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CHARACTERISTIC DESIGN STUDY OF MIXED-COMPRESSION TWO-DIMENSIONAL INLETS WITH LOW-ANGLE COWLS FOR THE MACH NUMBER RANGE 2.70 TO 1.80

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ABSTRACT

An analytical study was performed to evaluate the effects of several design variables at off-design Mach numbers. Major improvements were realized in overall surface Mach number distributions at off-design conditions by decreasing the internal compression rate in two ways: (1) extending the overall supersonic compression length to avoid surface inflection point and (2) requiring greater compressive turning by the cowl lip shock. Decreasing the compression rate provided nearly equal cowl and centerbody Mach numbers and Mach number gradients on design.

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SUMMARY

An analytical study was performed on two-dimensional mixed-compression inlets over the Mach number range 2.70 to 1.80. The on-design wedge configuration was composed of two ramps with each one providing 5.0° compression and which focused the shocks just ahead of the cowl lip. Contouring of the second ramp provided an additional 4.0° of isentropic compression which fell inside the cowl lip. This wedge configuration provided about the maximum external compression which can be used with a 0.0° internal cowl lip angle. The inlet configuration incorporated a collapsing ramp geometry and permitted a translating cowl lip when necessary. The present study evaluated the effects on performance of several design variables. Specifically these design variables included more gradual turning of the internal surfaces and variations in hinge locations and initial cowl lip angle.

Major improvements in off-design operation were realized (as indicated by the surface Mach number distributions) when the internal compressive turning rate was reduced. This was accomplished in two ways: (1) extending the overall inlet length and (2) requiring greater compressive turning by the cowl lip oblique shock. Both these changes improved off-design flow fields by increasing the minimum Mach number upstream of the throat and by decreasing localized compression rates. By avoiding a geometric cowl surface inflection point upstream of the throat (i.e., turning the cowl surface below the throat flow angle), the effective cowl surface turning rate was decreased and the aforementioned improvements were realized.

It was found that shifting the hinge joints of this variable geometry inlet could provide increases in the supersonic spillage without significant internal performance reductions. In addition, a relocation of one hinge joint eliminated the need for cowl lip translation.

INTRODUCTION

Development of inlet systems for supersonic aircraft depends heavily on theoretical as well as experimental techniques. Once the inlet performance requirements have been established, suitable contours for the supersonic inlet must be determined. Choice of the inlet contour often depends greatly on the off-design behavior of the inlet. The inlet contours are usually developed by an iterative process with the aid of computer programs which use the method of characteristics (ref. 1). It has been demonstrated that inviscid flow field contours can be used for inlet systems up to at least a free-stream Mach number of 3.5 (ref. 2). Viscous effects do have an important influence on the performance of inlets. However, if the boundary layer is properly controlled by bleed, inviscid calculations provide a good representation of the flow field upstream of the throat if shock waves are sufficiently weak so that boundary-layer separation does not occur.

Only limited information is presently available on the interrelation between inlet contouring and off-design behavior. One such study is presented in reference 3. There were several generalized conclusions drawn from the analytical studies performed on a bicone mixed compression inlet in reference 3. These conclusions attempted to relate the on-design inlet characteristics with acceptable off-design behavior. In general, it was found in reference 3 that low-contour curvature was related to low throat flow distortions at off-design. More important than this quality, the study indicated a relation between the on-design internal cowl and centerbody surface compression rates and the off-design behavior. When the surface compression rates on the cowl and centerbody become nearly equal, there was a greater likelihood of having low flow distortion at off-design conditions.

Because the surface pressure distribution can have such a large influence on boundary layer development, it becomes important that reasonable compression rates be maintained at all operating conditions. In addition, the surface compression distribution can influence such factors as angle-of-attack margin and the Mach number range wherein the inlet can operate with mixed compression. With this viewpoint in mind, the present study places a greater emphasis on the manner in which the flow field is compressed to the throat conditions rather than the inviscid throat distortion values.

With these concepts in mind, the objectives of this study are: (1) to design and evaluate the performance of a two-dimensional mixed-compression inlet, (2) to extend the two-cone axisymmetric study (ref. 3) on the interrelation between on-design characteristics and off-design inlet behavior, (3) to evaluate the effects of design changes initiated to increase the amount of supersonic spillage, and (4) to study possible methods to reduce the minimum Mach number at which an inlet can operate with mixed compression.

The inlet configuration used for this study was subjected to the following design requirements: (1) design Mach number of 2.700, (2) low cowl lip angle, (3) cowl shock on ramp shoulder at off-design conditions, (4) high on-design recovery, and (5) minimum complexity of variable geometry mechanisms. Calculations were performed using the computer program presented in reference 1. The inlets were studied over the Mach number range 2.70 to 1.80.

SYMBOLS

M	Mach number
P	total pressure
p	static pressure
x	ratio of dimensional axial distance from first wedge tip to cowl lip height
y	ratio of dimensional vertical distance from first wedge tip to cowl lip height
θ	positive angle with respect to x-axis

Subscripts:

AVE	average conditions
MAX	maximum conditions
MIN	minimum conditions
S	surface conditions
THR	throat conditions
0	free-stream conditions

RESULTS AND DISCUSSION

Theoretical computations for the inlet design study presented in this report were made using the computer program described in reference 1. The on-design configuration was established by prescribing the internal ramp surface contour and Mach number distribution and solving for the cowl contour and Mach number distribution. Downstream of the compression region, the Mach number was held constant to permit the establishment of uniform flow in the throat. The position where uniform flow was established is considered to be the geometric throat. Once the design configuration was established, off-design calculations were performed based on the design contours and the variable geometric features of the inlet. These variable features included a collapsing ramp surface and a translating cowl lip. Two simple hinge points were assumed for the supersonic portion of the ramp surface. The collapsing process therefore took place under the condition that no bending of the ramp segments be present. The cowl shock-on-ramp-shoulder condition was imposed to avoid shock reflection from the ramp surface and to permit boundary layer bleed in the same location relative to the shock impingement point on the ramp. This condition was accomplished by first selecting a nominal internal contraction ratio; this determined the choice of second ramp angle. The iterative process to satisfy the shock-on-shoulder condition, therefore, involved the free-stream Mach number and cowl lip position. At each free-stream Mach number, the internal ramp contour downstream of the shoulder hinge joint was determined by requiring that surface to remain parallel to the original design surface.

The discussion is subdivided into four main areas: (1) performance evaluation of a two-dimensional variable geometry "basic" inlet over the Mach number range of 2.70 to 1.80, (2) the performance gains achieved by recontouring the internal surfaces of the "basic" inlet to minimize total pressure distortion levels, (3) evaluation of an inlet design featuring a fixed cowl lip and increased supersonic spillage ("high-spillage" inlet configuration), and (4) methods to extend the operating range of mixed-compression inlets to lower free-stream Mach numbers ("low-curvature" inlet configuration). Behavior of the various inlet configurations is described in terms of surface Mach number distributions and an overall performance summary, which includes average throat Mach number, total pressure recovery, total pressure distortion, spillage mass flow ratio, and minimum Mach number ahead of the throat.

It should be pointed out that the results presented in this report are based on two-dimensional flow field calculations. Thus, the effects of side wall spillage are not taken into account at the lower free-stream Mach numbers except for an estimate of the mass flow spillage.

Inlet Configuration and Performance

Basic inlet. - Figure 1 presents the characteristic solution and static pressure distribution for the basic inlet at the design Mach number of 2.70. The inlet wedge was comprised of two ramps with initial compression angles of 5.0° each. Starting at $x = 1.02$, the second ramp was contoured to provide an additional 4.0° of compression. The second oblique shock, originating at the junction of the first and second ramp surfaces ($x = 0.67$), was located such that it intersected the cowl lip, while the initial ramp shock was located forward of this point. This provided supersonic spillage of 0.5 percent of the maximum capture mass flow. The compression from the contouring of the second ramp reflected from the internal cowl surface behind the cowl lip shock to avoid large shock losses across the second ramp shock and cowl oblique shock.

This inlet configuration had a 0° internal cowl lip angle. The resulting cowl lip shock was subsequently cancelled at the ramp shoulder point, $x = 3.09$ (fig. 1(b)). The static pressure ratio across the cowl oblique shock at the ramp shoulder point was 1.85. Downstream of the cowl oblique shock, the flow was compressed isentropically to a throat

Mach number of 1.30. The flow angle at the throat had a nominal value of -4.0°. Theoretical total pressure recovery behind the terminal shock in the throat ($x = 3.75$) was 0.953.

Off-design operation. - The basic inlet was designed to have a collapsing ramp section to allow the inlet to operate at off-design conditions. Shown in figure 2 are the variable geometry features incorporated into the basic inlet design. In order to control the internal contraction ratio (and thus the throat Mach number) with the cowl lip shock on the ramp shoulder, a translating cowl section was provided as part of the design (fig. 2(a)). The cowl lip and the collapsing ramp were positioned to provide the desired throat Mach number while maintaining the shock-on-shoulder condition. The inner and outer surfaces of the fixed portion of the cowling were assumed to be faired into those surfaces of the translating portion.

The second ramp was considered to have a rigid contour with hinge points located at the juncture with the first ramp (forward hinge joint) and at the shoulder point (shoulder hinge joint) (fig. 2(b)). At off-design conditions, the inlet ramp surface was assumed to collapse by a simple rotation of the second ramp about the forward hinge joint. Downstream of the shoulder hinge joint, the ramp surface was considered to follow the second ramp, but orientated such that it always remained parallel to the design position. As a consequence, the geometric throat always remains near the original design location. Shown also in figure 2(b) is the side plate configuration (dash-dot line) used to compute the side plate spillage mass flow.

Operating characteristics. - Presented in figures 3 to 8 are the surface Mach number distributions for the basic inlet operating between free-stream Mach numbers of 2.70 and 1.80. Circular symbols represent cowl surface Mach number, and square symbols signify ramp surface Mach number. Figures 3 to 8 also include cowl lip and ramp surface position (as indicated by the second ramp angle) for the corresponding Mach number distributions. The solid circular symbols indicate the physical positions of the mechanical hinge joints.

The Mach number distribution for on-design operation ($M_0 = 2.70$) is shown in figure 3(a) along with the design ramp and cowl lip positions (fig. 3(b)). The geometric throat of the basic inlet configuration was located at $x = 3.75$. The prescribed internal ramp surface Mach number distribution downstream of the shoulder point ($x = 3.09$), square symbols, produced a cowl inflection point at $x = 3.48$. The cowl surface angle at this point was about 2.0° lower than the cowl surface angle at the geometric throat ($x = 3.75$). The cowl inflection resulted primarily from attempts to maintain a short supersonic diffuser (see ref. 2). Based on the results of reference 3, the cowl inflection point should have an increasingly larger influence on the internal flow field as the free-stream Mach number is lowered.

At a free-stream Mach number of 2.60 (fig. 4), the effect of the cowl inflection point begins to appear as an expansion at $x = 3.48$ on the cowl surface and $x = 3.75$ on the ramp surface. A decrease in the strength of the cowl oblique shock resulted from the lower second ramp angle. Although the throat distortion was small, it was caused primarily by the cowl inflection point.

At a free-stream Mach number of 2.40 (fig. 5), the effect of the inflection point becomes more pronounced, particularly on the ramp surface. The expansion fan that results at the inflection point appears on the ramp surface just downstream of $x = 3.76$ (fig. 5(a)).

At free-stream Mach numbers of 2.20, 2.00, and 1.80 (figs. 6 to 8), the problems associated with the cowl contour become increasingly apparent. Where an expansion and resulting throat distortion was the most obvious problem at higher Mach numbers, an overcompression on the ramp surface caused by excessive cowl curvature becomes a more serious problem at lower Mach numbers. At Mach number 2.20 (fig. 6(a)), a throat Mach number of about 1.23 was obtained while the minimum Mach number ahead of the throat was 1.15. This large discrepancy in Mach numbers characterizes the inflection point problem in this type of inlet.

For the inlet operating at Mach 2.00 (fig. 7), the second ramp shock was replaced by a small expansion at the forward hinge joint ($x = 0.67$). This results from dropping the second ramp angle below the initial ramp angle. Although the average throat Mach number is reasonably high ($M_{THR} = 1.24$), a minimum local surface Mach number of 1.12 occurred on the ramp surface at $x = 3.83$ (fig. 7(a)). At a free-stream Mach number of 1.80 (fig. 8), this minimum local surface Mach number dropped to a value of 1.05 at this ramp position. Also a high compression rate appears on the ramp surface between $x = 3.60$ and $x = 3.82$. Both the low minimum Mach number and the large compression rate can markedly affect the angle-of-attack capability of this inlet. These factors also imply that reasonable started inlet operation below 1.80 is difficult to realize. However, the problems associated with the excessively low local Mach number can partially be alleviated by operating the inlet at a lower internal contraction ratio with a resulting decrease in performance.

Effect of internal contraction ratio. - Presented in figures 9 and 10 are inlet Mach number distributions to show the effect of contraction ratio or throat Mach number. At a free-stream Mach number of 2.30 (fig. 9), cowl and ramp Mach number distributions were obtained at average throat Mach numbers of 1.22, 1.27, and 1.31. Variation of the internal contraction ratio produced a family of Mach number distributions on the cowl surface (fig. 9(a)) and ramp surface (fig. 9(b)). This family of Mach number distributions were characterized by essentially the same Mach number gradient. As the ramp surface was lowered (increasing average throat Mach number), an expansion just behind the shoulder point on the ramp surface increased. This expansion appears again on the cowl surface just behind the inflection point ($x = 3.48$) with increased amplitude. This family of distributions were also characterized by the minimum local Mach number on the ramp surface occurring along a single curve between $x = 3.70$ to $x = 4.00$ (fig. 9(b)).

Similar behavior was found at a free-stream Mach number of 1.80 (fig. 10). By increasing the average throat Mach number from 1.22 to 1.30, the minimum local Mach number (on the ramp surface) was increased from 1.05 to 1.11 (fig. 10(b)). In spite of the higher throat Mach number, the minimum local Mach number still represented an inherent limit in the operation of this inlet. Also, the higher average operating throat Mach number did not produce a substantial change in the high compression rate on the aft end of the ramp surface (fig. 10(b)). Therefore, decreasing contraction is not a very satisfactory way of achieving low Mach number started performance.

Although the calculations are not presented, computations were performed to study the effect of internal contraction ratio (or throat Mach number) at the inlet design Mach number of 2.70. The results were substantially the same as the cases presented, except that with decreasing throat Mach number, a weak shock instead of an expansion developed just downstream of the shoulder point. In spite of the formation of the weak shock, the total pressure distortion levels in the throat remains low (see following section).

Summary of inlet performance. - A summary of the overall performance of the basic inlet is presented in figures 11 and 12. Figure 11 shows the effect of inlet throat Mach number on the total pressure recovery, distortion, and two-dimensional capture mass flow ratio. Inlet throat Mach numbers were varied while retaining the cowl shock on the ramp shoulder by coordinating the cowl lip translation with ramp rotation. Calculations were performed at free-stream Mach numbers of 2.70, 2.30, and 1.80.

For a free-stream Mach number of 2.70 and a design throat Mach number of 1.30, the total pressure recovery behind the terminal shock in the throat was 0.953 (fig. 11(a)). Decreasing the throat Mach number to 1.21 results in the total pressure recovery increasing to 0.959. Greater increases in total pressure recovery were not realized because of the increased strength of the second ramp and cowl oblique shock at the higher ramp angle. At free-stream Mach numbers of 2.30 and 1.80 (figs. 11(b) and (c)), slightly higher gains in total pressure recovery were realized for a comparable throat Mach number variation.

The total pressure distortion variations indicate increasing levels as the ramp is positioned away from the design position. This accounts for the reversal of slope in distortion curve that occurred between free-stream Mach numbers of 2.70 and 2.30. The finite slope of the distortion variations with throat Mach numbers in figure 11 implies the existence of an optimum ramp angle to ensure a minimum inviscid throat distortion. The throat Mach number at which this minimum will occur depends on inlet geometry.

A relatively small variation of two-dimensional capture mass flow occurred over the range of throat Mach numbers investigated. There were two factors in this inlet design which influenced the amount of two-dimensional spillage: (1) ramp angle setting and (2) cowl lip position. The initial cowl angle will also affect the capture mass flow and would have to be considered in a sliding cowl design concept. The cowl lip position schedule for the basic inlet is listed in table I as a function of free-stream Mach number and throat Mach number.

A summary of the overall performance capability of the basic inlet is presented in figure 12 as a function of free-stream Mach number. Circular symbols represent actual operating points investigated with the computer program. No symbol distinction is made for variation of throat Mach number at a given free-stream operating Mach number. However, table I presents the second ramp angle and cowl lip translation schedule for each of the free-stream conditions shown.

Over the range of free-stream Mach numbers considered, the inlet could operate between throat Mach numbers of 1.21 and 1.30. This range is represented by the solid line indicating a nominal throat Mach number of 1.30, and the dashed line representing a nominal throat Mach number of 1.20. Maximum translation of 14.4 percent of the cowl lip height was necessary for this span of inlet operation (see table I). The upper operating limit of 1.30 was dictated by the requirement that the second ramp oblique shock should not fall inside the inlet, while the shock-on-shoulder condition was maintained. This requirement only existed between free-stream Mach numbers of 2.20 and 2.70, since below this range, there was no second ramp shock. Thus, in spite of the flexibility of a sliding cowl lip, complete choice of operating throat Mach number was not fully realized. The lower throat operating Mach number limit was dictated by the requirement that supersonic flow be maintained in the region upstream of the throat. Hence, at Mach 1.80, the basic inlet could not operate appreciably below a throat Mach number of 1.21 because a minimum local Mach number of 1.05 existed ahead of the throat. Although the inlet could operate below the 1.21 lower limit at the higher free-stream Mach numbers, a nominal operating range between 1.20 and 1.30 was the desired objective. Thus, the range of operating throat Mach numbers indicated in figure 12 does not represent the entire capability of the basic inlet.

In spite of the fact that the average throat Mach number could be kept within the desired limits ($M_{THR} = 1.20$ to 1.30), the minimum Mach number ahead of the throat exhibited a decrease well below that which is desirable. The rapid decrease in the minimum Mach number thus represents one of the more serious limitations of this inlet configuration at lower free-stream Mach numbers. It should be noted, however, that the calcultions were based on two-dimensional flow and do not include the effects of side wall spillage. The corresponding total pressure recovery variation for this range of operating throat Mach numbers are represented by a solid line for a nominal average throat Mach number of 1.30, and a dashed line for a nominal throat Mach number of 1.20 (fig. 12). The total pressure recovery variation ranged from 0.953 at Mach 2.70 to 0.988 at Mach 1.80. The maximum total pressure distortion occurred at a free-stream Mach number of 1.80, with the inlet operating with an average throat Mach number of 1.30. There was a rapid reduction in total pressure distortion as the inlet throat Mach number was reduced for the Mach 1.80 operating point. This can also be seen in figure 11(c).

Only small variations in the capture mass flow were found to exist over the span of operating throat Mach numbers. Thus the capture mass flow span is represented by a single curve. The total capture mass flow is divided into two components, two-dimensional supersonic spillage over the cowl and side wall spillage around the side plates. Side wall spillage was computed based on the analysis presented in reference 4. The geometric side plate configuration used for the calculations is schematically represented in figure 2(b). The inlet was designed to spill 0.5 percent of the capture mass flow supersonically at a free-stream Mach number of 2.70 (for a throat Mach number of 1.30). At a free-stream Mach number of 1.80, the total supersonic spillage was composed of a two-dimensional component (about 6.0 percent) and a side wall component of 3.0 percent. Hence, the total inlet mass flow was about 0.910 at Mach 1.80.

Incorporating a sliding cowl provided inlet throat Mach number control, but since the cowl was required to move forward as the free-stream Mach number decreased (table I), the supersonic flow spillage was relatively small at low operating Mach numbers. Large changes in the amount of supersonic spillage must be thus affected by changes in the collapsing procedure. This point is investigated in detail in later sections.

Low-Distortion Inlet Configuration

In order to investigate further the full potential of this inlet concept, a "low-distortion" inlet was designed and evaluated at free-stream Mach numbers from 2.70 to 1.80. The wedge configuration was identical to the basic inlet, while the internal coutour of the low-distortion inlet was chosen to eliminate the excessively low local Mach number encountered in the basic inlet at off-design speeds. This was accomplished by essentially eliminating the cowl surface inflection point upstream of the throat. Geometrically, the length of the supersonic diffuser was extended 6.7 percent and the nominal flow angle in the throat was decreased from -4.0° to -6.0°. Decreasing the nominal throat flow angle to -6.0° (which corresponds to the cowl surface angle at the inflection point of the basic inlet) provided no inflection point at a shorter overall length than could be obtained with a -4.0° throat flow angle.

Low-distortion inlet. - Presented in figure 13 is the characteristic solution of the low-distortion inlet along with the static pressure distribution on both surfaces. This inlet configuration was designed for Mach 2.70 operation with a throat Mach number of 1.30. The ramp surface of the low-distortion inlet was identical to that of the basic inlet previously discussed. A zero internal cowl angle was prescribed and the subsequent cowl lip shock was cancelled at the ramp shoulder ($x = 3.09$). In this inlet configuration, the geometric throat was located at $x = 4.00$ rather than $x = 3.75$ for the basic inlet. The internal ramp contour and the corresponding Mach number distribution were chosen specifically to avoid a geometric cowl surface inflection point upstream of the throat. As a consequence of this requirement, the static pressure gradient or Mach number gradient on the cowl and centerbody surfaces become nearly equal (fig. 13(a)). The internal static pressure gradient on the ramp surface was thus reduced as compared to the basic inlet (see fig. 1(a)). The minimum local surface cowl angle was -6.0°, the same as the basic inlet; but it occurred at the geometric throat ($x = 4.00$). This essentially reduced the cowl and ramp surface curvature of the low-distortion inlet as compared to the basic inlet. The total pressure recovery of this inlet was 0.953 behind the terminal shock in the throat, the same as the basic inlet.

Operating characteristics. - The same variable geometry features were incorporated into the design of the low-distortion inlet as the basic inlet. Thus this inlet configuration had the flexibility in controlling the internal contraction ratio (or throat Mach number) while maintaining the shock-on-shoulder condition.

Presented in figures 14 to 19 are the surface Mach number distributions for the low-distortion inlet operating between free-stream Mach numbers of 2.70 and 1.80. The corresponding ramp positions are also shown. Mach number distributions for on-design operation ($M_0 = 2.70$) are presented in figure 14(a), along with the corresponding ramp position in figure 14(b). The internal Mach number gradients on both cowl and ramp surfaces were nearly equal for design operation. The on-design cowl Mach number distribution reached a minimum value at about $x = 3.76$, which corresponds to the geometric throat of the basic inlet. On the ramp surface, however, the minimum (or throat) Mach number occurred at $x = 4.00$. If the ramp surface Mach number was forced to reach its minimum value at the same x-location as the cowl surface minimum Mach number (basic inlet configuration), a geometric cowl inflection point would be formed. This inflection was avoided by the present design.

The off-design Mach number distributions, presented in figures 15 to 19, were calculated at the same free-stream Mach numbers and nominal internal contraction ratio as presented for the basic inlet (figs. 4 to 8). At a free-stream Mach number of 2.60 (fig. 15), the internal Mach number distribution on the cowl and ramp surfaces still retained its intrinsic design character. For Mach 2.40 inlet operation (fig. 16), the characteristic expansion just downstream of the ramp shoulder point begins to appear. This expansion reappears on the cowl and ramp surfaces at $x = 3.63$ and $x = 3.86$, respectively, with increasing amplitude. In each case, reappearance of the expansion is followed by a compressive region, the gradient of which tends to increase in the downstream direction.

At free-stream Mach numbers of 2.20, 2.00, and 1.80 (figs. 17, 18, and 19, respectively), the minimum local Mach number occurred in the neighborhood of the geometric throat. In addition, at each of these off-design conditions, the minimum local Mach number on the cowl and ramp surface were essentially equal. This minimum local Mach number also corresponded closely to the desired throat Mach number; hence, flow distortion that occurred in the throat region tended to increase the average throat Mach number above the desired value. The effects of eliminating the cowl inflection point is particularly noticeable at Mach 1.80 (fig. 19), when compared with the distribution of the basic inlet (fig. 8). The characteristically high compression rate on the aft-ramp section in the vicinity of the throat was relieved along with the excessively low local ramp Mach number.

In summary, elimination of the geometric inflection point on the cowl surface greatly improved the capacity of this type of inlet to operate in the low Mach number range. This improvement was realized when the Mach gradient on both the cowl and ramp surfaces were essentially similar for design Mach number operation. This is substantially the same finding as in reference 2.

Summary of inlet performance. - A summary of the overall performance of the low-distortion inlet is presented in figure 20. Because of the translating cowl section, the low-distortion inlet can operate over the same throat Mach number scheduling as the basic inlet. The cowl lip position schedule for the low-distortion inlet was essentially the same as the basic inlet (table I). The pressure recovery and capture mass flow variations with free-stream Mach number are substantially the same as the basic inlet. However, a reduction in total pressure distortion from 0.025 to 0.013 was realized at Mach 1.80 for the low-distortion inlet. Along with this reduction in distortion, the capacity of the inlet to operate over a larger throat Mach number range (at $M_0 = 1.80$) was increased.

More significant than the reduction in the total pressure distortion was the elimination of the excessively low local Mach number upstream of the throat. At a comparable operating throat Mach number of 1.20 (fig. 20), the minimum local Mach number was increased from 1.05 to 1.18. This would increase the capacity of the inlet to operate with mixed compression below a free-stream Mach number of 1.80. Also an increase in the angle-of-attack margin at Mach 1.80 would be anticipated with this improvement.

High-Spillage Inlet Configuration

One of the major problems that confronts the inlet designer is the inlet-engine matching requirements. Since the drag penalty associated with bypassing airflow is normally greater than the penalty for external supersonic spillage, it is desirable that the inlet configuration minimize the excess capture of mass flow. Inherent in high internal compression inlets, because of the small initial forebody angles, is the relatively low supersonic spillage. In this section, the possibility of increasing the amount of supersonic spillage is examined. The study presented does not attempt to match a particular engine corrected weight flow schedule. Rather, it seeks to find the maximum spillage capacity inherent in this inlet which is not injurious to inlet performance.

High-spillage inlet. - The inlet configuration chosen for this study was the low-distortion inlet previously discussed. To increase the supersonic spillage, the forward hinge point was shifted downstream from $x = 0.67$ to $x = 1.02$. The new forward hinge point location was thus located at the end of the straight section of the second ramp (see discussion of basic inlet configuration). Other than this hinge point relocation, no additional modifications were incorporated into the high-spillage inlet configuration. Consequently, the two 5.0° compression ramps were always maintained during off-design operation. Excessive flow turning at the cowl lip was relieved by the expansion fan originating from the new forward hinge point location.

Operating characteristics. - Shown in figures 21, 22, and 23 are the off-design Mach number distributions for the high-spillage inlet at free-stream Mach numbers of 2.40, 2.10, and 1.80, respectively. Circular symbols represent the cowl surface Mach number distribution, while square symbols indicate the Mach number on the ramp surface. The on-design Mach number distribution ($M_0 = 2.70$) is identical to the low-distortion inlet presented in figure 14. For off-design inlet operation, only a collapsing ramp was required without any cowl translation for throat Mach number control for the range of free-stream Mach numbers from 2.70 to 1.80. However, at Mach 1.80 (fig. 23), the cowl oblique shock was permitted to reflect from the ramp surface just downstream of the shoulder hinge joint. The shock strength was sufficiently weak such that no performance losses occurred. This shock reflection could have been eliminated if the cowl lip had also been permitted to translate.

The basic difference in the behavior of the high-spillage configuration at off-design conditions occurs on the ramp surface. Instead of weakening the second ramp oblique shock, an expansion takes place downstream of the junction of the two ramp sections. At a free-stream Mach number of 2.40 (fig. 21), this resulted in a Mach 2.00 plateau followed by an expansion which increased the ramp surface Mach number to 2.10. The cowl lip Mach number (before the oblique shock) was about 2.04, as compared with 2.08 for the low-distortion inlet. As would be expected, part of this expansion enters the inlet resulting in an increase in cowl surface Mach number (fig. 21(a)) between the cowl lip ($x = 2.14$) and $x = 2.31$. At a free-stream Mach number of 2.10 (fig. 22), the expansion at the forward hinge joint was equivalent to the strength of the second ramp shock. In spite of the entrance of this expansion into the inlet, the internal flow was not appreciably distorted (fig. 22(a)). A possible explanation for this phenomenon can be seen more readily at an inlet operating Mach number of 1.80 (fig. 23). The expansion originating at the forward hinge joint was attenuated in the downstream direction, as can be seen by the expansion amplitudes between $x = 2.14$ to 2.43 on the cowl surface, $x = 3.14$ to 3.37 on the ramp surface, and $x = 3.72$ to 4.00 on the cowl surface (fig. 23(a)). Thus, the expansive disturbance originating on the external ramp section appears to attenuate through the inlet while external compressive disturbances amplify. This would be expected since compression waves tend to coalesce and expansion waves tend to diverge. This is also indicated by increased compressive rates of the external ramp compression as it appears again on the cowl and ramp surfaces (fig. 23(a)). The pronounced amplification of the flow compression rates, particularly at the lower Mach numbers, is characteristics of off-design behavior of high internal compression inlets. This property essentially determines the range over which a mixed-compression inlet can operate. Methods to extend the operating range over which a mixed-compression inlet can operate are discussed in later sections.

Summary of inlet performance. - Presented in figure 24 is a summary of the overall performance of the high-spillage inlet configuration. Essentially the same throat Mach number operating band was achieved with the high-spillage inlet as obtained with the basic and low-distortion inlets. At equivalent free-stream Mach numbers, somewhat lower total pressure recoveries resulted.

However, major increases in supersonic spillage were achieved by a downstream shift in the forward hinge point. The total supersonic spillage at Mach 1.80 was in creased from 9 to 16 percent of the capture mass flow with the same side plate configuration as the basic inlet (see fig. 2(b)). Two-dimensional spillage over the cowl increased from 6.0 to 12.0 percent of the capture mass flow, while side wall spillage increased from 3.0 to 4.0 percent. The major gain in supersonic spillage was thus achieved from the two-dimensional spillage component. For the high-spillage inlet configuration, the cowl lip required no translation at all free-stream Mach numbers between $M_0 = 2.70$ and $M_0 = 1.80$.

As indicated in figure 24, the high-spillage inlet configuration provided both reasonable average throat Mach numbers and minimum Mach numbers upstream of the throat over the free-stream Mach number range of 2.70 to 1.80. For this inlet, the minimum Mach number was slightly lower than the average throat Mach number at each free-stream Mach number investigated. With a fixed cowl lip, both the average and minimum throat Mach numbers were able to be maintained between the desired limits of 1.20 to 1.30.

Low-Curvature Inlet Configuration

One of the inherent difficulties of high internal compression inlets is the inability to operate satisfactorily with mixed compression over a large Mach number range. This stems, in part, from the large surface displacements required to achieve the necessary contraction ratio at off-design conditions. It has been shown in reference 3 that improvements in off-design behavior can be realized either by increasing the supersonic diffuser length or by assigning a greater portion of flow turning to the cowl oblique shock. Both methods essentially reduce the curvature of the internal inlet surfaces. In the following sections, the effect of reducing the cowl lip angle will be studied. For this inlet configuration, cowl lip translation was incorporated into the design.

Inlet configuration. - The inlet chosen for this study is basically the low-distortion inlet configuration which has been modified to use a -2.0° internal cowl lip angle. Presented in figure 25 is the characteristic solution of the low-curvature inlet (fig. 25(b)), along with the surface static pressure distribution (fig. 25(a)). For a design free-stream Mach number of 2.70 and throat Mach number of 1.30, the total pressure recovery was 0.940. The wedge geometry of the low-curvature inlet was identical to the basic and low-distortion inlets. Due to the lower cowl lip angle, the ramp shoulder occurred at $x = 3.04$ which is somewhat upstream of that used in the other inlet designs. The -2.0° cowl lip angle increased the static pressure ratio of the cowl oblique shock (at the ramp shoulder point) from 1.85 to 2.07. As with the other inlets discussed, the cowl lip oblique shock was cancelled at the shoulder point while subsequent compression was achieved isentropically.

A comparison of the cowl surface angular distribution for the three inlet configurations of this study is shown in figure 26. By decreasing the cowl lip angle from 0.0° to -2.0°, it was found that the cowl surface angle at the geometric throat ($x = 4.00$) could be increased from -6.0° to -4.0° without incurring an inflection point on the cowl surface. Hence, with a 2.0° reduction in cowl lip angle, the total amount of flow turning along the cowl surface was reduced 66.7 percent (comparing triangular symbols with square symbols). Both the low-curvature and low-distortion inlets had no cowl inflection point upstream of the throat, while the basic inlet displayed the cowl inflection point at about $x = 3.48$ (circular symbols).

Operating characteristics. - Presented in figures 27 and 28 are the surface Mach number distributions of the low-curvature inlet for free-stream Mach numbers of 2.70 and 1.80. The calculations were performed at or about the same internal contraction ratio, so that comparisons with the other inlet configurations can be made.

For the design free-stream Mach number of 2.70 (fig. 27), both the magnitude and gradient of the surface Mach number distributions were nearly equal. As indicated by the solid circular symbols, the hinge joints were located similarly to the basic and low-distortion inlets. At an inlet operating Mach number of 1.80, the large reduction in surface curvature along the cowl gave rise to a large reduction in the overall flow compression rate along the ramp surface (fig. 28(a)). The characteristic expansion just behind the ramp shoulder point, $x = 3.05$, appears on the cowl surface at about $x = 3.70$ with increased amplitude. Thus, it appears that expansions which originate on the external surface and enter the inlet are attenuated, while expansions which start internally are amplified.

The overall improvement of the surface Mach number distribution that occurred with the low-curvature inlet was realized at the expense of total pressure recovery. Thus, by assigning 2.0° of additional turning to the cowl lip oblique shock, the total pressure recovery decreased from 0.953 to 0.940. However, the ability of the inlet to operate with mixed compression below a free-stream Mach number of 1.80 has been increased.

CONCLUDING REMARKS

A collapsing biramp inlet can be designed aerodynamically which maintains a reasonable off-design capability over the Mach number range of 2.70 to 1.80. Most designs required a translating cowl lip to provide acceptable throat Mach numbers at off-design free-stream operating Mach numbers with the cowl lip shock on the ramp shoulder. With the translating cowl lip, the throat Mach number could be controlled between 1.20 to 1.30 over the free-stream Mach number operating range. One configuration did not require cowl lip translation to provide acceptable throat Mach numbers ($M_{THR} = 1.20$ to 1.30).

Two factors which tended to limit the operating range of this type of inlet were (1) the occurrence of low local Mach numbers upstream of the throat and (2) high local compression rates on the ramp surface. The excessively low upstream Mach numbers were caused by a cowl surface inflection point upstream of the throat. By increasing the supersonic diffuser length 6.7 percent, the inflection point was eliminated. This relieved the low local Mach number and high compression rate on the ramp surfaces. Consequently, the inviscid total pressure distortion at the inlet throat was decreased. It was also found that eliminating the upstream cowl inflection point caused the on-design compression gradients on the internal surfaces to become nearly equal.

Decreasing the initial cowl lip angle from 0.0° to -2.0° greatly improved the overall compressive Mach number distribution on the ramp surface at Mach 1.80. The total pressure distortion level in the throat, however, was not appreciably changed. It is anticipated, therefore, that this improvement would extend the Mach range in which this inlet can operate with mixed compression. This improvement was realized at the expense of decreasing the on-design total pressure recovery from 0.953 to 0.940. For this situation, the on-design surface compression magnitudes and gradients were nearly equal.

Increasing the amount of supersonic spillage by a downstream shift in the forward hinge point appears desirable. The inlet investigated for increased spillage also provided acceptable throat Mach numbers with a fixed cowl lip position. It is anticipated that the "high spillage" inlet configuration, which required no cowl tip translation, will be fabricated and tested in the 10- by 10-foot supersonic wind tunnel at Lewis Research Center.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 28, 1969,
126-15-02-11-22.

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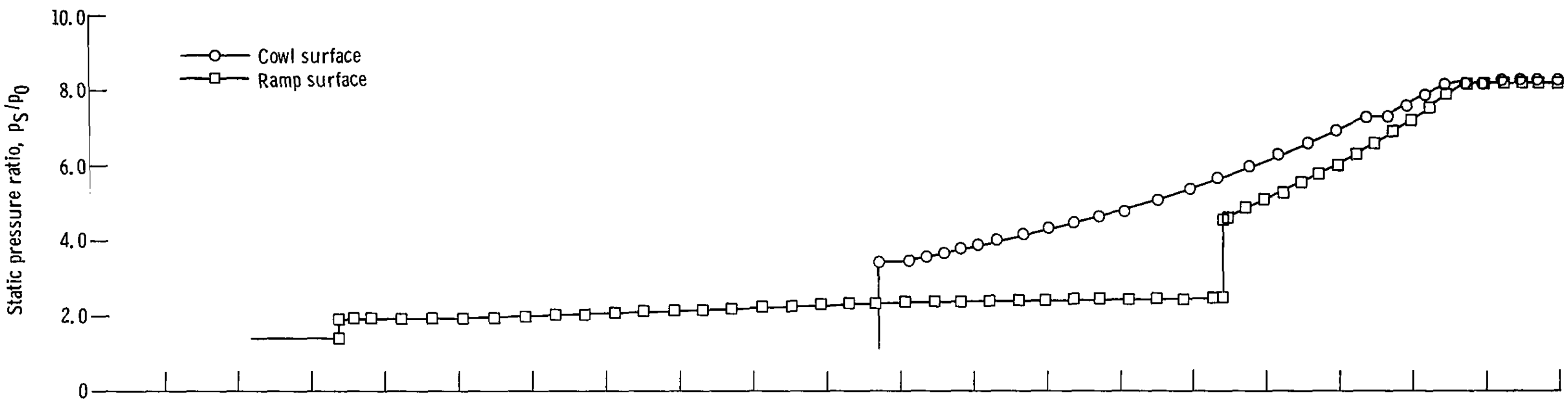
4. Petersen, Martine W.; and Tamplin, Gorden C.: Experimental Review of Transonic Spillage Drag of Rectangular Inlets. Rep. NA-66-10, North American Aviation, Inc. (AFAPL-TR-66-30), May 1966.

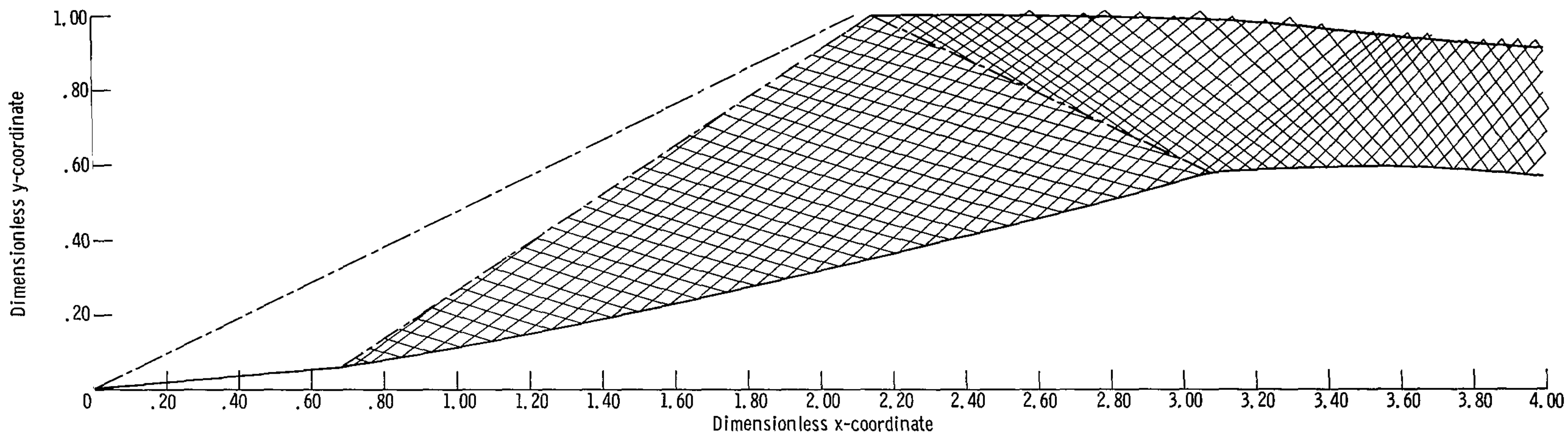
TABLE I. - COWL LIP POSITION AND SECOND RAMP ANGLE

SCHEDULE FOR BASIC AND LOW-DISTORTION INLETS

Free-stream Mach number, M_0	Average throat Mach number, M_{THR}	Second ramp angle, deg	Ratio of cowl lip forward translation to cowl lip height
2.70	1.21	10.75	-0.036
	1.26	10.25	-.018
	1.30	10.00	.000
2.65	1.28	9.75	0.000
2.60	1.27	9.50	0.008
2.50	1.25	8.75	0.020
2.40	1.24	8.00	0.034
2.30	1.22	7.25	0.052
	1.27	7.00	.074
	1.30	6.75	.084
2.20	1.23	6.25	0.070
2.10	1.24	5.25	0.089
2.00	1.28	4.00	0.109
1.90	1.29	2.75	0.128
1.80	1.21	2.00	0.106
	1.31	1.50	.144



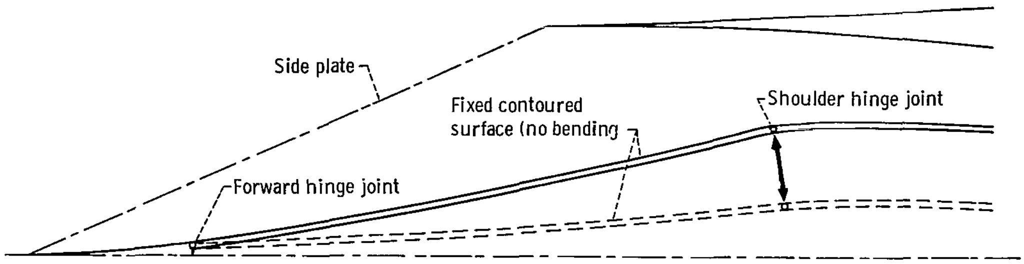
(a) Static pressure distribution.



(b) Characteristic solution.

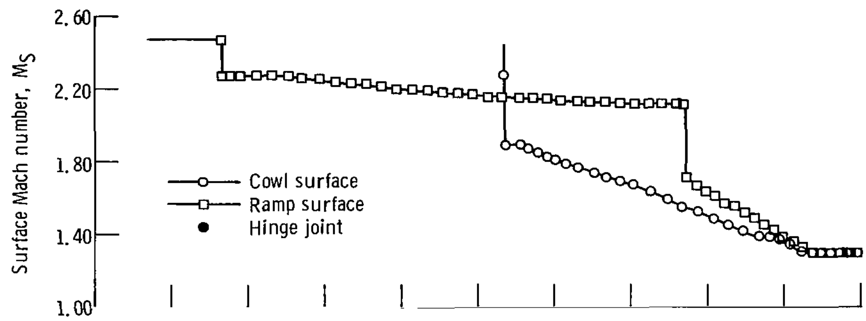
Figure 1. - Characteristic solution of basic inlet. Free-stream Mach number, 2.70.

(a) Translating cowl section.

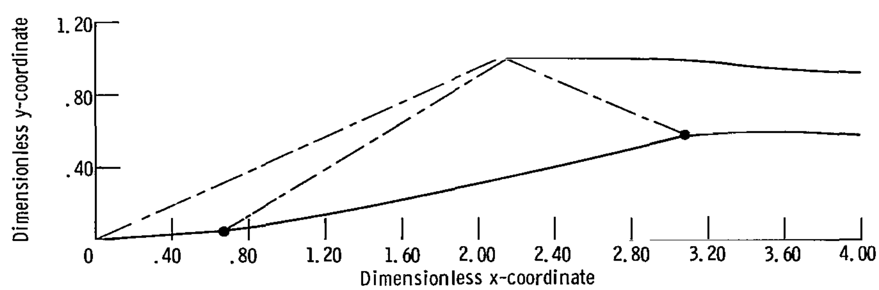


(b) Collapsing ramp section.

Figure 2. - Conception of variable geometry features in inlet.

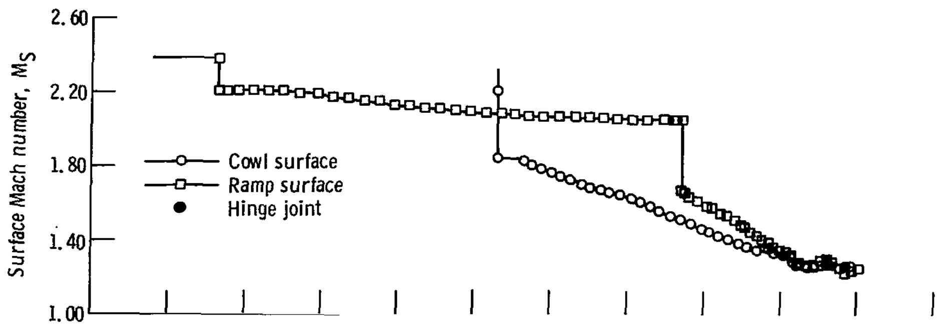


(a) Surface Mach number distribution.

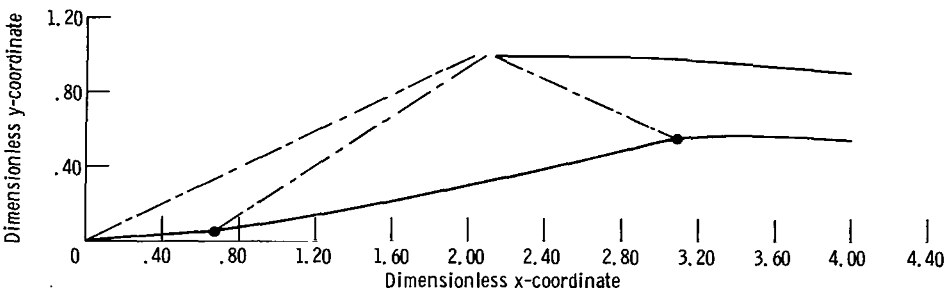


(b) Inlet configuration.

Figure 3. - Basic inlet Mach number distribution for on-design operation. Free-stream Mach number, 2.70; second ramp angle, 10.0°.

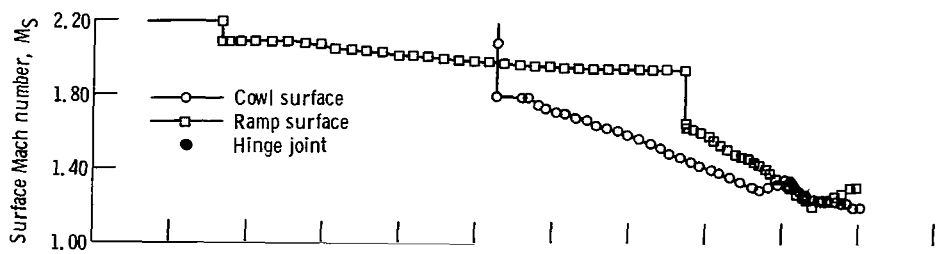


(a) Surface Mach number distribution.

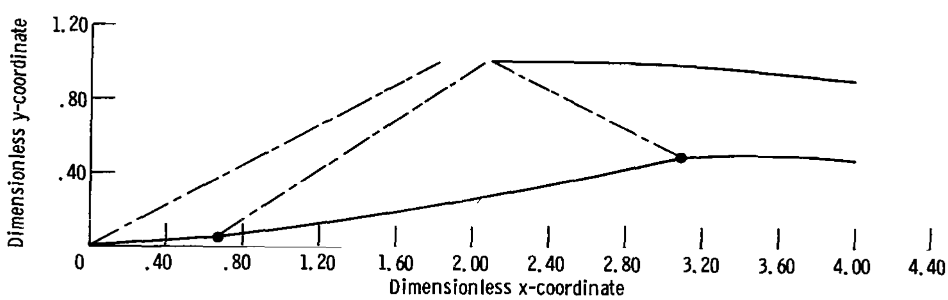


(b) Inlet configuration.

Figure 4. - Basic inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.60; second ramp angle, 9.5°.



(a) Mach number distribution.



(b) Inlet configuration.

Figure 5. - Basic inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.40; second ramp angle, 8.0°.

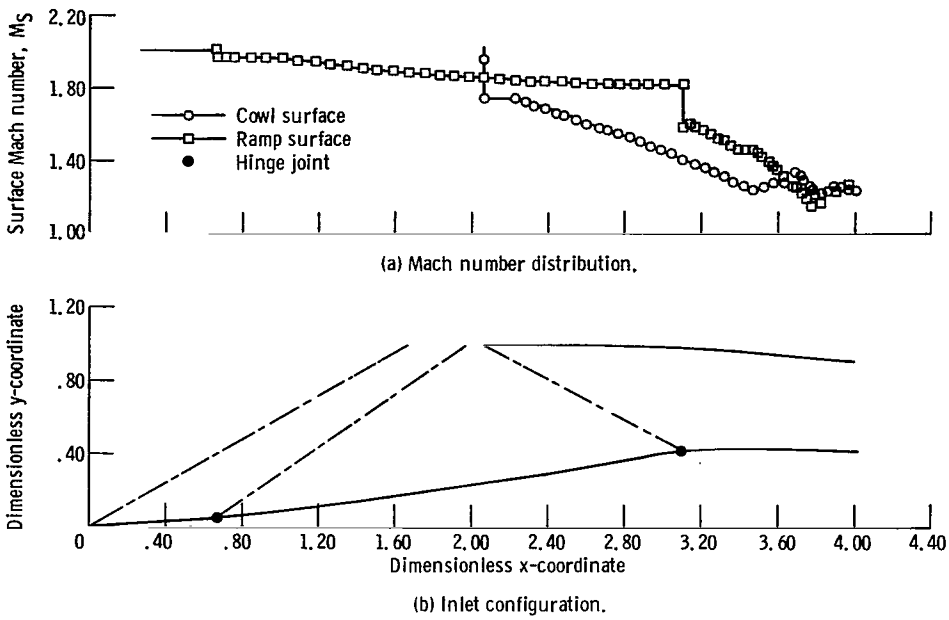


Figure 6. - Basic inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.20; second ramp angle, 6.25°.

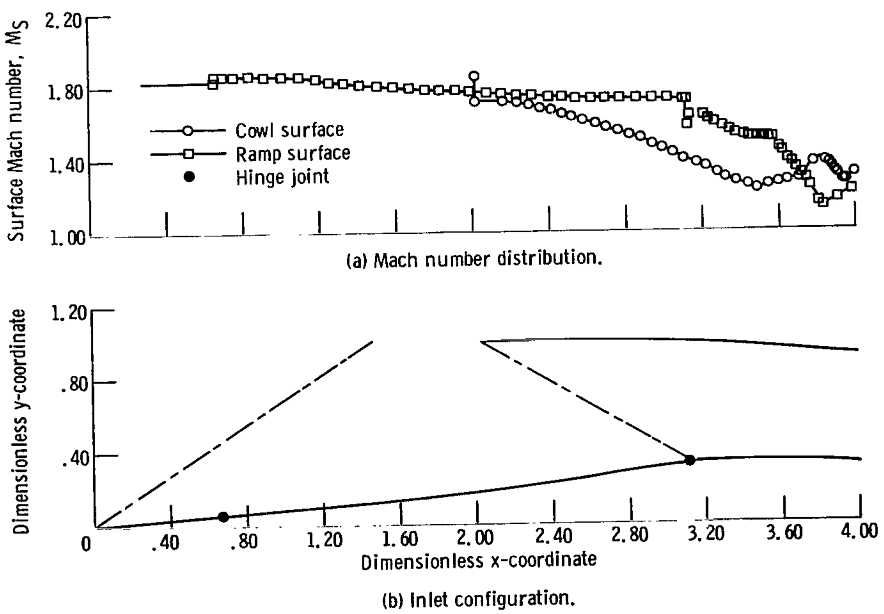


Figure 7. - Basic inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.00; second ramp angle, 4.0°.

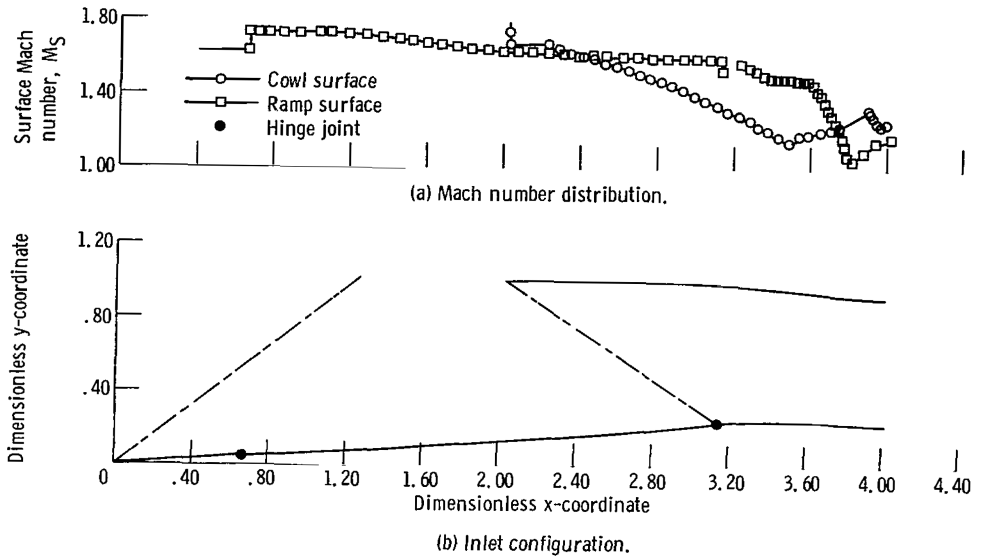


Figure 8. - Basic inlet Mach number distribution for off-design operation. Free-stream Mach number, 1.80; second ramp angle, 2.0°.

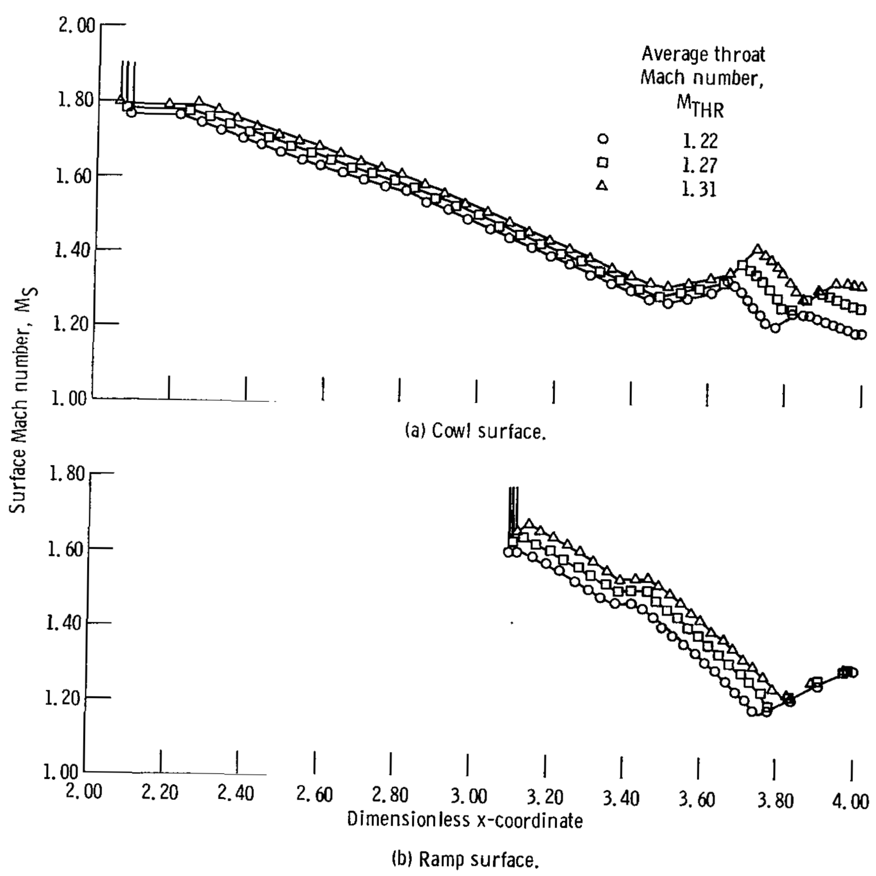


Figure 9. - Effect of throat Mach number on basic inlet Mach number distribution. Free-stream Mach number, 2.30.

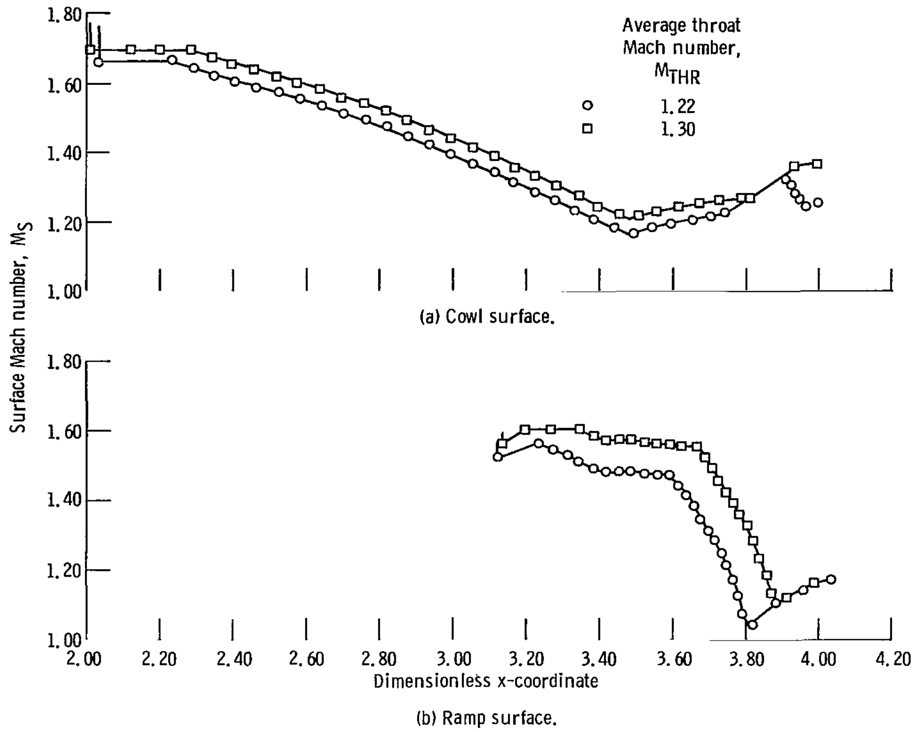


Figure 10. - Effect of inlet throat Mach number on basic inlet Mach number distribution. Free-stream Mach number, 1.80.

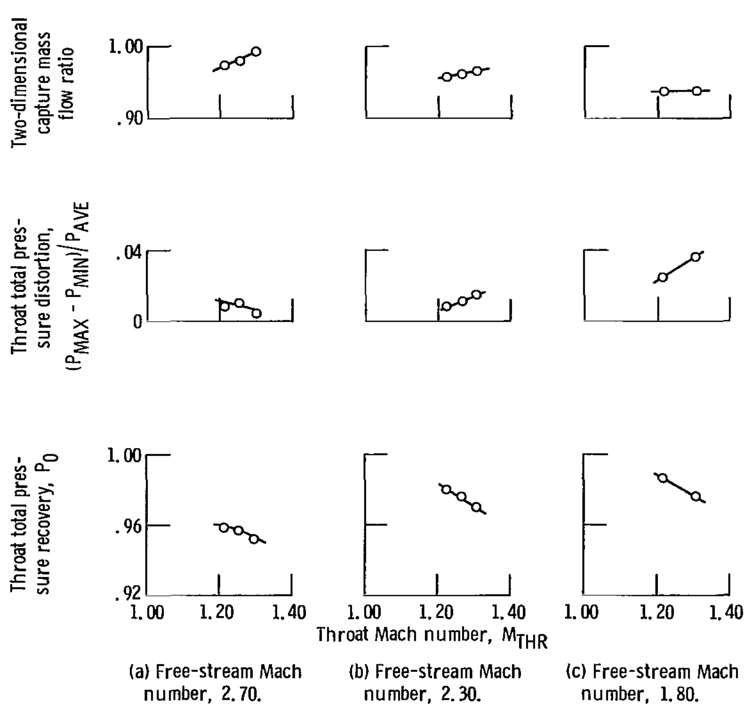


Figure 11. - Effect of throat operating Mach number on inlet performance.

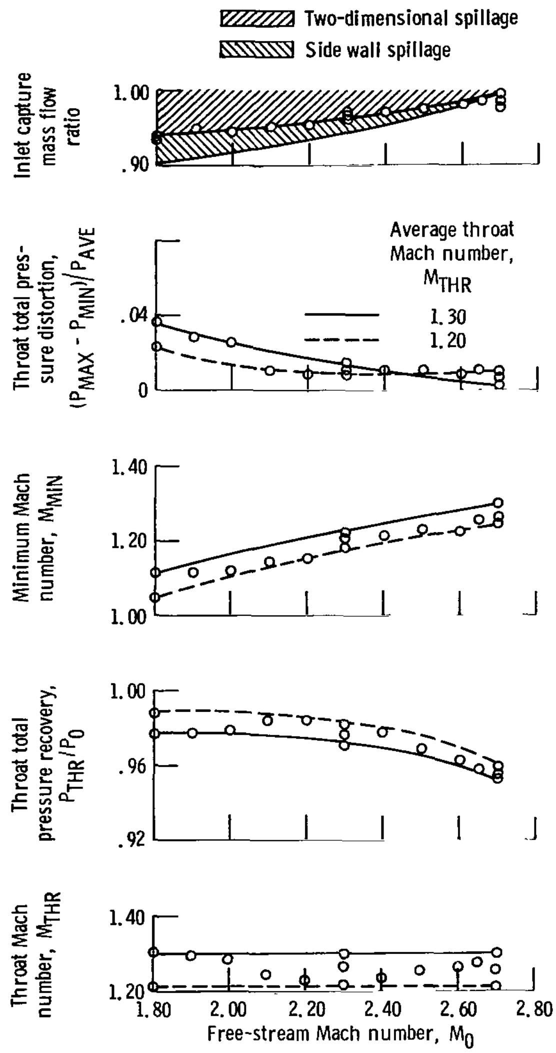
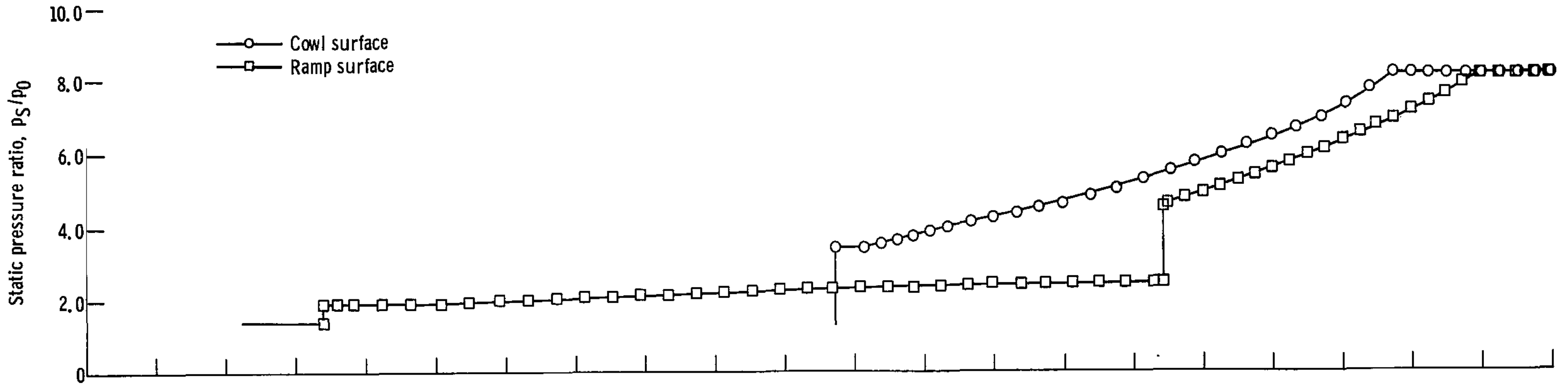
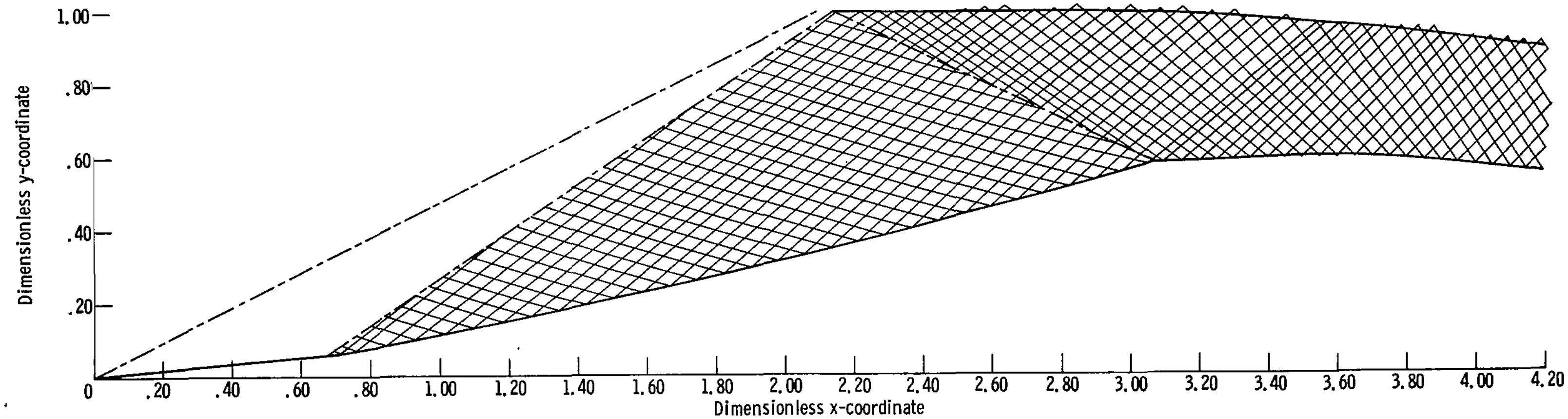


Figure 12. - Performance summary for basic inlet.

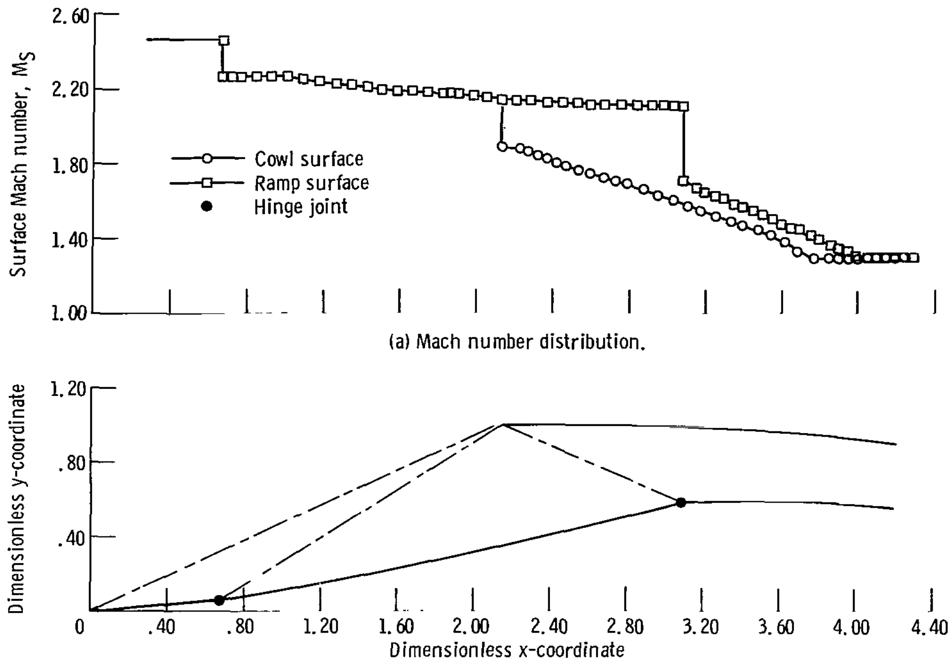


(a) Static pressure distribution.



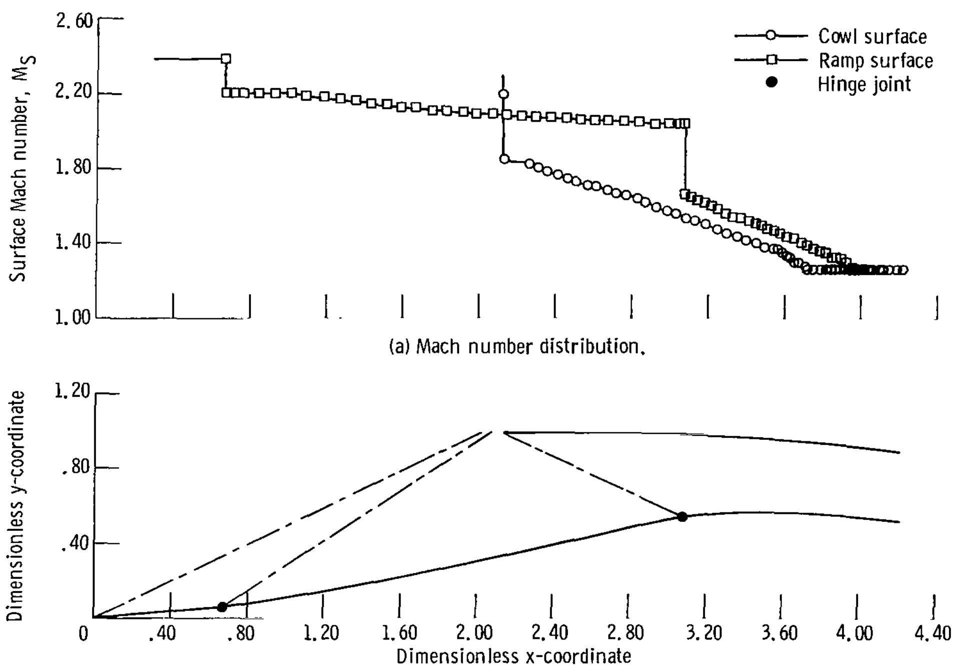
(b) Characteristic solution.

Figure 13. - Characteristic solution of low-distortion inlet. Free-stream Mach number, 2.70.



(b) Inlet configuration.

Figure 14. - Low-distortion inlet Mach number distribution for on-design operation. Free-stream Mach number, 2.70; second ramp angle, 10.0°.



(b) Inlet configuration.

Figure 15. - Low-distortion inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.60; second ramp angle, 9.5°.

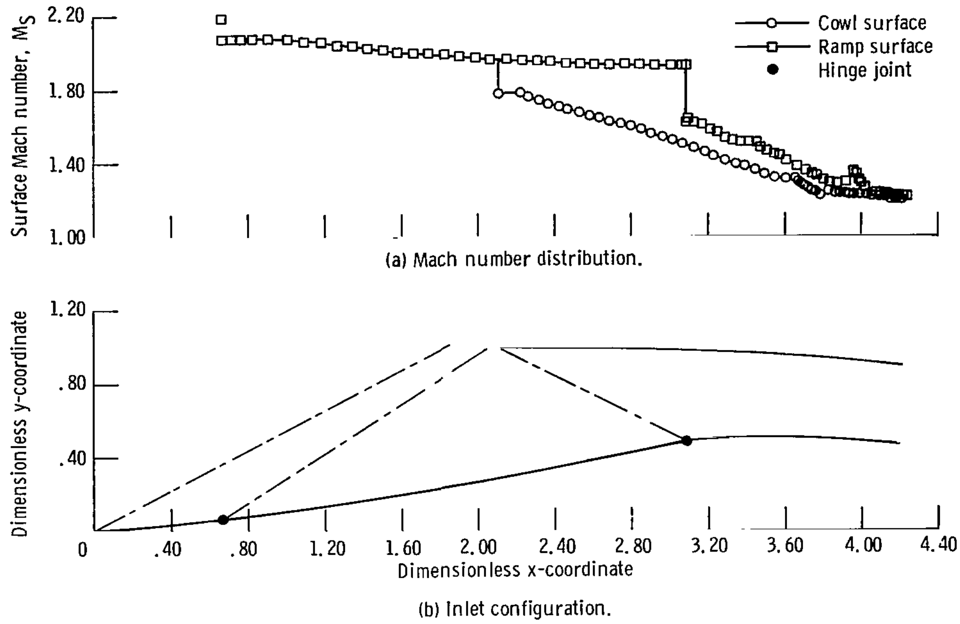


Figure 16. - Ion-distortion inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.40; second ramp angle, 8.0°.

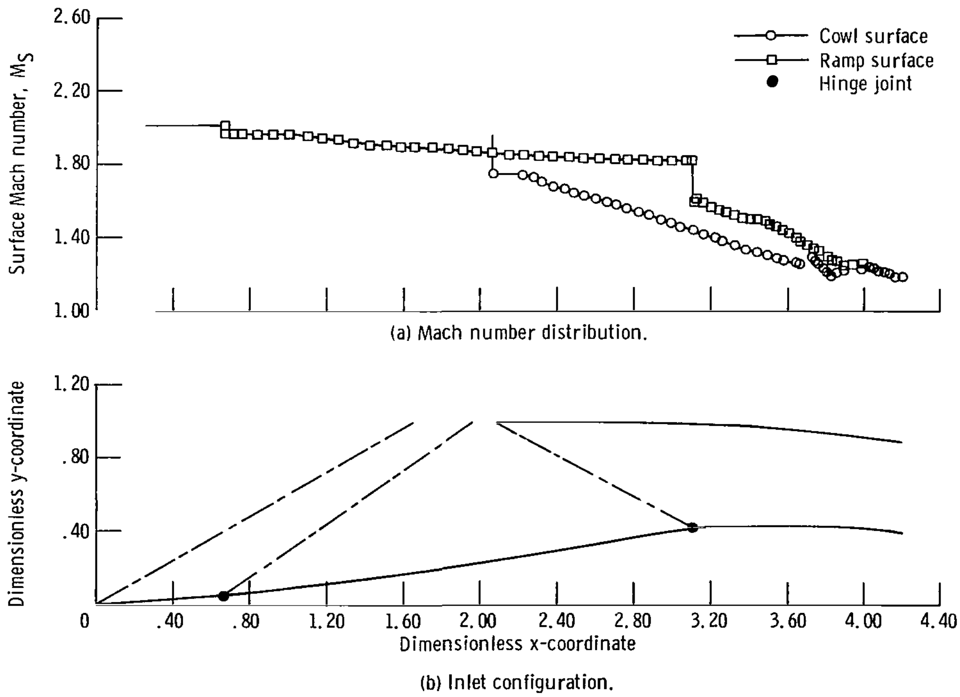


Figure 17. - Low-distortion inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.20; second ramp angle, 6.25°.

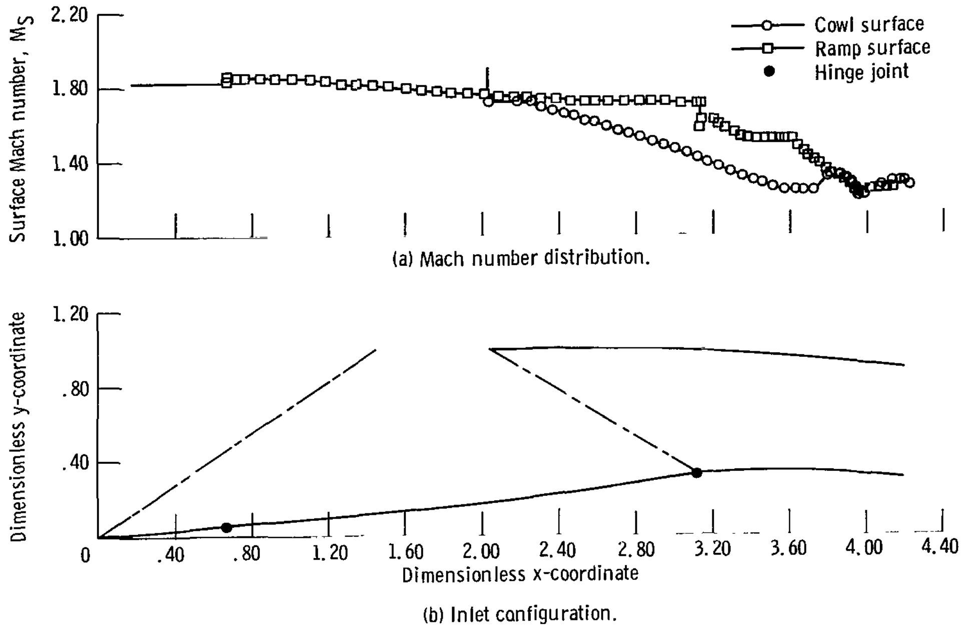


Figure 18. - Low-distortion inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.00; second ramp angle, 9.0°.

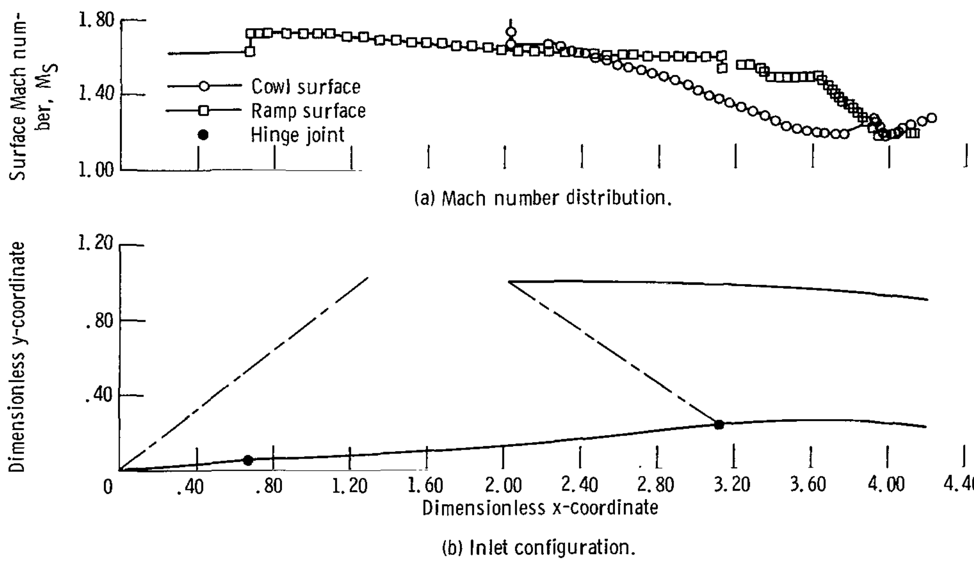


Figure 19. - Low-distortion inlet Mach number distribution for off-design operation. Free-stream Mach number, 1.80; second ramp angle, 2.0°.

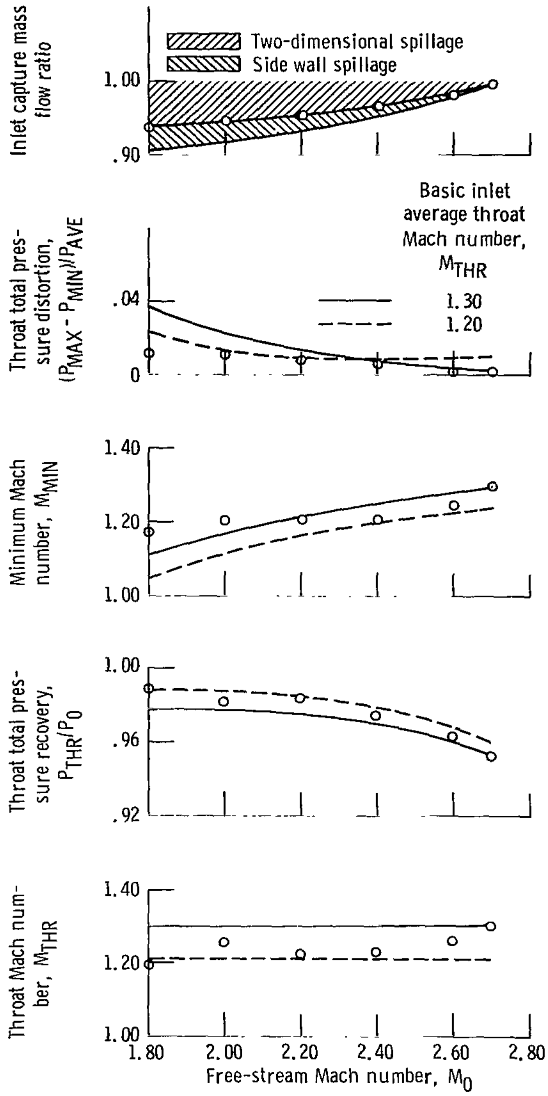


Figure 20. - Performance summary for low-distortion inlet.

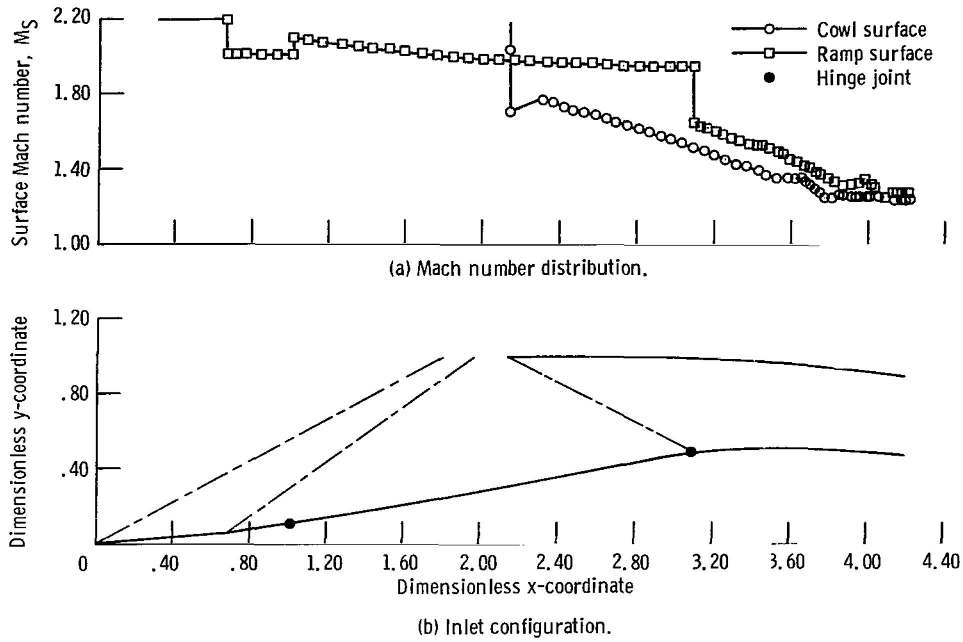


Figure 21. - High-spillage inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.40; no cowl lip translation.

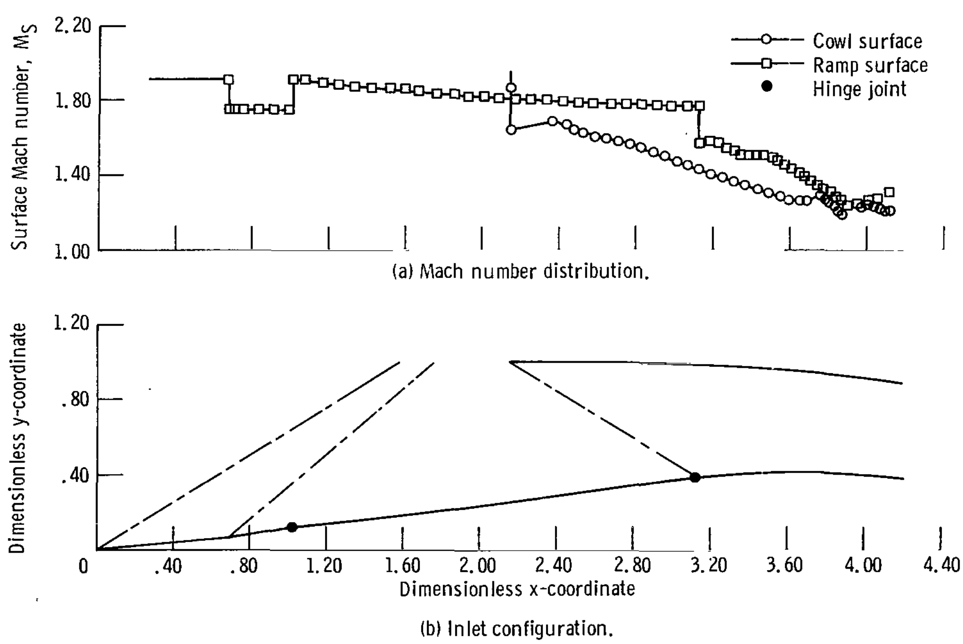


Figure 22. - High-spillage inlet Mach number distribution for off-design operation. Free-stream Mach number, 2.10; no cowl lip translation.

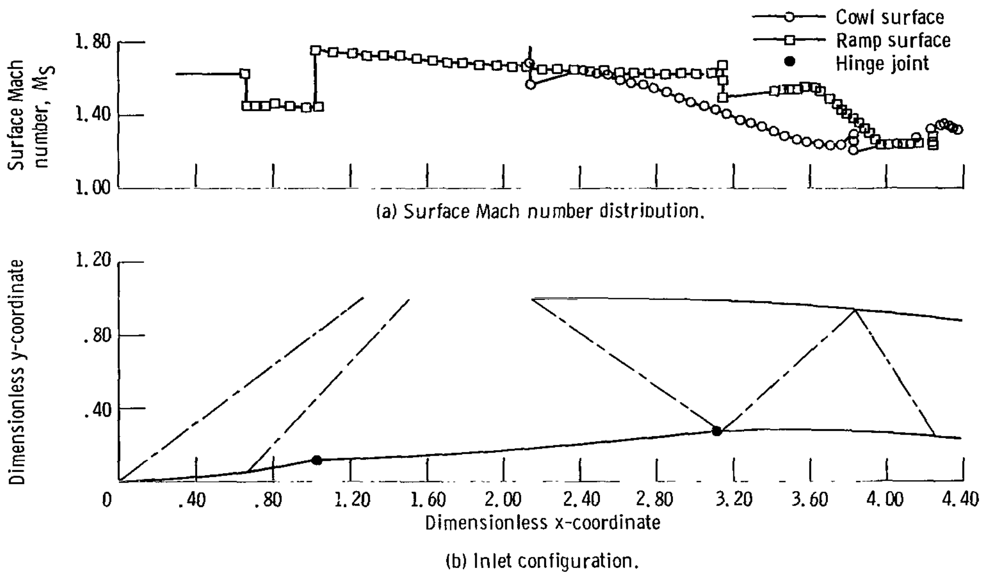


Figure 23. - High-spillage inlet Mach number distribution for off-design operation. Free-stream Mach number, 1.80; no cowl lip translation.

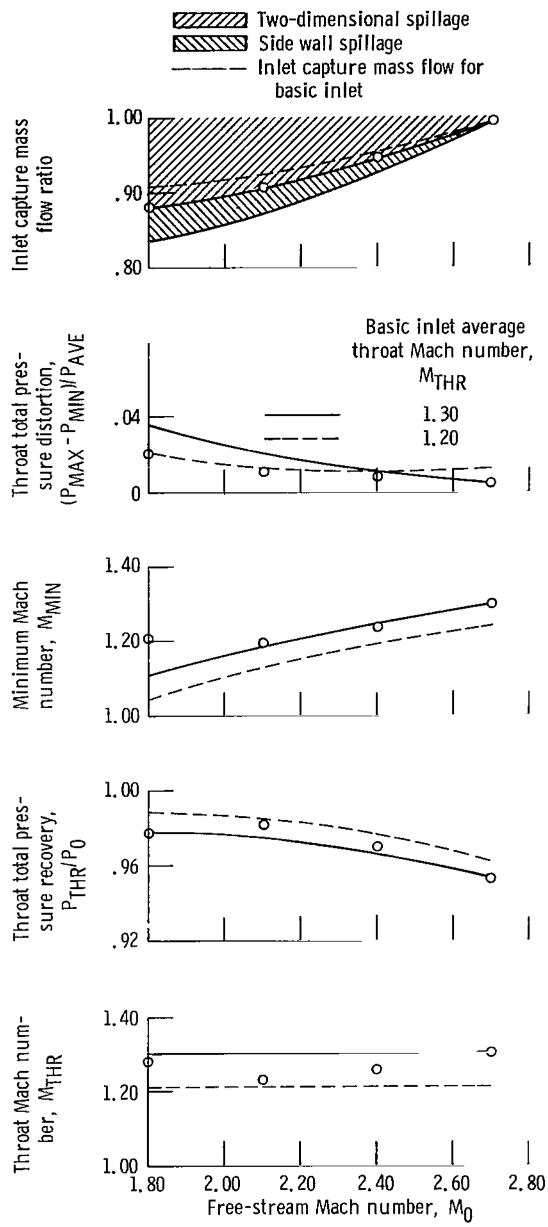
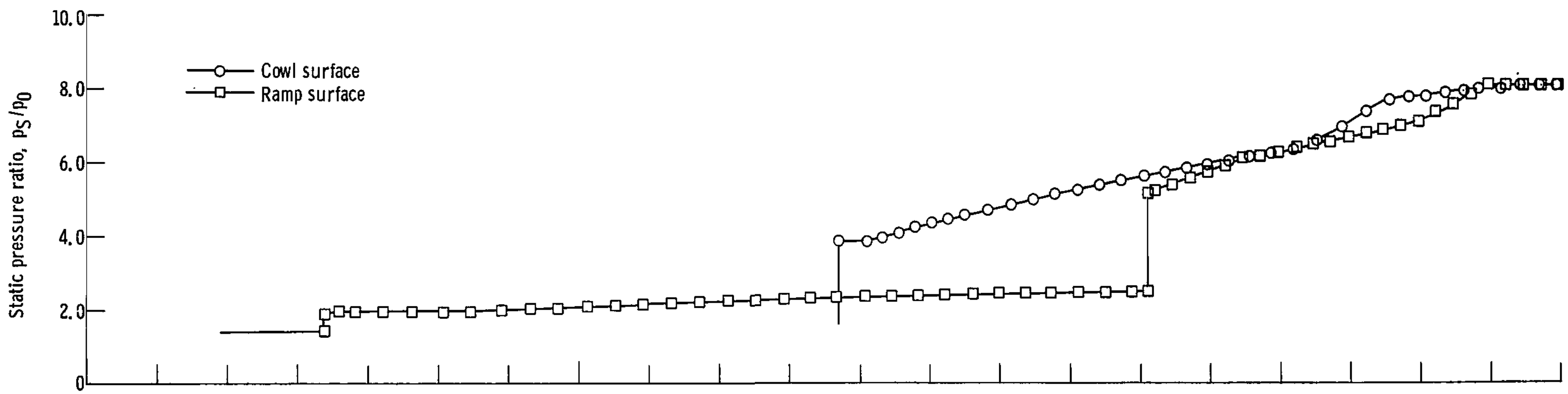
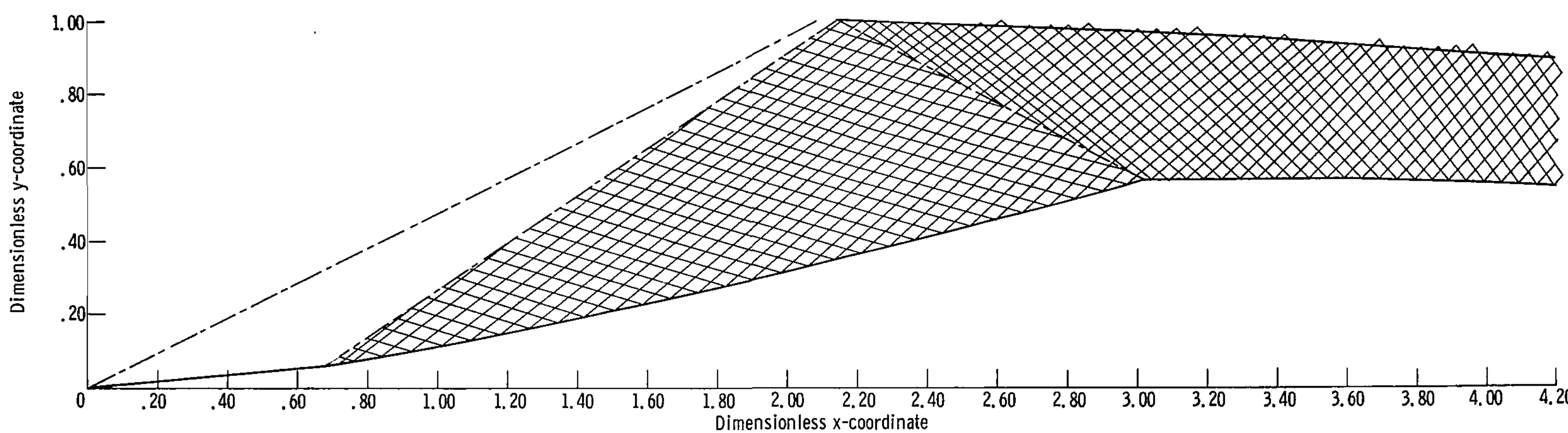


Figure 24. - Performance summary for high-spillage inlet. Fixed cowl lip position.



(a) Static pressure distribution.



(b) Characteristic solution.

Figure 25. - Characteristic solution of low-curvature inlet. Free-stream Mach number, 2.70.

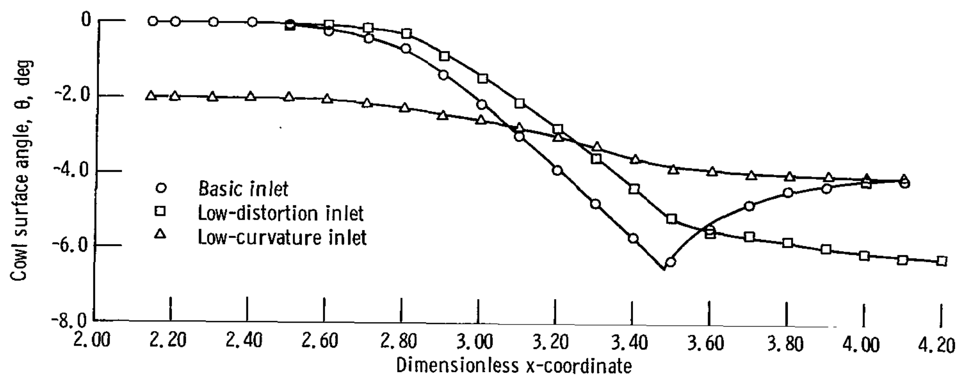


Figure 26. - Comparison of cowl surface angular distribution.

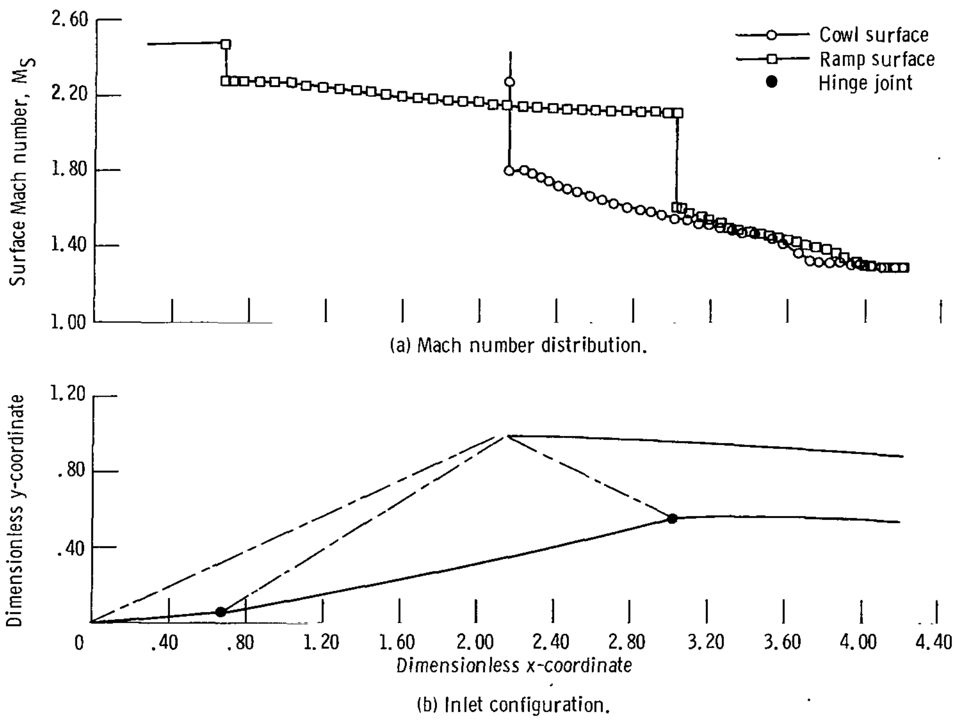


Figure 27. - Low-curvature inlet Mach number distribution for on-design operation. Free-stream Mach number, 2.70; second ramp angle, 10.0°.

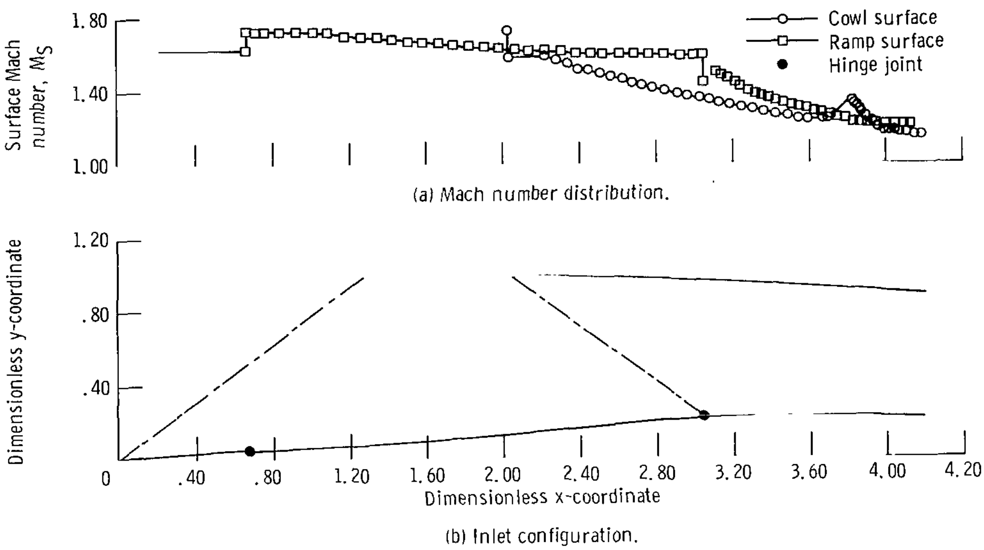


Figure 28. - Low-curvature inlet Mach number distribution for off-design operation. Free-stream Mach number, 1.80; second ramp angle, 2.0°.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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