Subsonic Diffusers Designed Integrally with Vortex Generators

ALAN C. BROWN,* H. FRANZ NAWROCKI,† AND PETER N. PALEY†
Lockheed-California Company, Burbank, Calif.

A short subsonic diffuser has been developed incorporating vortex generators as an integral design feature. The principle of operation is that line vortices, when suitably arranged, mutually interact to drive each other towards an adjacent plane wall. The wall may then be pulled away from the vortices at such a rate that the vortices remain a constant distance from it. The ideal arrangement, having the vortex lines running along the edge of the boundary layer, can thus be obtained by design. A simple, two-dimensional diffuser was developed at Lockheed using these principles. It was compared experimentally with a conventional high-performance trumpet-shaped diffuser. Two significant results were observed in this test series. One was that both pressure recovery losses and distortion were reduced by about 40% by the new design. The other was that vortex generator design mismatches carry larger penalties with the integrally designed diffuser than with the conventional type. The subsonic diffuser of an inlet for a Mach 2.7 supersonic transport airplane was shortened and redesigned in two stages, using the integrated vortex generator approach. First, vortex generators were tailored to a short subsonic diffuser of conventional design, and then a new inlet was tested which included a subsonic diffuser designed on the integral basis. The successive changes improved both pressure recovery and flow uniformity. Thus, the basic concept was validated in a practical application.

Nomenclature

C = airfoil chord
d = lateral distance between midchord points of paired airfoils
D = lateral distance between vortex pairs
h = airfoil height
K = vortex strength
m = mass flow
NDI = General Electric distortion index
P = static pressure
P_T = total pressure
$\bar{P}_T$ = area weighted average total pressure
ΔP_T = difference between maximum and minimum total pressures
r = radial distance from vortex centerline
t = time
v = circumferential velocity
w = velocity parallel to z direction
x = direction normal to flow and parallel to surface
y = direction normal to flow and surface
z = flow direction

Subscripts

av = average
max = maximum
min = minimum
0 = position at time zero
o = entrance to diffuser (see Figs. 6a and 6b); also free-stream
O = condition (see Figs. 11, 13, 16, and 17)

Introduction

THE design optimization of supersonic mixed-compression inlets often shows that uniformity of flow properties in the subsonic diffuser can be achieved efficiently by forced mixing. Small, low-aspect-ratio wings, known as vortex generators, have proved to be effective in exchangiug low-momentum air near the surfaces of a diffuser with the higher-momentum air outside the boundary layer. Some of the earliest work was performed in 1948 by Taylor.[1] Woolard[2] made an extensive bibliography and summary of the work done up to mid-1965. Of this, Pearcey's[3] was perhaps the most methodical from both the analytical and the experimental point of view.

When it was decided to shorten the subsonic diffuser of the Lockheed SST inlet, it was realized that forced mixing devices would probably be required to prevent local separation and to keep flow distortion within acceptable limits. In this report, a novel approach to the problem is described. An attempt was made to design a subsonic diffuser integrally with vortex generators rather than to adopt the more usual method of shortening a diffuser of conventional design and adding vortex generators to prevent flow separation. The validity of the method was explored in two series of aerodynamic tests. The more basic program involved two short, two-dimensional subsonic diffusers that were tested in the internal flow facility of Lockheed Research Laboratories. One was of conventional design and the other was cut away to match the anticipated paths of vortices shed from small generators. Both diffusers were tested with and without vortex generators of different types.

The second program was directly concerned with the development of the SST inlet. Vortex generators were installed in a short subsonic diffuser of conventional design with a nearly exponential area distribution. Pearcey's methods were adopted as a foundation for the tailoring techniques that were used to locate the vortex generators in the duct. A later subsonic diffuser incorporated an area variation that was more nearly matched to the predicted paths of the vortices. Its performance validated the analytical concept, and the design was incorporated into the SST propulsion system.

Analytical Background

The principle of boundary-layer control by vortex generators relies on the increased mixing between the external stream and the boundary layer which is promoted by vortices trailing longitudinally over the surface, adjacent to the edge of the boundary layer. Fluid particles with high momentum in the

Presented as Paper 67-464 at the AIAA 3rd Propulsion Joint Specialist Conference, Washington, D.C., July 17-21, 1967; submitted August 7, 1967; revision received November 13, 1967.

* Group Engineer, Propulsion Department.

† Propulsion Engineer-Senior, Propulsion Department.

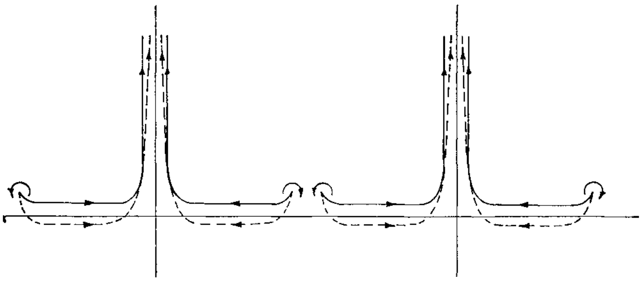


Fig. 1a Counterrotating vortices—close to a fixed plane, --- close to a moving constrained plane.

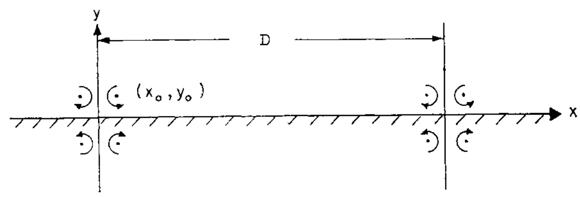


Fig. 1b Initial positions of vortices.

stream direction are swept along helical paths toward the surface to mix with and to some extent replace the retarded air at the surface. This provides a continuous source of reenergization to counter the natural boundary-layer retardation and growth caused by surface friction and adverse pressure gradients. Larger adverse pressure gradients can thus be imposed without causing separation.

Viscous dissipation will reduce the strength of the vortices as they travel downstream. Consequently, the adverse pressure gradient that can be supported by the boundary layer will diminish with distance downstream of the vortex generators. A typical subsonic diffuser may be designed to have a constant pressure gradient. This feature results in the characteristic trumpet shape common to many engine inlets. However, a diffuser designed to take advantage of the mixing capability of longitudinal vortices would have its largest pressure gradient just downstream of the vortex generators and a steadily diminishing gradient as the engine face is approached. The area would initially increase more rapidly with distance downstream than that of the conventional trumpet-shaped diffuser.

To make the vortices effective, they must run close to the edge of the boundary layer. It is clear that this is the only way in which a substantial interchange between high- and low-momentum air can take place. They must be in a region where the transverse gradient of longitudinal momentum is significant. Experience has shown[2] that a vane height of 1.2 boundary-layer thicknesses is satisfactory. However, it is not sufficient to make the vanes the correct height. The question of whether the vortices remain at the required height above the surface depends upon the way in which their filaments are moved by the velocity fields of their neighbors and their images. The velocity fields are determined by the initial spacing, height, and sense of rotation of the vortices.

A pair of counterrotating vortices of equal strength will move in a straight line in a direction normal to the plane containing them. If a plane surface is placed parallel to the vortex plane, so that the vortex plane approaches the surface, then the vortices will be forced away from each other. Other pairs of line vortices, parallel to the first and of similar sense, will repel their neighbors and cause the vortices that were approaching the surface to turn and move away. This vortex pattern is illustrated by the solid lines in Fig. 1a.

The derivation of the paths of the vortices is given in Fig. 1b. Let the x axis of a Cartesian coordinate system lie in the plane of the surface and be normal to the vortex lines. The y axis is normal to the plane. The origin of the system is on the surface and midway between two counterrotating vortices. The plane can be represented analytically by reflecting the vortices in it. The vortex pair is supposed to be one of an infinite set equally spaced a distance D apart. All are initially at the same height above the plane. The arrangement is shown in the Fig. 1b, where the vortex closest to the origin and in the first quadrant has the coordinates (x_0, y_0) at time zero. By symmetry, the motion of the complete set of vortices can be inferred from the motion of any single one.

If K is the strength of a vortex, then the induced circumferential velocity at distance r from the vortex in $v = K/2\pi r$. The velocity components of the vortex in the x and y directions can be calculated, assuming that all vortices have the same strength, as follows:

$$\frac{dx}{dt} = \frac{K}{2\pi}\left\{\frac{1}{2y} - \frac{2y}{(D-2x)^2+(2y)^2} + \frac{2y}{D^2+(2y)^2} - \frac{2y}{(2D-2x)^2+(2y)^2} + \cdots - \frac{2y}{(2x)^2+(2y)^2} + \frac{2y}{D^2+(2y)^2} - \frac{2y}{(D+2x)^2+(2y)^2} + \frac{2y}{(2D)^2+(2y)^2} - \cdots\right\}$$

which after some manipulation gives

$$\frac{dx}{dt} = \frac{K}{2\pi}\left\{\frac{x^2}{2y(x^2+y^2)} + \sum_{n=1}^{\infty}\frac{16x^2y[-3n^2D^2+4(x^2+y^2)]}{(n^2D^2+4y^2)[n^4D^4+8n^2D^2(y^2-x^2)+16(x^2+y^2)^2]}\right\} \quad (1)$$

Similarly

$$\frac{dy}{dt} = \frac{K}{2\pi}\left\{\frac{-y^2}{2x(x^2+y^2)} + \sum_{n=1}^{\infty}\frac{16xy^2[3n^2D^2+4(x^2+y^2)]}{(n^2D^2-4x^2)[n^4D^4+8n^2D^2(y^2-x^2)+16(x^2+y^2)^2]}\right\} \quad (2)$$

If the plane below the vortices is pulled away from them, then the vortices will tend to follow the plane. In particular, the velocity of the plane can be chosen to be equal to the vertical component of velocity of the vortices, so that the distance between the vortices and the plane remains constant. The movement of the vortices is now made up of two distinct components. One is due to the mutual interaction between active vortices as described previously. The other is due to the expansion of the gas above the plane as it maintains local density equilibrium. This expansion will carry the vortices with it.

For reasons to be discussed later, the second mode of transport will be ignored for the present. Then the mutual interaction effect can be defined precisely by a simple alteration to Eqs. (1) and (2). As y in those equations is the distance of the vortices above the plane, whether moving or not, then it can be replaced by a constant y_0 its initial value. Solution of Eqs. (1) and (2) in this modified form will automatically give the result for the plane moving a constant distance below the generators. This now satisfies one of the primary requirements of the vortex/boundary-layer interaction problem, which is that the vortices remain approximately a constant distance above the surface.

Equations (1) and (2) have been solved for both the fixed plane and the moving plane case. The results are shown in Fig. 1a for vortices whose initial coordinates are $x_0/D = 0.05$ and $y_0/D = 0.08$.

The results of this calculation can be applied to the design of a subsonic diffuser by applying a time-distance transformation. Suppose that in the z direction, normal to the x-y plane, a subsonic flow with velocity w exists. If a fixed plane, parallel to the x-z plane, is imagined some distance above the initial position of the vortices, then the gas will flow through

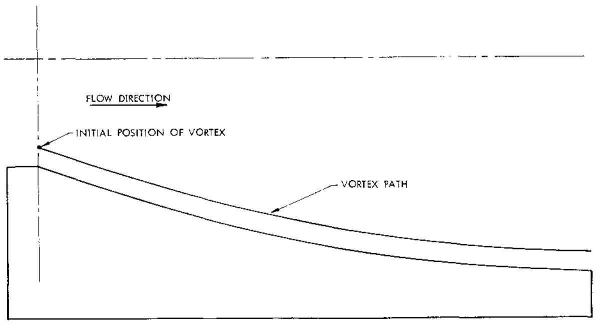


Fig. 2 Integrally designed subsonic diffuser.

a two-dimensional channel. As the moving plane drops, the velocity w will decrease because of the increase in flow area and so, in effect, will become a function of time. Now apply the transformation

$$z = \int_0^t w \, dt \qquad (3)$$

The position of the plane is given by Eq. (2), which also determines the local flow area and, hence, w (t). Thus the coordinates of the wall in terms of y and z are determined. For purposes of subsonic diffuser design, the curved wall should be terminated at or before reaching the minimum value of y.

It can be seen from the example shown in Fig. 2 that the subsonic diffuser would have a very steep, discontinuous, initial slope. A practical design would allow some rounding of this corner. However, without the presence of the vortices, the flow would undoubtedly separate at the beginning of the diffuser. It is for this reason that the effect of expansion of the flow around the corner has been ignored in the determination of the wall shape. It has been assumed that the natural expansion of the flow makes no contribution to the effective shape of the wall. This is, of course, in direct contrast to the design of a conventional diffuser, where vortices are either assumed not to be present or not to contribute to the possible diffuser expansion. The real diffuser would benefit from both effects.

Experimental Program—Internal Flow Facility

The Internal Flow Facility Tunnel in the Lockheed Research Laboratories is, in essence, a small blowdown supersonic wind tunnel, incorporating provisions for regulating boundary-layer bleed flow on the floor and on the ceiling in the test section. The tunnel size and flow Mach number were originally selected for approximate simulation of the internal flow of one side of a two-dimensional intake for a typical supersonic transport airplane flying at a Mach number of 3.0. The test section Mach number of 1.54 corresponded to that just ahead of the terminal shock, whereas the throat dimensions of 4 in. × 16.8 in. were one-third of the full-scale values. Boundary-layer bleed was provided for simulation of the bleed flow at the inlet terminal shock. With the shock wave positioned at the bleed section, the flow downstream of it simulated the internal flow in the subsonic diffuser.

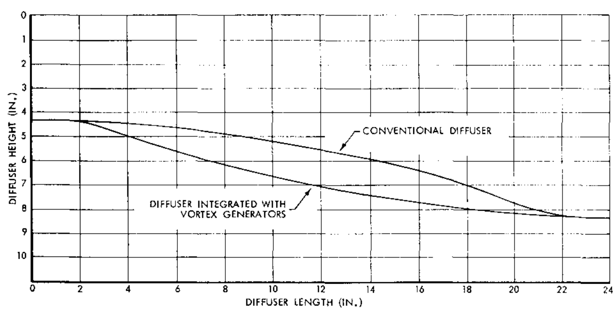


Fig. 3 Two-dimensional subsonic diffusers.

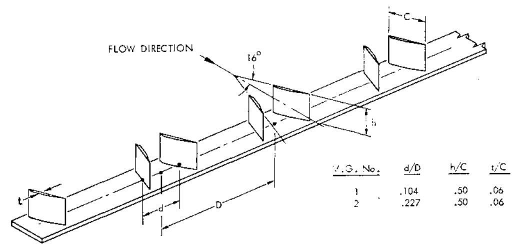


Fig. 4 Vortex generator design.

Two subsonic diffusers were made for this facility, as shown in Fig. 3. One was conventional and the other was designed according to the principles set forth in the preceding section. The initial discontinuity given by the analysis was faired out to reduce the severity of the local adverse pressure gradient.

Vortex Generator Design

The vortex generators used in this program were rectangular vanes arranged in pairs, shown in Fig. 4. They had flat-bottomed cambered airfoil sections, 6% thick, designed to operate satisfactorily at high subsonic Mach numbers. The angle of attack of 16° has been found by several experimenters, including ourselves, to be optimum for this application. Past experience also dictated the ratio of vane height to boundary-layer thickness, which was selected as 1.2. The chord of the vane was made equal to twice the height, because slender wing theory shows that no increase of lift can be expected from a further increase of the chord length.

When the pairs were arranged so that the distance between two vanes at the midchord point was one-tenth of the distance between pairs, matching the calculation discussed earlier, the airfoils were close enough to each other to produce a significant lift interference with consequent loss of vortex strength. Two methods were tried to overcome this problem. One was to mount a small, low-aspect-ratio wing at high angle of attack on a pylon of about the same height as the boundary layer, and the other was to arbitrarily increase the distance between the generators in the hope that the increased lift effectiveness would counteract the reduction in induced vortex motion toward the diffuser wall. As will be discussed later, the latter approach gave satisfactory results.

Test Arrangement

The tests that are pertinent to this paper were conducted at a duct entrance Mach number of 0.5 and with a turbulent boundary layer 0.27-in. thick at the subsonic diffuser entrance. The first row of vortex generators was mounted 0.5 in. downstream of the diffuser entrance. Comprehensive boundary-layer and static-pressure instrumentation was installed down the length of the diffusers, together with a rake of 70 pitot probes at the diffuser exit. The boundary-layer rakes were designed to be removed easily and replaced by flush plugs

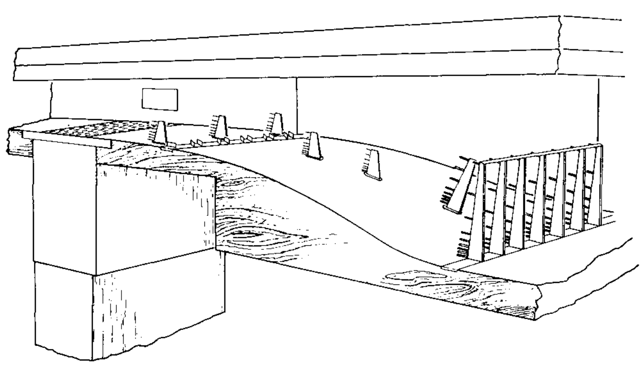
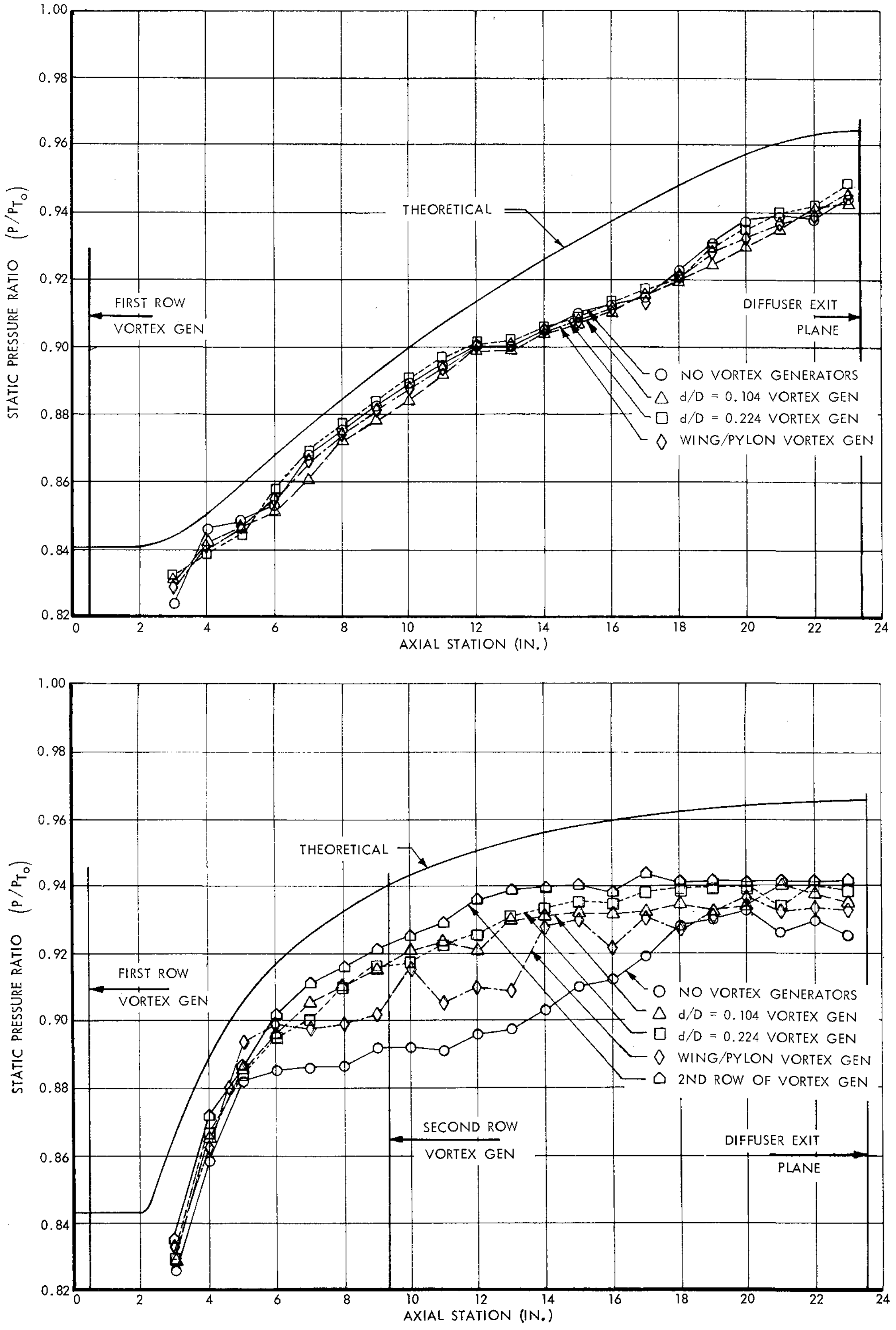


Fig. 5 Diffuser with Pitot pressure rakes.



a) Conventional diffuser

b) Diffuser integrated with vortex generators

Fig. 6 Static-pressure distributions.

during the course of a tunnel run. The instrumented diffuser is shown in Fig. 5. Boundary-layer bleed was provided on both sides of the diffuser entrance to help maintain two-dimensional flow. The terminal shock position was controlled by a variable-area discharge downstream of the diffuser section.

At the beginning of a typical test, all boundary-layer rakes would be installed and readings would be taken from those in the front row. Those rakes would then be replaced by flush plugs and a reading would be taken of boundary-layer pressures in the second row. The process would be repeated until only the exit rake remained in the tunnel. This procedure resulted in complete flow documentation of the configuration in 10 to 12 min.

Results and Discussion

The conventionally designed diffuser had good performance at a duct entrance Mach number of 0.5 and there was no evidence of flow separation, even without vortex generators. The effects of vortex generators, consequently, were not expected to be significant. This was the case, in fact. The static pressure distribution down the length of the diffuser, as shown in Fig. 6a, is almost unaffected by the presence of the generators.

The integrally designed diffuser has a higher potential pressure recovery than the conventional one. If the flow remains attached, the velocity drops more rapidly initially, and the integrated skin friction would be expected to be smaller. The amount of attached flow obtained in practice with different vortex generator arrangements can be visualized by examination of the static-pressure distributions shown in Fig. 6b. With no generators, the flow separated almost immediately after passing the corner, but separation was delayed considerably by vanes designed integrally with the diffuser. As discussed earlier, the lift effectiveness of the generators was impaired by mutual interference and two other designs were adopted to overcome the problem. The pylon-mounted wings were too small to generate sufficient vortex strength and, as shown in the figure, the static pressure distribution was not very different from that for no generators. The theoretically required small spacing between vortices determines the generator wingspan and, therefore, because of aspect ratio limitations, the effective wing area available. On the other hand, increasing the space between the vanes to improve the lift effectiveness had a beneficial effect on flow attachment. This demonstrates that it is more important to maintain a high vortex strength than to have an exact match to the theoretical requirement.

Some separation can be inferred from Fig. 6b, even for the best vortex generator arrangement. It was decided to add a second row about one-third of the way down the diffuser to provide reinforcement to the vortices. However, it is extremely important to place the vanes so that they reinforce the vortices and do not tend to nullify them. Furthermore, their angle of attack should be the optimum value with respect to the local flow direction and not the diffuser axis. A flow visualization technique using colored oil spots on a white background was employed to determine the paths of the vortices as they moved downstream, as shown in Fig. 7. From this the best location for the generators in the second row was determined. The required axial position was determined from the static-pressure distribution to be 6.2 in. downstream from the diffuser entrance. The flow pattern was as expected, the vortices moving away from each other rapidly until they approached their neighbors on the other side.

The distance between vanes was determined by noting that the vortices should pass though the vanes, and that at any axial station the flow inclination to the diffuser axis is greatest directly under the vortices. The measured direction at the surface is associated with the flow rotation as well as with the vortex line direction. As it was not practical to build twisted vanes, it was assumed that the local average flow angle was one-half of the measured value at the wall. Then the required angle of attack was added to the average flow angle to give the angle of incidence of the vanes. In this case, the oil streak was at 14° to the diffuser axis, the local average flow angle was 7°, and so the angle of incidence was 16° + 7° = 23°. The addition of a second row of generators with spacing and angle of incidence determined from the flow visualization photograph resulted in a further improvement in static pressure level in the diffuser, Fig. 6b.

Pitot pressure at the exit was measured using seven parallel rakes, each containing ten tubes. Knowing that there is a symmetry associated with the vortex pattern, the number of rakes was expanded analytically to 29 in order to improve the accuracy of pressure averaging and assessment of distortion. A pair of typical contour maps of total pressure is shown in Fig. 8a. Both are for the integrally designed diffuser, the first being without vortex generators and the second with the best single row of vortex generators. The first one demonstrates that the flow has fairly good two dimensionality and that the characteristic effects of early separation followed by reattachment can be seen. The boundary layer is not thick, but there is a noticeable total pressure loss in the nominally inviscid part of the flow. Figure 8b presents a comparable contour map for the conventional diffuser contour without vortex generators.

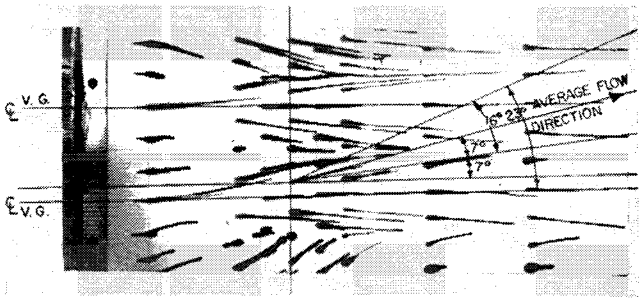


Fig. 7 Flow visualization of integrated diffuser.

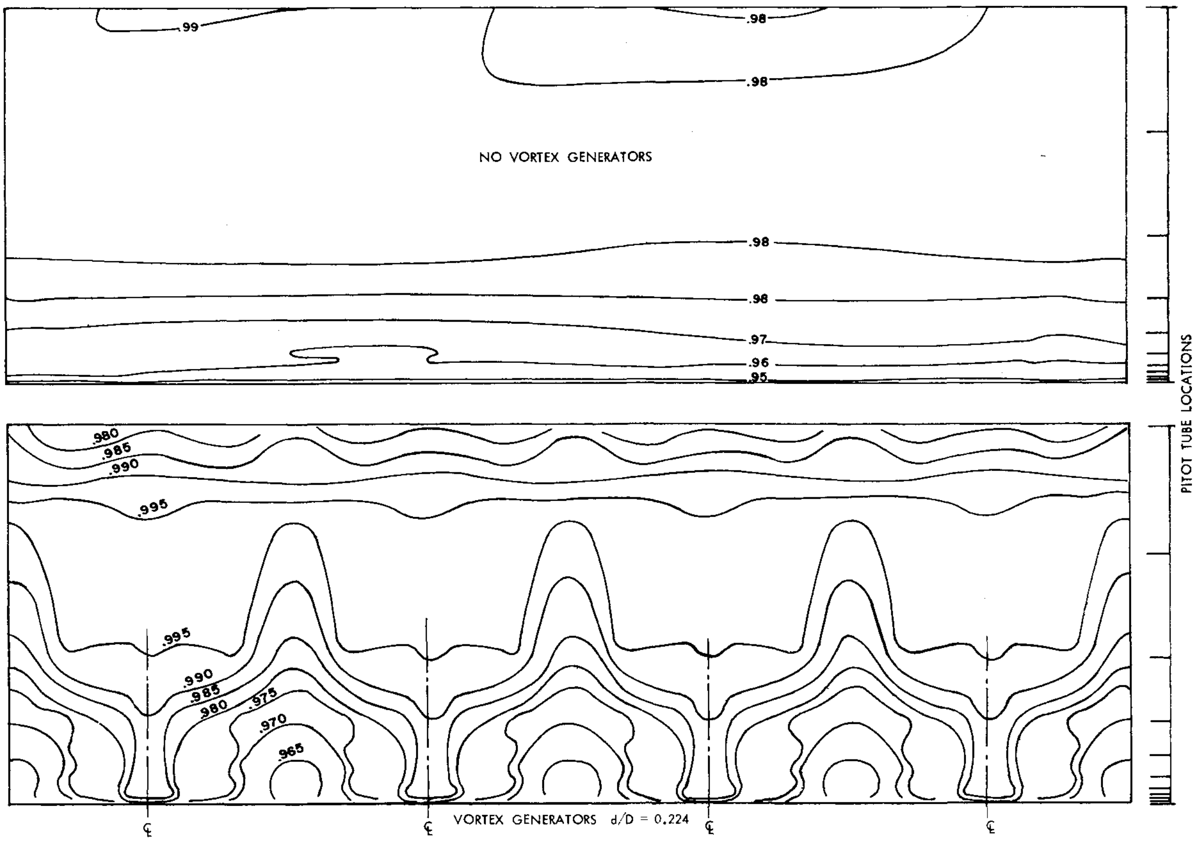
The second map of Fig. 8a shows the contours characteristically associated with counterrotating vortices. The flow is broken down into small pockets with high-pressure air knifing down between the vanes and low-pressure air being blown out into the main stream. This type of flow distortion involving large numbers of lower-pressure regions, each of small area, is preferred by the compressor to one where there may be a smaller number of large-area, low-pressure regions. Distortion was calculated using an adaptation of the General Electric method which accounts for both the size and form of low-pressure areas. Pressure recovery was calculated by area-weighting the data. Performance of the diffusers in terms of distortion and pressure recovery is summarized in Fig. 9. The results are consistent with the static-pressure distributions. All configurations involving the conventional diffuser give about the same result, a 2% loss in pressure recovery with a distortion index of 0.05. The new diffuser without vortex generators is a little worse than this, although not perhaps as bad as one may have guessed. Addition of the matched vortex generators resulted in a performance that exceeded that of the conventional diffuser; pressure recovery loss was down to 1.8% and distortion dropped to 0.038.

Replacing the vanes by a wing/pylon arrangement did not give enough vortex strength to overcome the initial severe adverse pressure gradient. The large distortion and pressure recovery loss shown in Fig. 9 substantiate the premature flow separation noted earlier. On the other hand, increasing the spacing between the vanes improved the performance; the loss of pressure recovery fell to 1.4% with a distortion of 0.03. The addition of the second row of vortex generators reduced the pressure recovery loss to 1.2% at about the same distortion level.

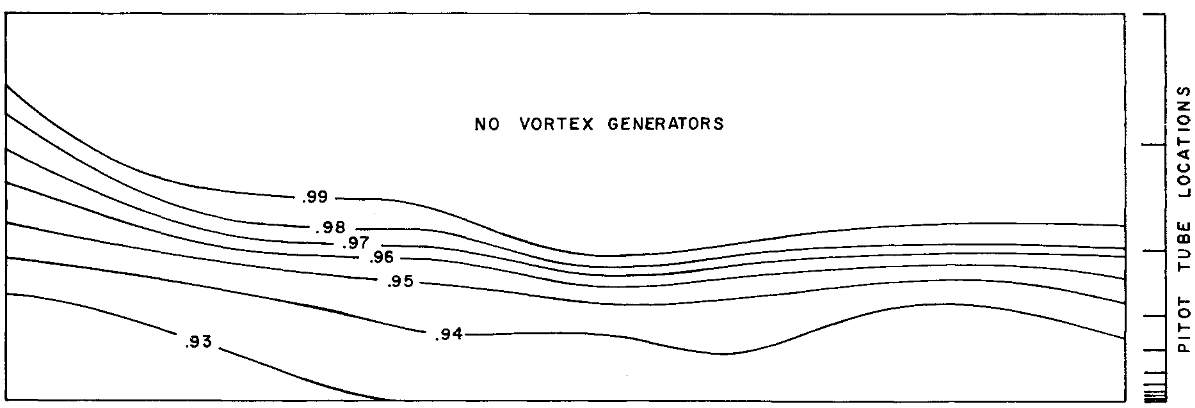
As a demonstration of the importance of sizing vortex generators correctly, a set was made which was similar to the matched generators, but had vanes which were 60% larger. The generated vortices were stronger, but they were further from the boundary layer. The performance was no better than that of the bare diffuser (Fig. 9), indicating that the drag of the vanes and the incorrect positioning of the vortices offset any general mixing effect due to flow rotation.

Summary of Basic Development

Vortex generators can be used in an integral design approach to maintain attached flow in the presence of significant adverse pressure gradients. The higher potential performance of diffusers with large initial pressure gradients can be realized. In our tests, distortion and pressure recovery losses were both reduced by about 40% as compared with a well-designed, conventional diffuser. Care must be taken in selection of vortex generators. Design mismatches carry larger penalties with the integrally designed diffusers than with those of conventional type.



a) At integrated diffuser exit



b) At conventional diffuser exit

Fig. 8 Pitot pressure profiles.

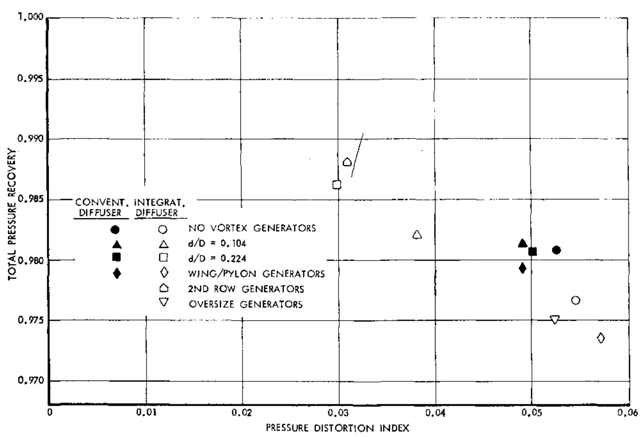


Fig. 9 Pressure recovery and flow distortion.

SST Subsonic Diffuser Development

The inlet that was designed for the Lockheed supersonic transport has a rectangular entrance and is divided into two isolated ducts by a variable-geometry centerbody. One side of the subsonic diffuser, which is shown in Fig. 10, makes a smooth transition from a rectangular cross section at the throat to a semicircular cross section at the engine face. The more severe adverse pressure gradients in the diffuser occur on the centerbody, which has significant curvature, and at the top of the duct. The diffuser sweeps up to meet the engine, which is partially buried in the wing. Consequently, when the subsonic diffuser was first shortened, it was anticipated that forced mixing would be required to avoid flow separation in the top corner.

Test Arrangement

Three subsonic diffusers were evaluated with their appropriate supersonic inlets in a freestream wind-tunnel en-

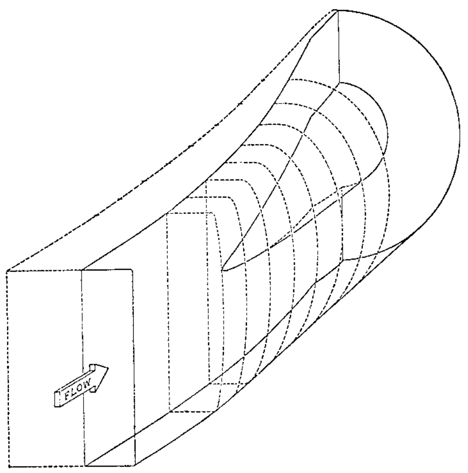


Fig. 10 Lockheed SST subsonic diffuser.

vironment, as opposed to the direct-connected two-dimensional diffuser discussed in the previous section. A long and short diffuser of conventional trumpet-shaped design were evaluated with an inlet designed and tested at a freestream Mach number of 2.5. Boundary-layer bleed was adjusted for optimum over-all performance. The duct Mach number at the diffuser entrance was typically 0.8, with a distortion of about 3%.

Another short diffuser of integrated design was evaluated in a later test series in conjunction with a supersonic inlet of improved design. This inlet was designed for and tested at a freestream Mach number of 2.65. Boundary-layer bleed was again incorporated to improve performance. The typical diffuser entrance Mach number was 0.75, and the distortion was less than half the previous value.

The total pressure rakes used to evaluate flow properties at the diffuser entrance were removed after optimizing the supersonic inlet. The resulting engine face pressure recoveries quoted herein necessarily include the supersonic inlet loss.

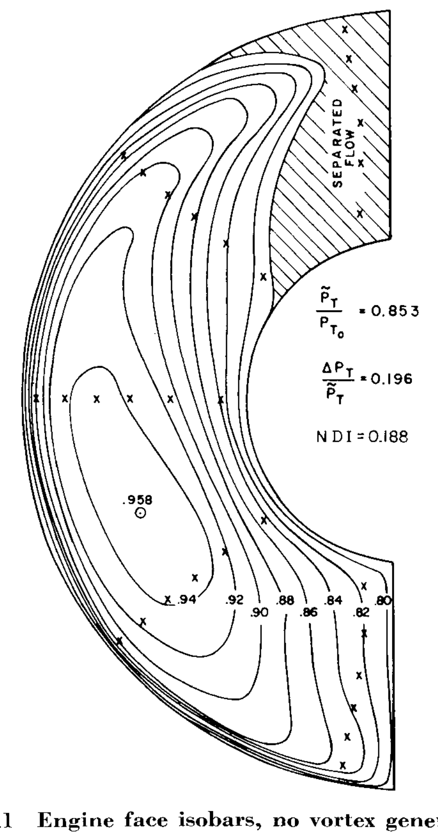
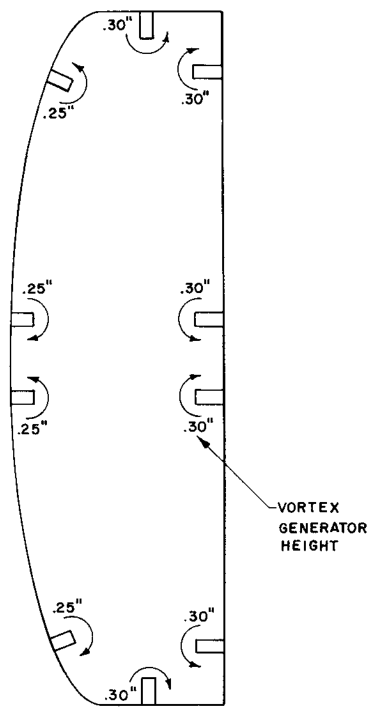
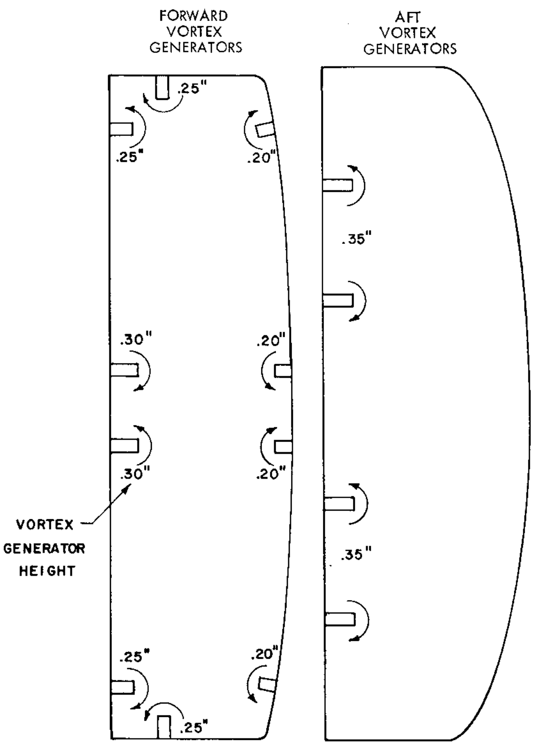


Fig. 11 Engine face isobars, no vortex generators.

a) Single row





b) Double row

Fig. 12 Vortex generators.

Vortex Generators in a Conventional Subsonic Diffuser

A pressure contour map measured at the engine face of the first shortened subsonic duffuser without vortex generators is shown in Fig. 11. As was anticipated, there is a significant region of separated flow at the top of the diffuser. On the basis of inviscid vortex image theory and knowledge of the local boundary-layer thickness, the set of vortex generators shown in Fig. 12a was designed. The vanes were installed about a third of the way down the subsonic diffuser. This diffuser, although short, was of conventional trumpet-shaped design. The aim in design of the vortex arrangement was to insure that the line vortices remained close to the surfaces and

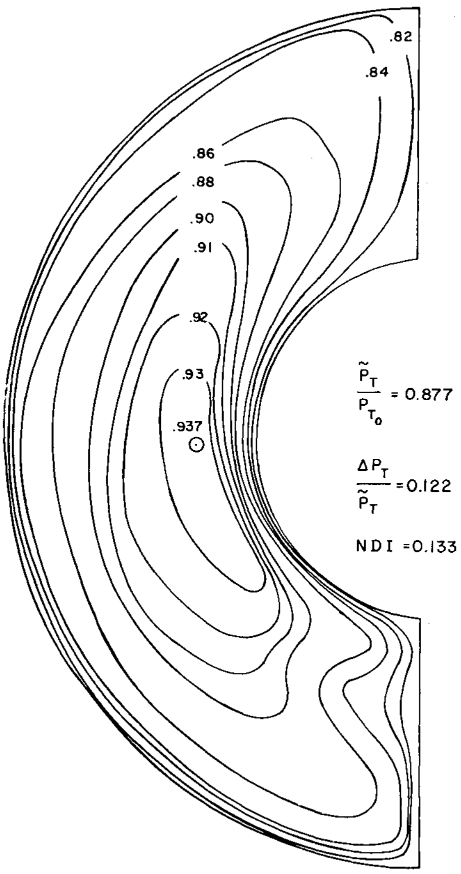


Fig. 13 Engine face isobars, two rows of vortex generators.

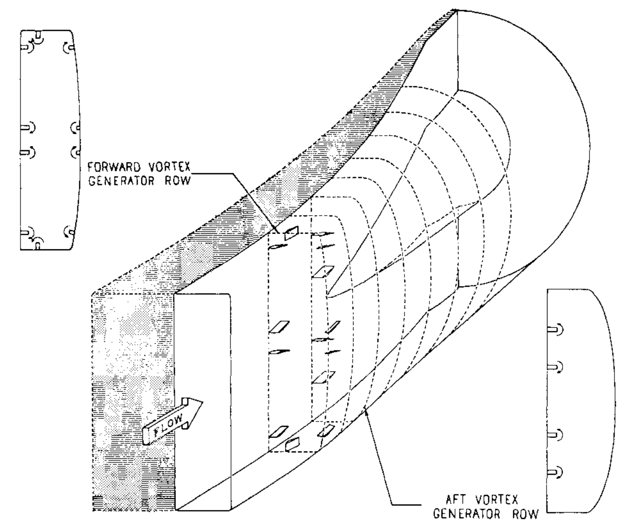


Fig. 15 Subsonic diffuser optimum vortex generator configuration.

did not move significantly towards the central core before reaching the engine face. As may be anticipated, this problem is more difficult with a diffuser of practical cross section than for the simpler two-dimensional case discussed earlier. For example, it was thought necessary to drive the air in toward the corners, which involves a pair of counterrotating vortices (see Fig. 12a). However, the image system for this pair adds six more vortices to the field, and the effects of neighboring vortices close to curved surfaces makes the total interaction problem quite complicated. Vane positioning requirements, such as having to avoid local lift interference and being at the right height relative to the boundary layer, put other restrictions on the over-all design. The consequence is that although a good first cut can be taken at the vane layout, some iteration is always expected.

The selected design had a pressure recovery of 0.867, compared with 0.853 for the clean diffuser, and an improvement in maxmin distortion from 0.196 to 0.153. Maxmin distortion is defined here as $(P_{T_{\max}} - P_{T_{\min}})/P_{T_{av}}$. The separated region still existed in the top corner, and it was decided to add a second row of vortex generators on the centerbody, following similar design techniques to those discussed earlier. After a series of tests, the configuration shown in Fig. 12b was reached. The positioning of the second row of vanes reflects the fact that pairs of counterrotating vortices move away from each other as they travel downstream. With this configuration, separation was eliminated completely. An arrangement of this type resulted in a further improvement in performance as noted in Table 1. For convenience, the General Electric distortion index has also been calculated for these cases.

Pressure isobars for the diffuser with two rows of vortex generators at a pressure recovery of 0.877 are shown in Fig. 13. The flow is obviously pushed well into the corners and there is no evidence of separated flow. In Fig. 14, pressure recovery and mass flow are compared for a bare diffuser and one with two rows of vortex generators. The pressure recovery differential is maintained at 1.8% over the mass flow range. All

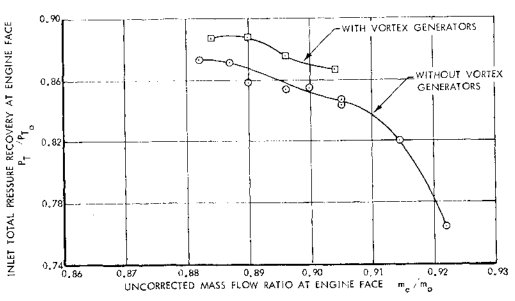


Fig. 14 Performance with and without vortex generators.

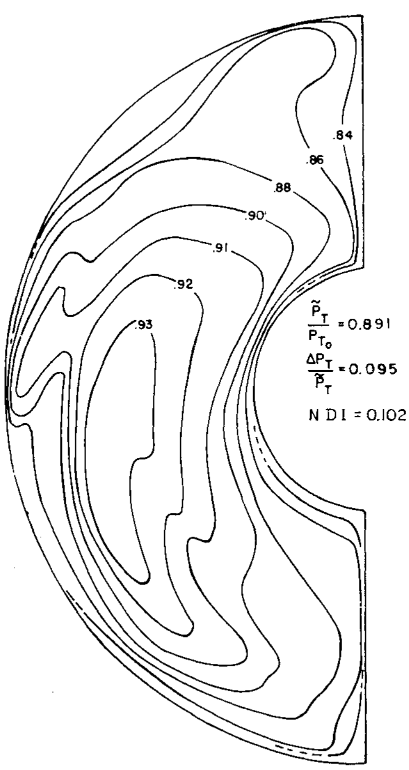


Fig. 16 Engine face isobars, integrally designed subsonic diffuser.

Table 1 Performance improvement of SST inlet with vortex generators

Configuration	Total pressure recovery	Maxmin distortion	Distortion index (NDI)
Clean diffuser	0.853	0.196	0.188
One row generators	0.867	0.153	0.169
Two row generators	0.877	0.122	0.133

of the tests discussed in this series were conducted at a freestream Mach number of 2.5 (diffuser entrance Mach number of 0.8).

An Integrated Subsonic Diffuser Design

A later subsonic diffuser was designed for the airplane, taking advantage of the results of the previous test series and of the integral design procedure. Structural and off-design performance requirements limited the amount of modification to small changes in the centerbody contours. The design is shown in Fig. 15. A limited amount of testing was conducted with this configuration, but the results were extremely gratifying. The operating pressure recovery was raised to 0.891 and the distortion dropped to 0.095 at a freestream Mach number of 2.65 (diffuser entrance Mach number of 0.75). The strong effects of the vortex generators in driving the flow into the corners, and the generally higher levels of pressure recovery due both to more rapid subsonic diffusion and improved supersonic compression are apparent in the total pressure contour map shown in Fig. 16. Some evidence of lower pressure regions between vortex pairs can be seen.

A total pressure contour map for the optimized original long diffuser of conventional trumpet-shaped contour is presented on Fig. 17. Comparison with Figs. 13 and 16 shows that although the long conventional diffuser has better performance than an otherwise similar short diffuser, it is inferior to a short diffuser of integrated design. The advantages obtained from shorter diffusers are significant, but discussion is beyond the scope of this paper.

Conclusions

The major conclusions of the program are as follows: 1) The integrally designed subsonic diffuser with vortex generators can be made to achieve its potentially high-pressure recovery. 2) The incorrect choice of vortex generator design and arrangement can lead to significant performance losses. 3) The designer has some flexibility in moving total pressure contours in a predictable manner to improve distortion acceptance by the compressor. 4) An entirely practical subsonic diffuser was produced, which, although 30% shorter than the previous one, showed a significant improvement in both pressure recovery and flow uniformity.

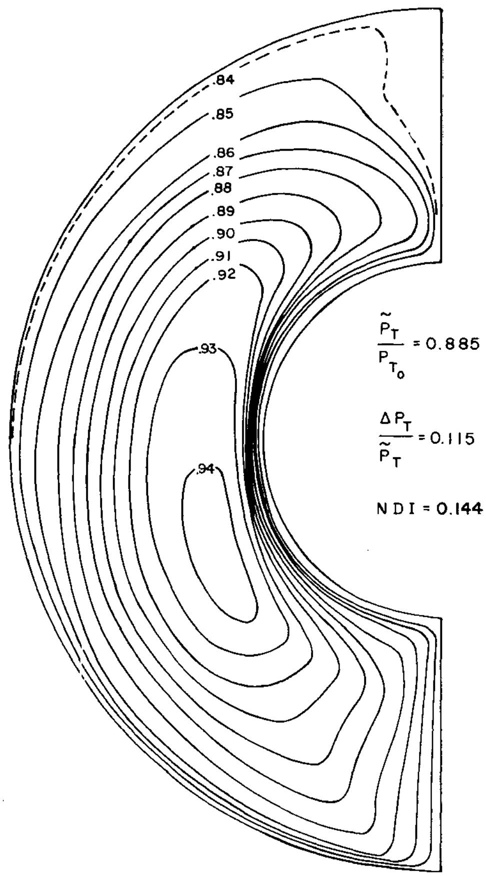


Fig. 17 Engine face isobars, original long conventional subsonic diffuser.

References

[1] Taylor, H. D., "Application of Vortex Generator Mixing Principles to Diffusers. Concluding Report," R-15064-5, Dec. 31, 1948, United Aircraft Corp. Research Dept.

[2] Woolard, H. W., "Boundary-Layer Forced Mixing Investigation—Literature Survey and Progress Report," LR 18478, Nov. 1965, Lockheed-California Co., Burbank, Calif.

[3] Pearcy, H. H., "Shock Induced Separation and Its Prevention by Design and Boundary Layer Control," *Boundary Layer and Flow Control*, Vol. 2, edited by G. V. Lachmann, Pergamon Press, 1961, p. 1166.