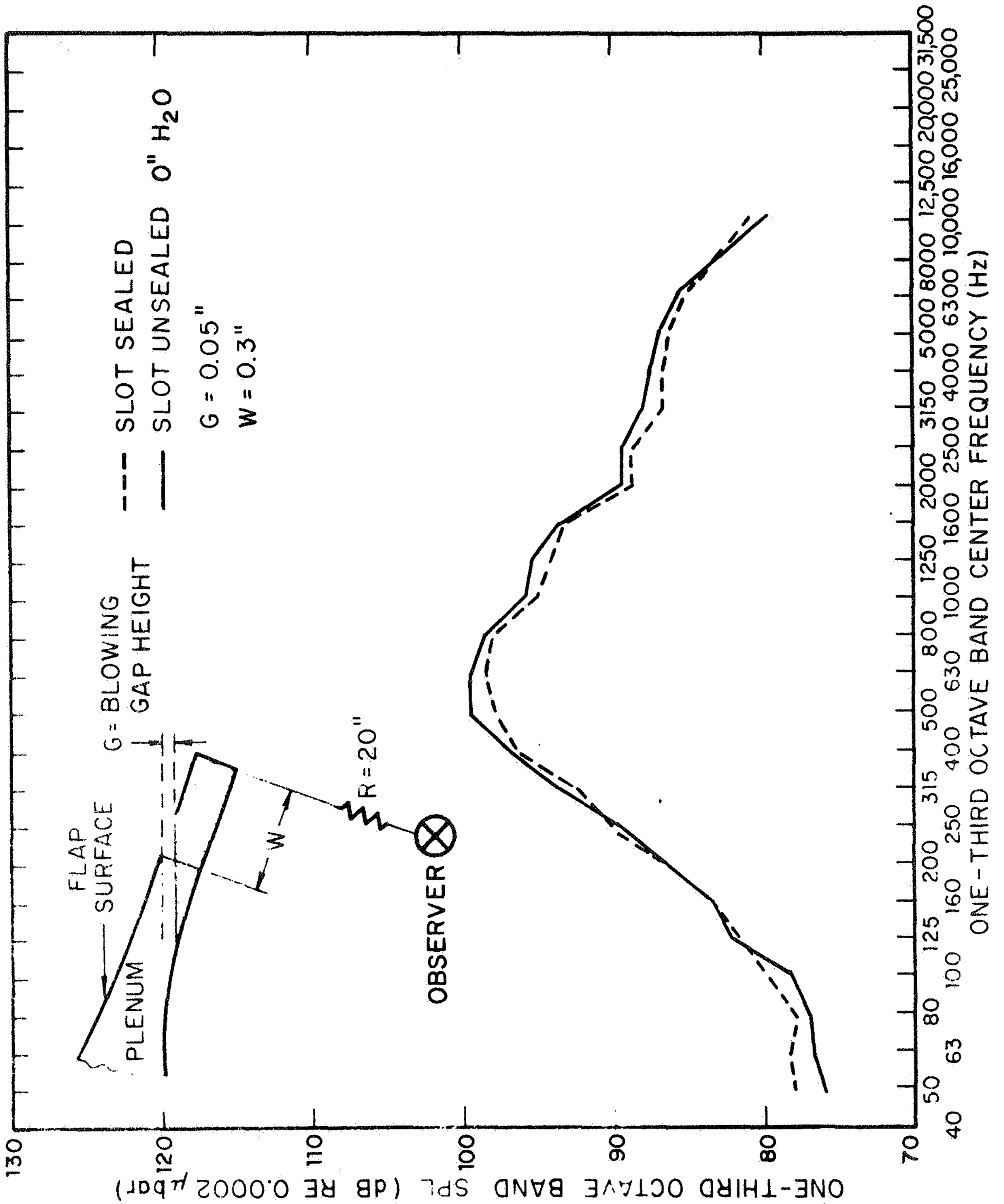

FIG. 18 SOUND SPECTRA FROM BASIC FLAP WITH AND WITHOUT SLOT SEALED.

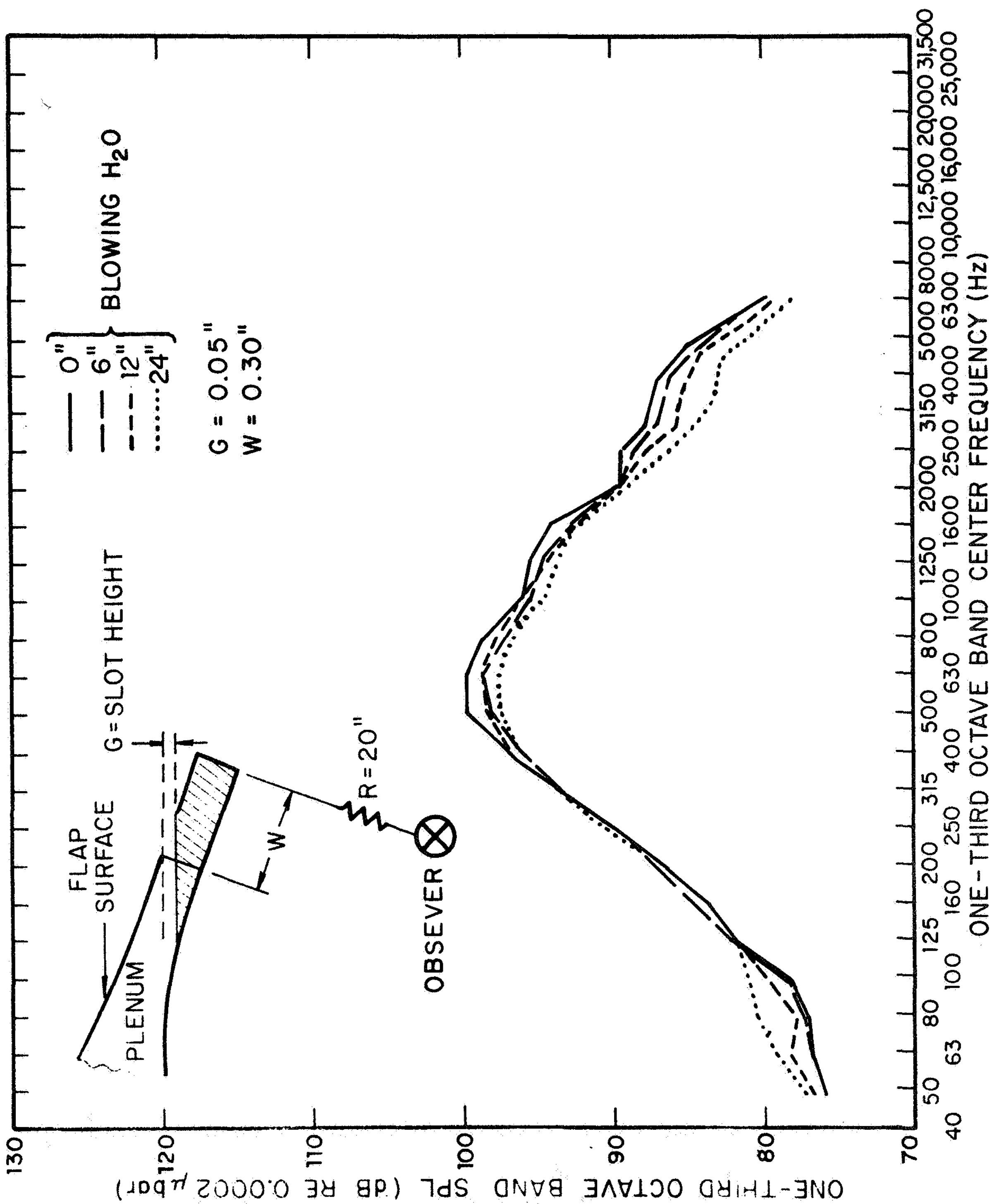

FIG. 19 SOUND SPECTRA FOR VARIOUS AMOUNTS OF BLOWING WITH SLOT NEAREST EDGE AND SMALL GAP HEIGHT.

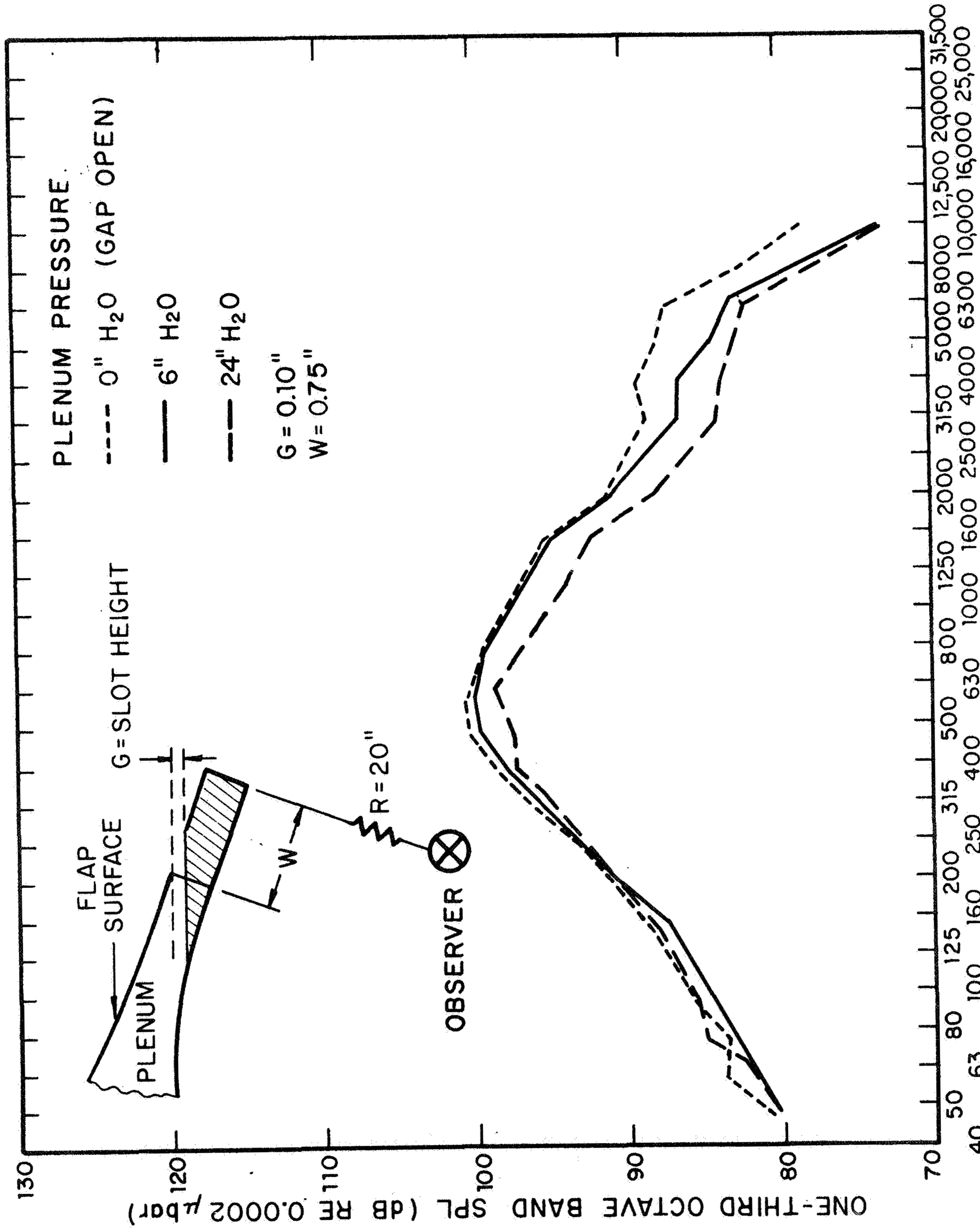

FIG. 20 SOUND SPECTRA FOR VARIOUS AMOUNTS OF BLOWING (LARGE SLOT).

2) Secondary blowing reduces the far field sound in mid and high frequency ranges, the effect being greater at the higher frequencies. At the peak frequencies in the spectra, blowing reduces the far field noise by 2 to 3 dB, and at higher frequencies the sound reduction is 3.5 to 5.5 dB.

3) The greatest sound reduction occurs with the largest slot gap and the largest separation between slot and trailing edge. However, with the current small scale model, optimization of the secondary air system is difficult.

4) The sound reduction increases with pressure of secondary air (at least up to 24 inches H_2O) but this high pressure condition causes a small increase in the noise at very low frequencies (less than 100 Hz model scale).

Surface Pressure Fluctuations

In conjunction with the far field acoustic measurements in Figs. 18-19, surface pressure fluctuations were measured on the flap between the slot and the flap trailing edge. One-third octave band data are presented in Fig. 21 for a Mach number of 0.5 at the primary jet nozzle. The spectral shape is different from that for the far field, in that the spectrum peaks occur in the frequency range 2000-4000 Hz rather than 500-630 Hz.

Certain trends observed in the far field acoustic data for the upper surface blowing (Figs. 18 and 20) can be seen in the surface pressure spectra but the magnitudes of the changes are now greater. Sealing the gap appears to increase the local low frequency pressures but this is probably a spurious effect caused by the method of scaling. Secondary blowing reduces the surface pressure fluctuations throughout the frequency range, except at

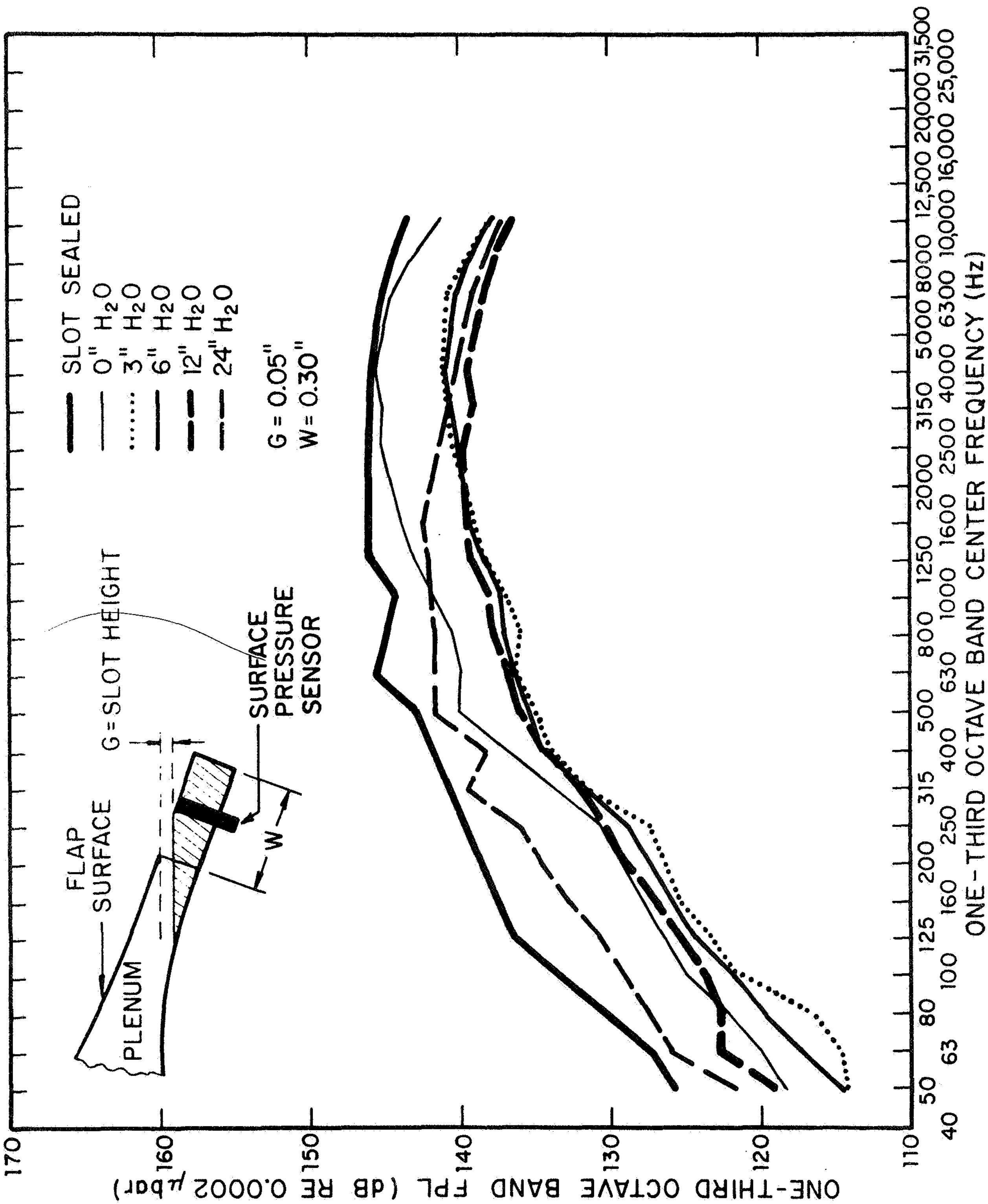

FIG. 21 SURFACE PRESSURES AT TRAILING EDGE FOR VARIOUS AMOUNTS OF BLOWING.

the high secondary air pressure when the low frequency pressure fluctuations show an increase. At intermediate pressures for the secondary air, the reductions in the surface pressure fluctuations near the trailing edge vary from 2 dB at low frequencies to 6.5 dB at high frequencies.

Pressure Correlations

Maximum cross correlations between the surface and far field pressures were measured in the two octave bands centered at 1000 Hz and 8000 Hz, the test condition being the same as for the data in Figs. 19 and 21. Normalized cross correlation coefficients are shown in Fig. 22 where it is seen that the secondary air has no significant effect on correlation at 1000 Hz but reduces the correlation at 6000 Hz to about one-half of the value for no blowing. Thus, at high frequencies, the pressure fluctuations downstream of the slot are associated with a smaller percentage of the far field pressures when there is secondary blowing than when there is no blowing. Conversely, when there is secondary blowing the pressure fluctuations on the turning flap surface immediately upstream of the blowing slot become more important in determining the far field acoustic radiation.

Conclusions and Recommendations

Blowing of secondary air from a slot in the upper surface of the turning flap near the trailing edge of the flap, can reduce the far field noise of an upper surface blowing system by at least 5.5 dB at certain frequencies. As a consequence of the secondary blowing, sources "upstream" of the blowing slot assumes greater importance in determining the far field sound levels. Thus it is recommended that further studies be performed to investigate the use of multislots, or of distributed blowing through holes or porous surfaces, to maximize the noise reduction achieved in the far field.

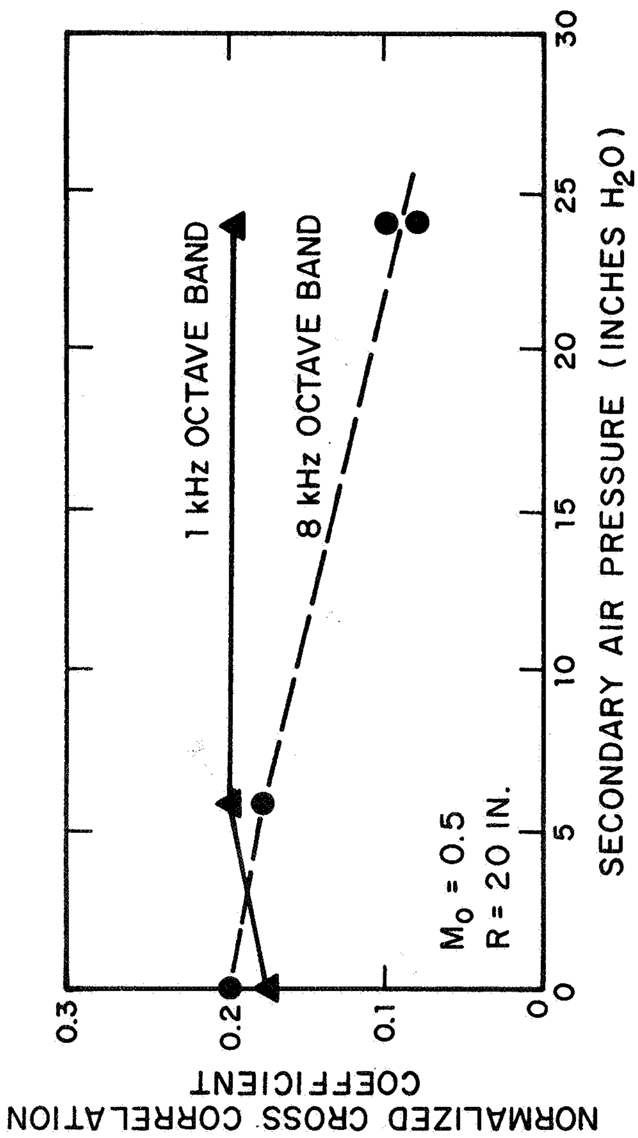

FIG. 22 CROSS CORRELATION BETWEEN SURFACE PRESSURE AT EDGE AND RADIATED SOUND FOR VARIOUS AMOUNTS OF BLOWING.