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# RESEARCH MEMORANDUM

## EFFECTS OF INTERNAL BOUNDARY-LAYER CONTROL ON THE PERFORMANCE OF SUPERSONIC AFT INLETS

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# EFFECTS OF INTERNAL BOUNDARY-LAYER CONTROL ON THE PERFORMANCE OF SUPERSONIC AFT INLETS

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## SUMMARY

Removal of compression-surface boundary layer from the throat of a supersonic aft inlet is shown to increase the critical total-pressure recovery to values comparable to the better axisymmetric nose inlets. Throat bleed on two-dimensional- and three-dimensional-type inlets by discrete slots or by porous plates has provided gains in critical recovery of as much as 7 percent at Mach number 2.0. A proper combination of bleed ahead of the inlet and at the inlet throat to control both fuselage and compression-surface boundary layer is shown to produce maximum values of propulsive thrust.



## INTRODUCTION

For some time it has been realized that the fuselage boundary-layer air must be removed ahead of a side inlet to obtain acceptable inlet performance. However, a new boundary layer is formed on the compression surface and its interaction with the inlet terminal shock may also adversely affect the inlet performance. A typical example of the flow into a supersonic inlet is shown in figure 1. The oblique shock generated by the two-dimensional ramp falls just ahead of the inlet lip and the terminal shock is located just outside the cowl. If the static pressure gradient across the terminal shock is high enough, the boundary layer formed along the compression surface will separate ahead of the shock and will form effectively another wedge, throwing up an additional oblique shock. Therefore, in a real or viscous flow there will be some area across the inlet face for which three-shock compression exists. The extent of the second oblique shock will be controlled by the amount of boundary-layer separation which, in turn, depends on the strength of the inlet normal shock. The boundary layer considered here is only that formed on the compression surface; however, a somewhat similar condition would also result if the fuselage boundary layer were allowed to flow into the inlet.

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The added compression wave generated by the separated region increases the recovery across the supersonic portion of the inlet to a value higher than for the original two-shock geometry. However, the separated region may continue downstream becoming larger as it progresses as shown by the velocity profile and, finally, adversely affecting the subsonic diffuser pressure recovery. Even if the separated flow should reattach along the diffuser wall, it would still be a region of low-recovery air which would have to mix with the higher energy air of the main stream and again result in low subsonic diffuser recovery. Usually this poorer subsonic recovery will more than offset any gains made in the supersonic compression region of the diffuser. 4005

From this concept a solution to the problem is evident. If this low-energy air can be eliminated before it can adversely affect the subsonic diffuser recovery, the over-all performance of the inlet should be improved. There are at least three ways to eliminate the low-energy air. In the first case, as shown by figure 2(a), if all the boundary-layer air on the compression surface were removed ahead of the inlet terminal shock, there would be no shock - boundary-layer interaction and, thus, no separated air to reduce the subsonic diffuser pressure recovery. In this case, additional oblique-shock compression could not be expected since its source, the separated region, has been removed. However, efficient supersonic compression can be built into the inlet simply through the geometry of the compression surface. This method of removal should require the least mass flow to be bled from the main stream. Second, the compression-surface boundary layer could be allowed to separate and form an additional wedge. The low-energy separated region could then be removed from the inlet either by a flush slot or by a ram scoop, as shown in figures 2(b) and 2(c). In either of the latter two cases, it should be possible to retain the advantage of the improved supersonic recovery available from the separation wedge without incurring the subsonic diffuser penalties attendant upon the simultaneous diffusion of low-energy and high-energy air streams. Although the two latter schemes probably require a greater amount of air to be bled from the inlet, they also offer compression by an aerodynamic surface and thereby may permit a larger throat area for subsonic or transonic speeds.

## EXPERIMENTAL DISCUSSION

These three methods of boundary-layer control were investigated at $M_0 = 2.0$ on a proposed inlet of a present-day supersonic airplane and are reported in reference 1. The results are shown in figure 3. Twin inlets were mounted on the sides of the fuselage and all the fuselage boundary layer was removed ahead of the inlets. Compression-surface boundary-layer control was effected in three ways: by a perforated second ramp to reduce or eliminate the boundary-layer separation or by an internal flush slot or ram scoop to remove it after separation. For

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this and the rest of the tests described herein, the bleed exit was vented to free-stream static pressure; thus, the boundary-layer air was pumped from the inlet only by the pressure differential existing between inlet and free stream. No external source of power was needed for any of the removal systems.

For the no-bleed inlet, that is, an inlet which effectively had the flush slot completely faired over, the critical total-pressure recovery was about 86 percent. Bleeding the boundary layer after it had separated by either a ram scoop or a flush slot increased the critical recovery to about 89 percent. Here about 3 percent of the mass flow was bled from the inlet as shown by the difference in supercritical mass-flow ratios. Although both methods of removal were equally effective at critical mass-flow ratio, the subcritical performance of the flush slot bleed was superior to that of the ram scoop bleed. Thus far, for inlets tested at the Lewis laboratory using comparable ram scoop and flush slot bleeds, the flush slot configurations have been as good or better aerodynamically.



When the compression-surface boundary layer was removed through perforations on the second ramp, no increase in critical total-pressure recovery was obtained. In this case, about 1 percent of the mass flow was bled from the inlet. Here, apparently, the improved subsonic diffusion which would be expected from removal of the low-energy air was offset by a lower supersonic recovery, since with bleed on the ramp no added oblique compression shocks would be formed. However, even though the critical recovery was not increased, the stable subcritical range was extended. The lack of pressure recovery improvement at critical mass-flow ratio probably resulted both from too little bleed and from loss of extra supersonic compression rather than from any inherent disadvantage of bleed through a perforated surface.



Of course, if the bled air is discharged to the free stream without being used for any other purpose, such as cabin ventilation, the inlet must be charged with an additional drag term. Calculations were made for these inlets using reasonable values of bypass drag and, as shown in reference 1, boundary-layer throat bleed in this case paid for itself by increasing the propulsive thrust level by almost 4 percent.

Another two-dimensional type of inlet which used throat bleed was investigated both at the Langley laboratory (ref. 2) and at the Lewis laboratory by John L. Allen and Thomas G. Piercy. This inlet (fig. 4) also had double-ramp compression surfaces but was mounted as a ventral normal wedge inlet. Compression-surface boundary-layer air was bled from the inlet through porous plates extending from about midway along the second ramp to well inside the cowl lip. Removal of the boundary layer through the porous plates increased the diffuser critical total-pressure recovery by about 7 percent at Mach number 2.0. In this case, throat bleed increased the critical total-pressure recovery at Mach number 2.0 from a relatively poor value of 81 percent to a value comparable to the better nose inlets of 88 percent. As the free-stream Mach number decreased, the improvement in critical total-pressure recovery also decreased. This general trend for the greatest gains in pressure recovery to occur at the higher Mach numbers has been true for all the inlets tested to date. Recent preliminary tests at Mach 3.1 have also been in agreement with this trend. Inlet critical recoveries in these tests have been increased by 10 percent to 15 percent through the use of throat bleed.

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Area suction through a slotted plate has also been investigated by Ernest A. Mackley and Clyde Hayes of the Langley laboratory on a scoop inlet of the type shown in figure 5. Boundary-layer removal was used on the wall opposite the compression surface in this case. The slotted wall was flat, and the compressed flow ahead of the bleed plate was two-dimensional even though the outer cowl lip was elliptical in plan form as shown by section A-A. Again with this inlet the critical total-pressure recovery was increased by about 5 percent at Mach number 2.0 by bleeding in the order of 6 percent of the main mass flow.

So far, all the inlets discussed have had various types of two-dimensional supersonic compression. For these, boundary-layer bleed at the inlet throat has provided gains in total-pressure recovery of from 3 percent to 7 percent even on inlets which previously were considered good; for example, 86 percent for free-stream Mach number $M_0 = 2.0$ at critical mass-flow ratio for the first inlet. The same concepts of throat bleed can also be applied to three-dimensional inlets. The results from such an investigation (ref. 3) are shown in figure 6. This test was conducted on a twin side-inlet configuration which had half-cone supersonic compression surfaces mounted directly on the fuselage. Most of the fuselage boundary layer was diverted around the inlet by the cone and flowed under the floor of the inlet. The boundary layer developed on the cone was bled from the inlet throat either by a porous surface which extended from the cowl lip aft for about half the inlet diameter inside the inlet or by a flush slot located just aft of the inlet throat. The same amount of mass flow could be removed by either bleed system. For this inlet, bleeding the optimum amount of low-energy air from the inlet by a flush slot increased the diffuser total-pressure recovery by almost 6 percent. Incidentally, this inlet operated in a nonuniform flow field which had an average Mach number of about 2.1 at an airplane Mach number of 2.0. Thus the 87-percent total-pressure recovery obtained with the inlet operating slightly subcritical shows the merit of throat bleed. Removal of the boundary-layer air by the porous surface increased the peak total-pressure recovery to almost the same value as the flush slot inlet, but this peak was reached with slightly more boundary-layer removal and with somewhat more subcritical spillage.

The mass-flow ratios shown represent the total amount of air entering the inlet. In this case, it was possible to capture a slightly larger streamtube by bleeding the compression surface boundary layer. Values of mass-flow ratio greater than unity resulted from the choice of reference area in the reference mass flow.

The amount of throat boundary-layer air removed was also varied during this test. Calculations were made to indicate what increases in effective thrust minus drag could be realized by using throat bleed. It was calculated that the propulsive thrust of the flush slot configuration was about 5 percent greater than the no-bleed inlet. A mass-flow bleed of about 3 percent was required to obtain maximum thrust minus drag, and additional bleed only served to lower the inlet over-all thrust minus drag. Generally, the trend for the greatest gains from throat bleed to be made with about 3- to 5-percent mass-flow removal has been observed in the inlet tests so far. Too much bleed has, in all cases to date, reduced the diffuser total-pressure recovery at critical mass-flow ratio.

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As might have been anticipated from the internal performance curves, the increase in propulsive thrust was less for the porous surface configuration than for the flush slot inlet. Somewhat more bleed mass flow was also required to reach peak thrust minus drag.

As discussed previously for the two-dimensional-type inlets, the performance gains were smaller at the lower Mach numbers. At Mach number 1.5, although the diffuser pressure recovery was increased by bleeding the boundary layer through the flush slot, the drag added by the bleed system almost counterbalanced the pressure-recovery gain and only a slight increase in propulsive thrust could be calculated. However, the fact that only a small gain in thrust minus drag was realized is not entirely an unfavorable result for it does indicate that the benefits of throat bleed which were obtained at the higher Mach numbers are not necessarily accompanied by performance penalties at the lower Mach numbers, at least to 1.5.

All the inlet installations discussed so far have had full fuselage boundary-layer removal or, expressed in the usual terms, were at $h/\delta$ of at least 1.0. Therefore, two boundary-layer removal systems are provided in the immediate vicinity of the inlet, and some combination of bleed ahead of the inlet and at the inlet throat should provide an optimum over-all system. This hypothesis was investigated recently by Robert C. Campbell of the Lewis laboratory. As shown in figure 7, this investigation was conducted on a bottom-inlet model with a single-ramp compression surface. The fuselage boundary-layer thickness is represented by $\delta$. The inlet was mounted to the body in such a manner that the distance $h$ from the ramp leading edge to the fuselage could be varied from the value of $\delta$, that is, a full boundary-layer thickness to 0 or flat against the fuselage. The internal boundary-layer air was removed through a flush slot opening at the inlet throat. The amount of air bled from the inlet was controlled by varying the size of the

bleed exit. Thus, at any selected value of h various amounts of mass flow could be bled from the inlet throat through the internal boundary-layer removal system. The performance of this configuration is shown in figure 8. The experimentally determined pressure-recovery - mass-flow curves are shown for $h/\delta$ values of 1, 2/3, 1/3, and 0. For the no-bleed inlet the expected trend occurred; as the inlet was moved into the fuselage boundary layer the critical pressure recoveries steadily decreased until at $h/\delta = 0$ a recovery of only about 72 percent was obtained. However, by using various amounts of throat bleed the critical total-pressure recovery could be kept at 88 percent as $h/\delta$ was reduced 4005
to 1/3. Although the complete data were not obtained, results from a similar model in this series of tests indicated that with more throat bleed it would be possible to maintain an 88-percent recovery even at $h/\delta = 0$.

As seen from the mass-flow increments, greater amounts of flow were removed through the internal bleed as the inlet was moved closer to the body. This flow was spilled out through openings in either side of the body, and the spillage drag, as well as the drag of the rest of the model, was measured by an internal balance. As such, the drags which were obtained from this investigation are valid only for this configuration; however, the trends of the inlet propulsive thrust parameter obtained with this configuration should at least be representative of most cases. Calculations of the inlet propulsive thrust were made for the various values of $h/\delta$ (fig. 9) and it was found that the thrust-minus-drag ratio for the no-bleed inlet steadily decreased as the inlet was moved into the fuselage boundary layer. Now, however, when the optimum amount of throat bleed was used, the inlet propulsive thrust was at all times greater than the no-bleed case and would have reached a maximum somewhere between $h/\delta = 1/3$ and 0. For this case, an increase of about 9 percent in propulsive thrust could be added to the aircraft through the use of throat bleed. In addition to increasing the aircraft performance potential, this investigation indicates by the flatness of the performance curve that the designer may have some choice in the amount of boundary-layer removal he must provide ahead of the inlet and at the inlet throat.

## CONCLUDING REMARKS

From the tests performed so far at the various laboratories, removal of the compression-surface boundary layer has emerged as a powerful method of increasing the diffuser total-pressure recovery. The critical total-pressure recovery of side inlets has been increased to about the same value as the best axisymmetric nose inlets. Throat bleed has increased the recovery on various types of side inlets: two-dimensional ramp-type inlets, scoop inlets which turn the supersonic air stream in toward the body, and three-dimensional half-cone compression inlets. Increases have also been made even when the no-bleed performance was considered quite acceptable. These increases have been obtained with various kinds of boundary-layer removal including concentrated removal by flush slots or ram scoops and area removal by porous plates. Throat bleed has proved most effective at the higher Mach numbers. Specifically, diffuser recoveries have been increased as much as 7 percent at Mach number 2.0 but only about 3 percent at Mach number 1.5. Preliminary results indicate that larger gains may be made at the higher Mach numbers. Too much bleed at any free-stream Mach number has generally reduced the total-pressure recovery at critical mass-flow ratio. From 3 percent to 5 percent of the main-stream mass flow appears to be about the optimum amount, although this may well depend on such factors as amount of boundary-layer separation and scale size or Reynolds number. It also appears that consideration should be given again to the fuselage boundary-layer removal ahead of the inlet. A proper combination of removal systems ahead of the inlet and at the inlet throat is required to obtain optimum values of propulsive thrust.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 1, 1955

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1. Obery, Leonard J., and Cubbison, Robert W.: Effectiveness of Boundary-Layer Removal Near Throat of Ramp-Type Side Inlet at Free-Stream Mach Number of 2.0. NACA RM E54I14, 1954.

2. Hasel, Lowell E.: Investigation at Mach Numbers of 1.41, 1.61, and 1.82 of Two Variable-Geometry Inlets Having Two-Dimensional Compression Surfaces. NACA RM L54K04, 1955.

3. Stitt, Leonard E., McKevitt, Frank X., and Smith, Albert B.: Effect of Throat Bleed on the Supersonic Performance of a Half-Conical Side-Inlet System. NACA RM E55J07, 1956.

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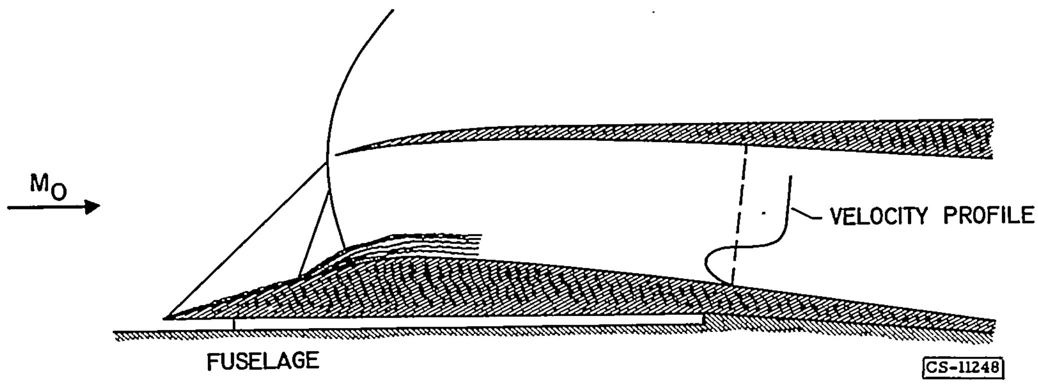


Figure 1. - Flow into supersonic inlet.

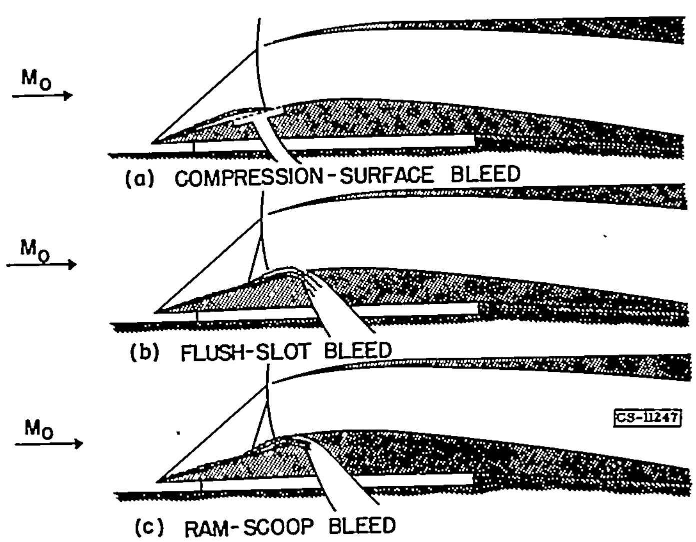


Figure 2. - Methods of compression surface boundary-layer control.

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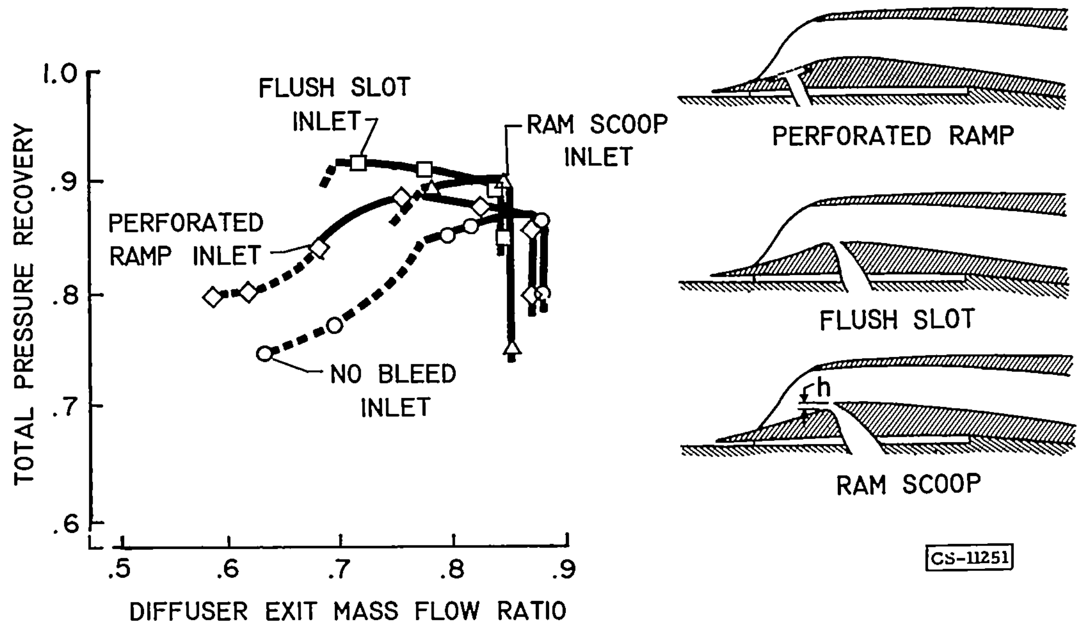


Figure 3. - Effect of throat bleed. Double ramp inlet; free-stream Mach number, 2.0; angle of attack, $0^{\circ}$.

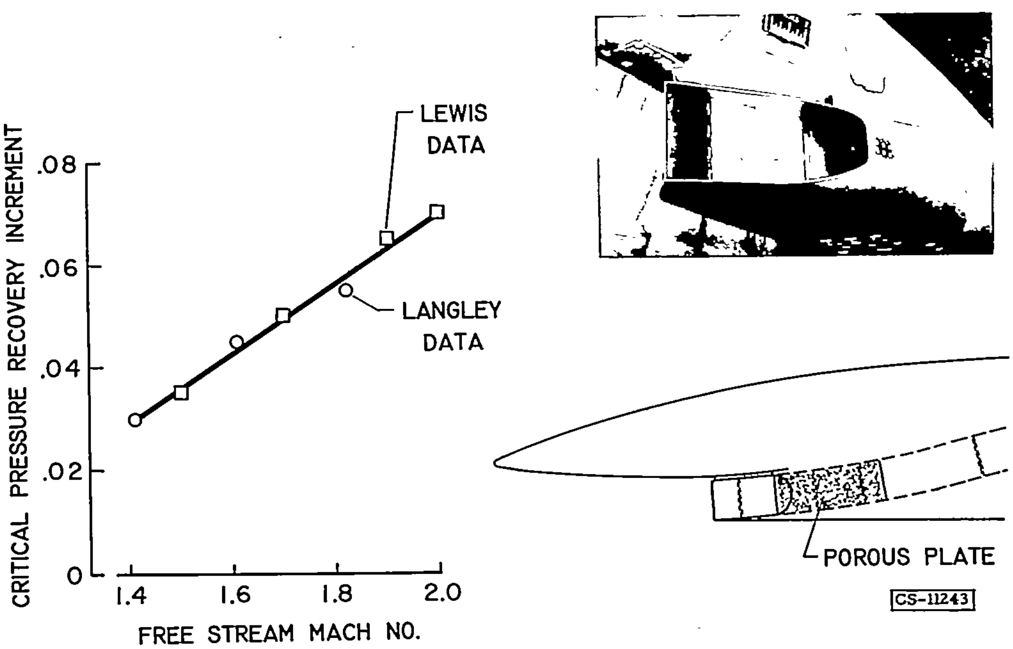


Figure 4. - Effectiveness of throat bleed with Mach number.

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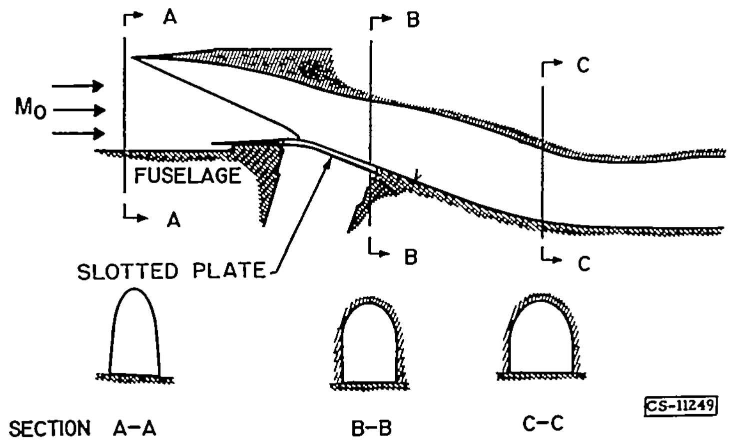


Figure 5. - Throat bleed system for scoop inlet.

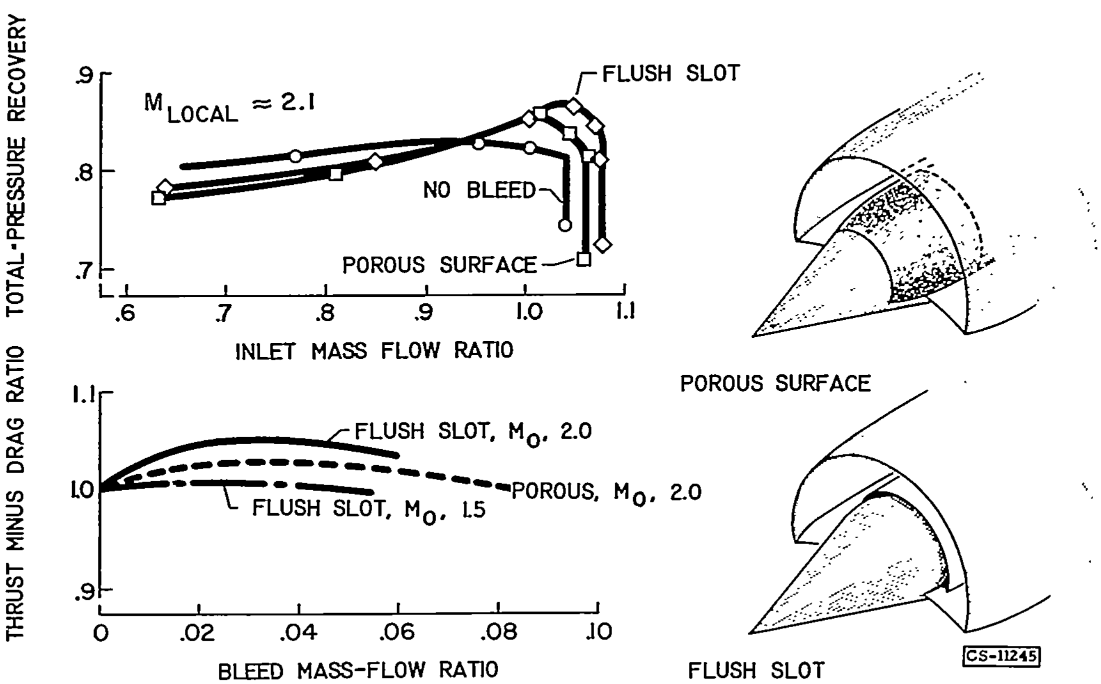


Figure 6. - Effect of throat bleed. Half-cone inlet; angle of attack, 0°.

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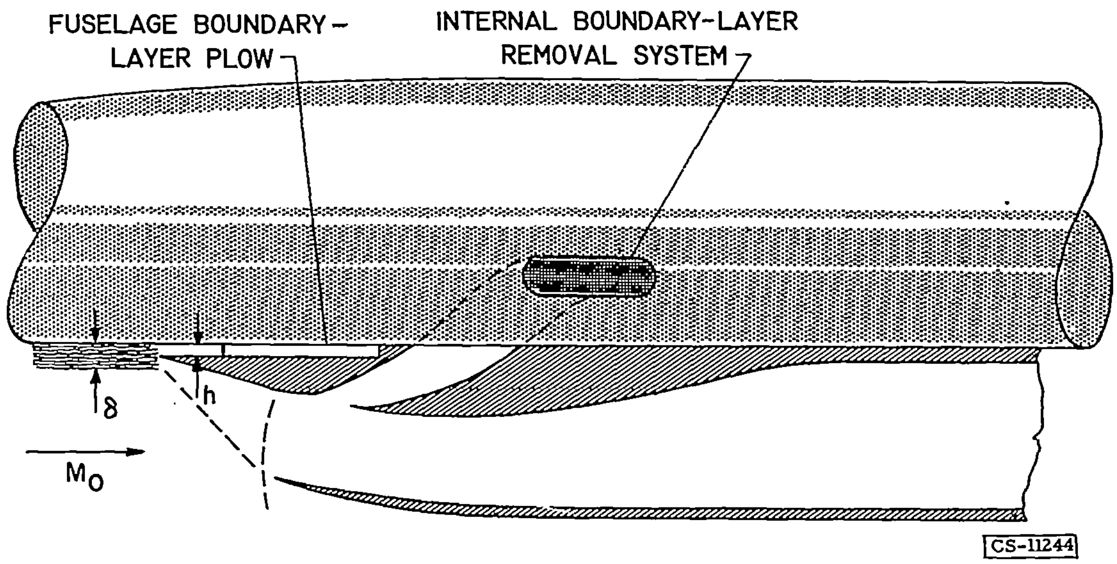


Figure 7. - Variable external and internal boundary-layer removal model.

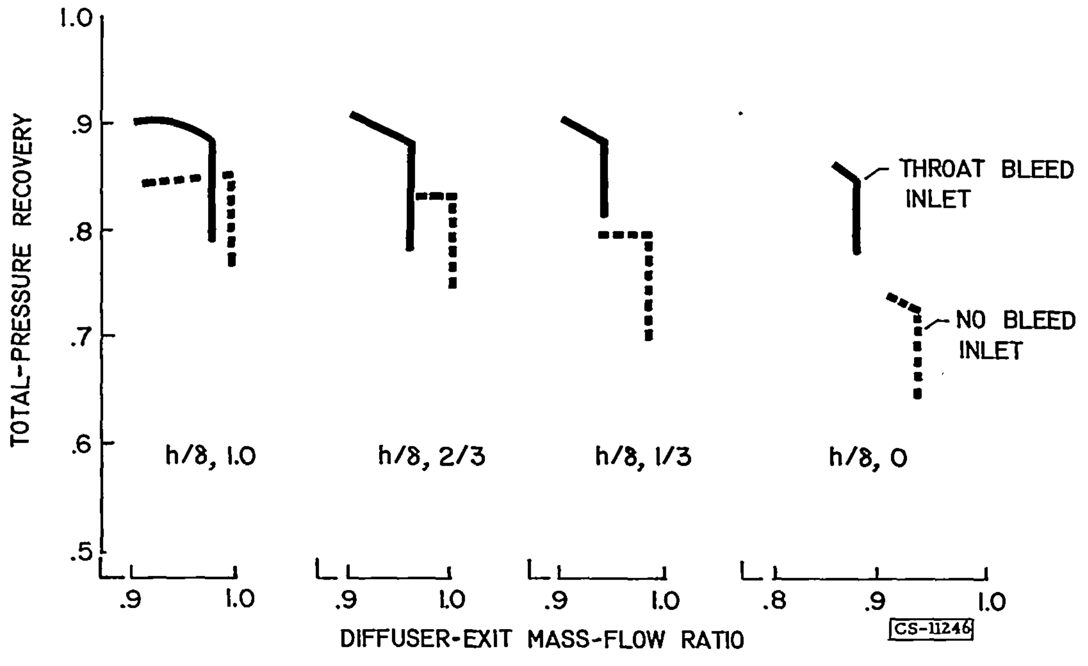


Figure 8. - Performance with variable bleed systems. Free-stream Mach number, 2.0; angle of attack, 0°.

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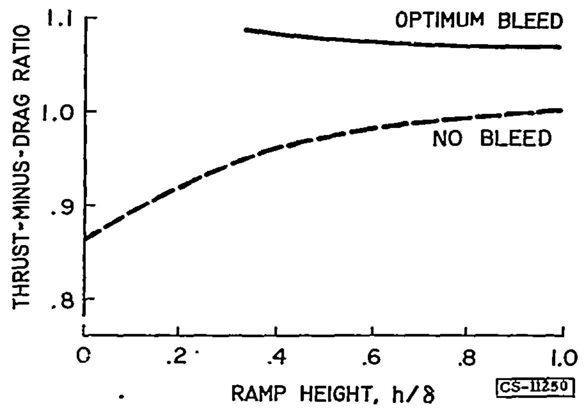


Figure 9. - Effect of variable bleed systems on propulsive thrust. Free-stream Mach number, 2.0.



NACA - Langley Field, Va.