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CHARACTERISTICS STUDY OF A BICONE MIXED-COMPRESSION INLET FOR MACH 1.80 TO 2.50

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Cleveland, Ohio

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ABSTRACT

A theoretical design study was made to evaluate the behavior of a bicone mixed-compression inlet over the Mach number range 1.800 to 2.500 and to explore the possibilities in overall performance that may be realized by modifications of the external and internal geometries. For the inlet operating on-design, the results indicate three characteristics are required for favorable surface compression distributions and low flow distortion near the throat at off-design Mach numbers. These are (1) low-contour curvature of the internal surfaces, (2) nearly equal compression rates on the cowl and centerbody surfaces, and (3) generally low distortion levels in the flow field upstream of the throat.

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SUMMARY

A theoretical design study, using the method of characteristics, was made to evaluate the behavior of a bicone mixed-compression inlet over the Mach number range 1.800 to 2.500. The inlet was designed to have a collapsing centerbody section to allow inlet operation at off-design conditions. The collapsing process took place under the constraint that the cowl oblique shock be maintained on a fixed shoulder point on the centerbody at all conditions. The total-pressure recovery of the inlet at the design free-stream Mach number (M_0 = 2.500) was 0.968. Over the Mach number range studied, the average throat Mach number was kept above a minimum required limit of 1.20 with reasonable throat distortion levels.

A study was also made to inquire into the ramifications of the following design considerations: (1) length of internal supersonic compression, (2) amount of internal turning imposed on the flow field, (3) effect of throat Mach number, (4) effect of cowl lip angle, and (5) effect of the ratio of external to internal supersonic area contraction.

Substantial reductions in throat flow-field distortion at the lower Mach numbers were realized by proper contouring of the internal surfaces. This contouring prevented an inflection point from occurring on the cowl surface upstream of the throat. It appears that nearly equal compression rates on the centerbody and cowl surfaces along with low distortion levels of the flow field upstream of the throat, for the inlet operating on-design, were indigenous to favorable internal compression distribution and low distortion levels in the throat regions at off-design conditions. Reductions in the surface curvature of the internal surfaces of the design inlet were always associated with these, as well as the preceding, considerations and were accompanied by reductions in flow distortion near the throat at off-design conditions. There also appears to be an optimum internal cowl lip angle, associated with the study inlet, which will minimize this distortion over a Mach number range.

INTRODUCTION

Very little information is currently available on the on- and off-design problems associated with internal compression inlets over a large Mach number range. Computer studies of the type presented herein which use characteristic theory can be very useful in making comparative studies of design variables which are not easily accomplished with experimental models. Although characteristic theory has attained a high degree of sophistication with the advent of high-speed computers, the time required to optimize an inlet which achieves acceptable on- and off-design behavior can be considerable. A reduction in time may be anticipated if general inlet properties can be determined which are consistent with reasonable off-design behavior. These would provide a reasonable starting configuration and, therefore, would reduce the iterations required to obtain a desirable inlet.

While viscous interactions can have a pronounced effect on the performance of inlets, in some instances inviscid calculations provide a remarkably good representation of the flow field in the region upstream of the inlet throat (see ref. 1). In addition, inviscid flow field calculations do indicate problem areas which can greatly influence the viscous boundary layer development and, consequently, inlet performance.

Specifically, therefore, the objectives of this study were (1) to analytically evaluate the design and off-design characteristics of a bicone, mixed-compression inlet, (2) to explore the consequences in overall performance that may be realized by modifications of the external and internal geometries, and (3) to discover any flow properties that might provide good off-design performance.

The basic inlet configuration selected for this study was described first in reference 1. This inlet is a Mach 2.500 design having a 10.0° to 18.5° bicone forebody. The initial cowl angle was set at 5.0°, and the resulting cowl lip shock was canceled at the centerbody shoulder, while subsequent compression was achieved isentropically. With a design throat Mach number of 1.300, the total-pressure recovery behind the terminal shock was 0.968. The inlet was designed to have a collapsing second cone to allow the inlet to operate at off-design conditions. The collapsing process was to take place under the constraint that the cowl oblique shock should be maintained on the centerbody shoulder point at off-design conditions.

A canceled-shock inlet of the type described lends itself easily to a study of the effects of internal contour modifications since the internal Mach number distribution and surface contours can be systematically varied (see ref. 1). Thus, the effects of internal compression length, internal flow-angle distribution, and throat Mach number were studied by systematic modifications of the contour surfaces. This process permits the isolating of possible sources of flow distortion inherent in this type of inlet at off-design conditions. In addition, the effects of initial cowl angle and ratio of external-internal supersonic area contraction ratio (second cone angle) were examined to relate changes in on-design performance with off-design characteristics.

The digital computer program presented in reference 1 was the basis of the calculational procedures used in this study. The performance of the inlet was studied over the Mach number range 1.800 to 2.500.

SYMBOLS

A	annular flow area
A_{cowl}	capture area based on cowl lip radius
A_{lip}	annular flow area at cowl lip station
M	Mach number
P	total pressure
p	static pressure
x	dimensionless x-coordinate relative to cowl lip radius
y	dimensionless y-coordinate relative to cowl lip radius
α	angle

Subscripts:

av	average conditions
cowl	condition at cowl lip
dsc	design second cone conditions
max	maximum conditions
min	minimum conditions
thr	throat conditions
0	free-stream conditions

RESULTS AND DISCUSSION

Computations for the inlet design study presented in this report were made by using the computer program presented in reference 1. The computer program was written with the option that the internal centerbody contour and surface Mach number distribution could be direct program input variables for an inlet wherein the cowl shock was canceled at the centerbody. The program uses the method of characteristics to calculate the cowl contour necessary to satisfy both the prescribed centerbody boundary data and the initial conditions. The program also provides the resulting internal flow area. Once the design configuration was established, off-design calculations were performed which were based on the design contours and the variable geometry features of a collapsing centerbody section. The shock-on-shoulder condition was accomplished by an iterative process involving the free-stream Mach number and second cone angle. In each case, the internal centerbody contours were determined by requiring that the shoulder be hinged to the second cone and remained parallel to the design surface during the collapsing process. Hence, for off-design calculations, the equations of the respective surfaces became the program input data, and the terminal output included the flow field and conditions along each surface.

Using the computational technique described in reference 1, this study attempts to inquire into the off-design ramifications of the following inlet design considerations:

(1) Length of internal supersonic compression

(2) Amount of internal turning assigned to the flow field

(3) Amount of internal compression assigned to the flow field

(4) Cowl lip angle

(5) Ratio of external to internal supersonic area contraction

In addition to cataloguing the effects of these considerations, this study also seeks to arrive at general observations consistent with low flow-field distortion in the throat over the Mach number range 2.500 to 1.800.

To indicate the off-design flow-field changes that occur with these inlet design considerations, comparisons are made with a basic inlet design described in the following section. The basic inlet is a modified version of the bicone inlet described in reference 1. The modifications allow for a more favorable throat Mach number schedule with decreasing free-stream Mach number.

Inlet Configuration and Performance

Basic inlet. - Shown in figure 1 is the characteristic solution of a 10.0° to 18.5° bicone inlet design for a free-stream Mach number of 2.500. The second oblique shock (originating at the junction of the two conic surfaces) was located such that it intersected the cowl lip, while the initial cone shock was positioned forward of this point to allow for about 0.40-percent supersonic mass flow spillage. For this inlet configuration, the initial cowl angle was set at 5.0°. The resulting cowl oblique shock was canceled at the centerbody shoulder ($x = 2.78$), while subsequent internal compression was achieved with distributed compression. For a design throat Mach number M_{thr} of 1.30, about 60 percent of the supersonic area contraction took place externally. Theoretical total-pressure recovery behind the terminal shock in the throat ($x = 3.50$ to $x = 3.60$) was 0.968.

The internal contours of the inlet were determined with the requirement that the average throat Mach number should not be less than 1.20 over the free-stream Mach number range considered. In addition, attempts were made to minimize the distortion levels in the throat region. This, as will be seen, dictated the nominal flow angle in the throat and the internal compression length.

Off-design operation. - The inlet was designed to have a collapsing second cone to allow the inlet to operate at off-design conditions. Shown in figure 2 are the inlet contours for off-design operation between Mach numbers 2.500 to 1.800. The second cone was always positioned such that the cowl oblique shock intersected the centerbody shoulder point as the second cone was collapsed. Consequently, hinge points were located at the junction of the two conic surfaces ($x = 1.03$) and the centerbody shoulder point (indicated by the small-dashed line in fig. 2). The centerbody surface downstream of the shoulder was considered to remain hinged to the shoulder and parallel to the original surface during the collapsing process. The fully collapsed position (large-dashed contour in fig. 2) was defined as the position where the second cone angle was 10.0°, (i.e., equal to the first cone angle).

Presented in figure 3 is the off-design Mach number schedule for the second cone angle and the resulting internal area ratio A_{thr}/A_{lip}. At a free-stream Mach number of 1.800, the second cone could be positioned between 13.0° and 10.0° (fully collapsed position) since the cowl oblique shock was very weak and did not require cancellation at the cone shoulder. When the inlet is in the fully collapsed position (large-dashed contour in fig. 2), the internal contraction is sufficiently low to permit restarting the inlet at a free-stream Mach number of 1.800, and possibly at even lower Mach numbers.

The internal flow-area variation is presented in figure 4. The indicated contour positions are the same as those indicated in figure 3. The internal flow area was made dimensionless with respect to the cowl lip area (based on the cowl lip diameter). Since there was no relative translation between the cowl and centerbody, the cowl lip station remained fixed at $y = 2.15$. The dashed curve in figure 4 indicates the internal flow-area distribution for restart at Mach 1.800 (fully collapsed position). There was essentially no shift in the location of the geometric throat over the range of contour positions.

Inlet performance. - Figure 5 is a summary of the overall inlet performance for the Mach number range 2.500 to 1.800. Throat Mach numbers and total-pressure recoveries (behind the terminal shock) were based on area-weighted averages. The requirement of a minimum average throat Mach number of 1.20 was maintained, as indicated in figure 5. For this Mach number range, the average total-pressure recovery increased from about 0.968 (at Mach 2.500) to 0.988 at Mach 1.800. The inviscid distortion level for this Mach number range reached a maximum value of between 1.0 and 2.0 percent at Mach 1.800. When the centerbody was fully collapsed, there was a sharp increase in throat Mach number and flow distortion, while there was an appreciable decrease in the total-pressure recovery.

The value of inviscid throat distortion is not necessarily important in itself since the boundary layer can have a pronounced effect on the inviscid flow field. The manner in which the flow field is compressed to the throat conditions, however, is important since it determines the satisfactory operation of the inlet. For example, excessively low local Mach numbers upstream of the throat may cause inlet unstart at only small angles of attack. In addition, high local compression rates on the internal surfaces can markedly influence the boundary layer and, hence, bleed requirements. Thus, the emphasis is placed on flow-field characteristics in this study.

Inlet Characteristics

Static-pressure distribution. - Figure 6 is a comparison of the static-pressure distribution along the cowl surface (fig. 6(a)) and centerbody surface (fig. 6(b)) for free-stream Mach numbers of 2.500, 2.333, 2.167, 2.000, 1.900, and 1.800. The off-design pressure distributions are presented for the centerbody contour positions shown in figure 2 at the corresponding free-stream Mach numbers.

As the free-stream Mach number decreased (collapsing the centerbody) the static-pressure gradient in the region upstream of the geometric throat ($x = 3.50$ to $x = 3.60$) tended to decrease. During normal operation at the design Mach number, the compressive turning of the cowl oblique shock was canceled by the abrupt expansive turning at the centerbody shoulder point. Collapsing the inlet centerbody to permit operation at lower free-stream Mach numbers decreased the strength of the cowl oblique shock. The centerbody surface angle, downstream of the shoulder hinge point, remained constant. As a result, the expansive turning at the shoulder point decreased more slowly than did the cowl oblique shock compression and caused an expansion just behind the shoulder point. This expansion was further amplified by the rapid centerbody surface turning rate downstream of the shoulder point. This turning rate was one of the primary causes of flow distortion in this inlet. Methods of minimizing this cause of flow distortion are discussed in later sections along with selected inlet configurations.

Mach number distribution. - Figure 7 presents Mach number distributions on the cowl surface (indicated by circular symbols), and on the centerbody surface (square symbols) for free-stream Mach numbers between 2.500 and 1.800. The Mach number distribution for design conditions ($M_0 = 2.500$) is shown in figure 7(a). The geometric throat was located at $x = 3.50$. The flow area downstream of this station was held constant for calculational purposes. However, the possibility exists of minimizing the throat distortion during supercritical inlet operation by carefully choosing a supersonic Mach number distribution downstream of the geometric throat (see ref. 1).

The decrease in strength of the cowl oblique shock with decreasing free-stream Mach number is more apparent in figures 7(b) to (e), particularly on the centerbody shoulder. The alternating expansion and compression regions on both the centerbody and cowl surfaces were caused by the expansion waves originating from the intersection of the centerbody shoulder and the cowl oblique shock. In general, the expansion region tends to amplify in the downstream direction. In the lower free-stream Mach number range, the distorted flow field is such that low Mach number regions alternate from centerbody to cowl surfaces. Thus, distortion of the total-pressure recovery at the throat was dependent on the location of the terminal shock. Minimum distortion occurs at that station where the cowl and centerbody Mach numbers are equal. This is especially apparent when the inlet is operating in the Mach 1.800 position. In this instance, the station used to survey the throat flow field was located at $x = 3.60$ and indicated an inviscid total-pressure distortion of less than 1.0 percent. However, the Mach number distributions in the vicinity of $x = 3.50$ (the start of the geometric throat) are indicative of a higher flow-field distortion. In general, the minimum local Mach number did not fall appreciably below a value of 1.20, and this occurred reasonably close to the geometric throat.

Internal Contour Considerations

Presented in figures 8 to 12 are comparisons to indicate the effects of contour modifications on the off-design performance of the inlet. These modifications include shortening the internal compression length, decreasing the nominal flow angle in the throat region, and increasing the amount of internal compression by decreasing the design throat Mach number. In each example, the external configuration of the inlet was held fixed while the appropriate contour modifications were studied.

Effect of internal supersonic diffuser length. - Figures 8 and 9 indicate the effect of decreasing the overall supersonic diffuser length by decreasing the internal compression length. In the first example (fig. 8) the throat was placed at $x = 3.30$ (as compared to $x = 3.50$ for the original inlet), while in the second example (fig. 9) the throat was located at $x = 3.15$. In both examples, the Mach number and surface angle distribution along the centerbody were maintained similar to that of the basic inlet (i.e., the same Mach number and surface angle occurred at the same percent distance between the shoulder and the throat). The Mach number distribution for the basic inlet is indicated by a solid curve for the cowl surface and a dashed curve for the centerbody surface. Distributions for the modified inlet are indicated by circles for the cowl surface and squares for the centerbody.

Figure 8(a) is a comparison of the cowl and centerbody Mach number distribution for both the basic and modified inlets. As a result of the shorter compression length of the modified inlet, the Mach number gradients on both the centerbody and cowl were increased. In order to satisfy the prescribed Mach number and centerbody surface of the modified inlet, a cowl surface inflection point had to occur at $x = 3.10$. The effect of these contour changes at a free-stream Mach number of 2.000 (fig. 8(b)) was to amplify the distortion caused by the expansion just downstream of the centerbody shoulder. The additional amplification was caused, in part, by the greater turning rate of the centerbody surface downstream of the shoulder point. The cowl inflection point further amplified this additional expansion (between $x = 3.10$ and $x = 3.23$) and contributed to the decrease in the minimum surface Mach number upstream of the throat. Further reduction in the internal compression length (fig. 9) exaggerated both these characteristics to the point where severe coalescence of the compression waves occurred (fig. 9(b)).

The two modified bicone inlets described herein, with their larger rates of flow compression, had two basic characteristics which contributed to additional flow distortion: (1) larger geometric turning rate of the centerbody surface downstream of the shoulder point, and (2) the occurrence of a geometric inflection point on the cowl surface located upstream of the throat. The additional expansion that occurred near the shoulder point (caused by increasing the rate of turning of the centerbody surface) suggests that delayed turning of the centerbody downstream of the shoulder could reduce distortion levels caused by this characteristic. The "overturning" of the cowl surface upstream of the throat below its angular value at the throat, which thereby causes an inflection point, was not present in the basic inlet. However, decreasing the internal compression length caused increasingly larger negative angles at the inflection point of the modified inlets (the throat angle having been held constant). This permitted the compression waves to coalesce and contributed greatly to the higher distortion levels and lower minimum local Mach numbers occurring in the modified inlets. This result may suggest that overturning of the cowl surface, relative to the throat, could be avoided by specifying a more negative flow angle in the throat, thereby realizing a shorter inlet, provided reasonable off-design compression rates are maintained.

Effect of throat flow angle. - In the second type of internal contour modification, the internal compression length and Mach number distribution along the centerbody were held constant, while the amount of flow turning was increased by requiring more negative nominal flow angles at the throat. The calculations were performed under the condition that the same percent angular change (relative to the total centerbody turning angle) occurred over the same distance (along the centerbody) between the shoulder and the throat as that of the basic inlet. Thus, nominal throat flow angles of -3.0° and -5.0° were prescribed, and the results were compared to the original inlet, which had a throat flow angle of -1.0°.

Since the Mach number distribution on the centerbody was held constant for this type of contour modification, the Mach number differences that must arise for the design configuration occur along the cowl surface (figs. 10(a) and 11(a)). The increased turning of the cowl surface caused additional compression along that surface. At Mach 2.000, both modified inlets were collapsed to the same position in such a way that the shoulder point remained fixed. However, because of the inlet geometry, lowering the throat flow angle (and consequently the cowl surface) tended to increase the internal contraction ratio at Mach 2.000. This can be seen in figures 10(b) and 11(b) since the average throat Mach number was decidedly lower.

Overcompression of the flow along the cowl surface for the modified inlet with a -5.0° throat flow angle (fig. 11(b)) caused coalescence of the compression waves within the throat region. This same effect was observed with the -3.0° modified inlet, but at lower free-stream Mach numbers. Therefore, if larger negative throat angles were desirable, a different method of collapsing the inlet would be required.

Effect of throat Mach number. - Figure 12 shows the effect of increasing the internal contraction ratio of the inlet by decreasing the throat Mach number from 1.30 to 1.20. The internal contour of the modified inlet was chosen on the basis that the same percent change in the Mach number (relative to the total Mach number change) along the centerbody occurred at the same distance between the shoulder and the throat. The centerbody contour of the modified inlet was the same as that of the original inlet.

Comparison of the on-design Mach number distributions for the basic and modified inlet are presented in figure 12(a). At Mach 2.000, the internal flow field of the modified inlet (fig. 12(b)) degenerated to where coalescence of the compression waves caused severe compression rates to develop upstream of the throat region.

External Contour Considerations

The two types of contour modifications that are studied in this section are (1) decreasing the initial cowl angle and (2) increasing the design internal contraction ratio by decreasing the amount of external compression on the bicone forebody. This section deals primarily with ramification of these types of changes as they affect the off-design characteristics of the inlet.

Effect of cowl lip angle. - Comparisons presented in figures 13 and 14 indicate the effects of decreasing the initial cowl angle α_{cowl} from 5.0° to 2.0°, while keeping the ratio of external to internal area contraction the same as that of the basic inlet. The surface contours of the 2.0° cowl angle inlet are presented in figure 13. Again, a 10.0° to 18.5° bicone forebody configuration was chosen. The design throat Mach number and nominal flow angle were 1.30 and -1.0°, respectively. This gave a theoretical total-pressure recovery of 0.959 behind the terminal shock, as compared with 0.968 for the basic inlet.

Shown in figure 14(a) are comparisons of the Mach number distribution and the contour changes for both the basic and modified inlets. Decreasing the initial cowl angle

α_{cowl} from 5.0° to 2.0° had the effect of increasing the oblique shock static-pressure ratio across the centerbody shoulder from 1.46 to 1.79. This also produced an upstream shift of the centerbody shoulder point as a result of the increased cowl oblique shock angle. As a consequence, the throat station was moved upstream from about $x = 3.50$ to $x = 3.42$ in order to maintain the same length of internal compression along the centerbody surface. Because more compression took place across the cowl oblique shock, the Mach number gradient was substantially reduced for the modified inlet. In addition, a reduction in the difference between Mach numbers of the cowl and centerbody (distortion level upstream of the throat) was realized. The increased flow compression across the cowl oblique shock also resulted in decreasing the surface curvature of both the cowl and centerbody (fig. 14(a-2)) and caused a nearly equal compression rate to occur on the internal surfaces.

The reduced curvature of the internal contours of the modified inlet greatly reduced the flow distortion at the inlet throat, $x = 3.42$ at free-stream Mach numbers of 2.000 (fig. 14(b-1)) and 1.800 (fig. 14(c-1)). This large reduction in flow field distortion was probably realized because the decreased curvature of cowl and centerbody surfaces tended to minimize the misalinement of the two surfaces during the collapsing process. In addition, the distortion caused by the expansion region behind the centerbody shoulder at the lower free-stream Mach numbers was greatly reduced as a result of the increased cowl shock strength.

The large reductions in flow-field distortions, however, were realized at the expense of a lower average throat Mach number. For example, at Mach 2.000 (fig. 14(b-1)) the average throat Mach number was reduced from 1.23 to 1.19, while 1.800 (fig. 14(c-1)) the throat Mach number was decreased from 1.29 to 1.15. At Mach 1.800, it was necessary to position the second cone of the modified inlet about 1/2° higher than the basic inlet to maintain the shock-on-shoulder condition.

Effect of supersonic area contraction ratio. - Figures 15 to 17 show the effect of increasing the supersonic area contraction occurring internally from about 40 to 43 percent by decreasing the design second cone angle from 18.5° to 16.5°. The inlet design used for this comparison is shown in figures 15(a) and (b). A cowl angle of 2.0° was chosen for the first modified configuration, which resulted in a total-pressure recovery of 0.964. In the second inlet example (fig. 15(b)) the cowl angle α_{cowl} was reduced to 0°. This gave an average total-pressure recovery of 0.962 behind the terminal shock in the throat, as compared with 0.968 for the basic inlet.

The comparisons of the on-design Mach number distributions presented in figure 16(a-1) correspond to the inlet contours shown in figure 16(a-2). The internal contours of the 10.0° to 16.5° bicone inlet with the 2.0° cowl were determined on the basis that the internal Mach number distribution on the centerbody was the same as that of the basic inlet. As a result of these changes, the Mach number gradient on the cowl surface tended to be lower than that of the modified inlet. In addition, reductions also occurred in the flow-field distortion associated with the isentropic compression downstream of the cowl lip shock ($x = 2.78$). The oblique shock static-pressure rise at the centerbody shoulder was increased from about 1.43 to 1.60. The centerbody shoulder was kept at about the same x-position as the basic inlet by requiring no supersonic spillage. This moved the cowl lip position upstream from its original position.

At a free-stream Mach number of 2.000, the off-design second cone angle was positioned at about 13.0°, as compared to 15.0° for the basic inlet (fig. 16(b-2)). In general, the distortion level for the modified inlet was somewhat lower than that of the basic inlet because the average pressure recovery was higher. This high-pressure recovery was caused by the lower average throat Mach number of the modified inlet. The primary source of flow distortion in this modified inlet, however, arises from a cowl contour inflection point located at $x = 3.17$, upstream of the throat station. This inflection point resulted from the prescribed Mach number and surface angle distribution on the centerbody of the design configuration. Thus, the flow along the cowl surface was overcompressed to a Mach number value of about 1.27 ($x = 3.18$) and then re-expanded to 1.29 at $x = 3.25$. This unnecessary compression and expansion reinforced the expansion zone inherent in the region just downstream of the shoulder and tended to amplify the flow-field distortion. This cause of flow-field distortion is very characteristic of this type of inlet, particularly at high internal contraction ratios. It presented a major problem in minimizing the distortion level of the bicone inlet described in reference 1 at the lower Mach numbers.

In figure 17(a), the on-design characteristics of the 10.0° to 16.5° bicone inlet (with a 0° internal cowl angle) are compared with the basic inlet. As a consequence of the lower initial cowl angle α_{cowl}, the static-pressure rise across the oblique shock at the centerbody shoulder point increased from 1.46 to 1.85. The modified inlet in this example was characterized by substantially lower distortion level in the flow field upstream of the throat, in addition to nearly equal Mach number gradient on the centerbody and cowl surfaces (fig. 17(a-1)). In spite of the lower curvature in this inlet configuration, a cowl surface inflection point was still present in the configuration.

At a free-stream Mach number of 2.000 (fig. 17(b)), the reduced curvature of the internal surfaces reduced the distortion level in the inlet throat. However, the average throat Mach number was decreased from 1.22 to 1.16.

CONCLUDING REMARKS

A collapsing bicone inlet can be designed aerodynamically to maintain a reasonable off-design capability while scheduling the second cone position such that the centerbody shoulder intercepts the cowl oblique shock. Major off-design problems associated with this type of inlet are encountered in trying to maintain a reasonably high throat Mach number and low distortion. However, substantial reductions in throat flow distortion can be realized by proper contour modifications. But these changes usually require longer supersonic diffusers. Requiring lower cowl lip angles greatly improved the distortion problem and tended to shorten the supersonic diffuser length, but this type of alteration tended to lower the average off-design Mach number in the throat region. This improvement appears to be related to smaller contour curvature of the cowl and centerbody surfaces, and reduces the effects of misalinement of the two surfaces during the collapsing process. It also appears that (1) generally lower distortion level in the isentropic flow field downstream of the cowl shock and (2) more equal compression rates on the cowl and centerbody surfaces are related to the lower surface curvature and indigenous to lower distortion in the throat region at off-design conditions. Note, however, that the reduced average throat Mach effect resulting from smaller contour curvature is geometric in nature and associated with axisymmetric flow. Had the average throat flow angle been higher (such that the design throat occurred at a larger radius), the average throat Mach number could have increased. This, however, may result in greater turning losses in the subsonic diffuser.

There appears to be an inherent limit to the amount of supersonic area contraction that can be assigned to the internal section of this type of inlet. This limit is caused by an inlet throat Mach number lower limit at off-design conditions. This contraction limit will change, depending on the mission requirements of the inlet, or more specifically, the Mach number range over which the inlet is to operate. It also appears that decreasing the cowl lip angle reduces the throat distortion and improves the internal compression distribution by reducing the amplitude of surface Mach number oscillations in the downstream direction.

A serious source of flow-field distortion that is characteristic of this type of inlet, particularly at the higher internal contraction ratios, is the overturning of the cowl surface upstream of the throat to an angular value below that at the geometric throat. This upstream geometric inflection point on the cowl surface was the major cause of distortion for the bicone inlet described in reference 1. It caused severe and unnecessary coalescence of the compression waves, particularly in the restart position. By extending the supersonic compression length and modifying the Mach number distribution along the centerbody of the bicone inlet described in reference 1, the cowl inflection point was shifted downstream to the geometric throat. As a result of these modifications, large reductions in distortion were realized.

In general, this type of inlet lends itself easily to contour modifications without jeopardizing the on-design performance. The choice of internal compression length, throat angle, and throat Mach number depend to a large extent on the mission requirements placed upon the inlet. The choice of initial cowl angle and supersonic internal contraction ratio depend not only on the mission requirements, but also on the design compromises that are acceptable.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 4, 1968,
126-15-02-11-22.

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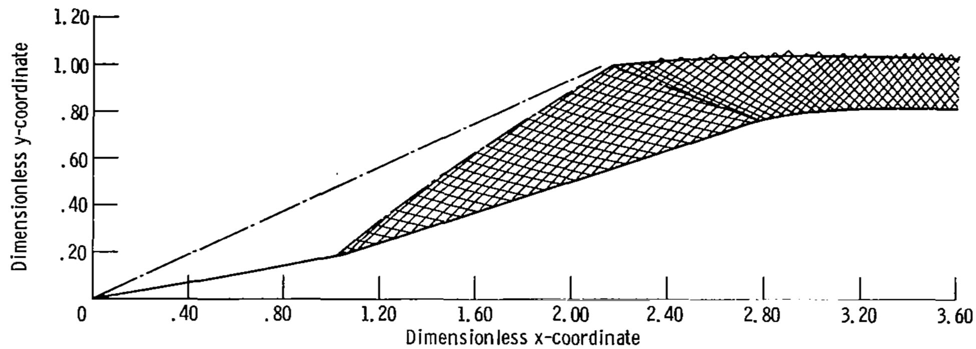


Figure 1. - Characteristic solution for basic 10° to 18.5° bicone inlet designed for Mach 2.500. Initial cowl angle, 5.0°; design throat Mach number, 1.300; total-pressure recovery, 0.968.

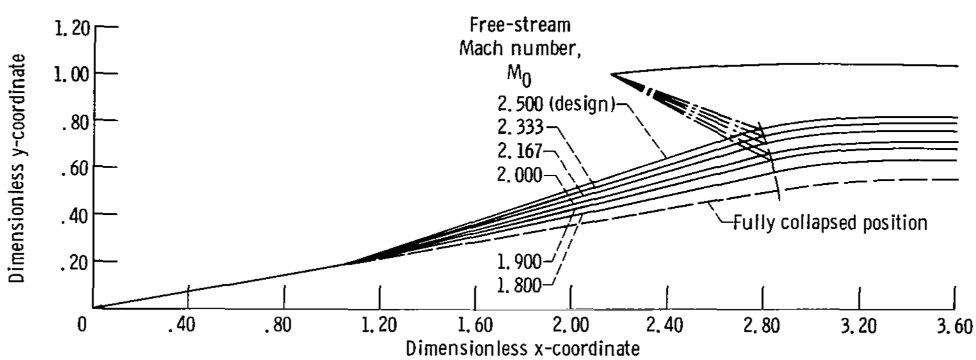
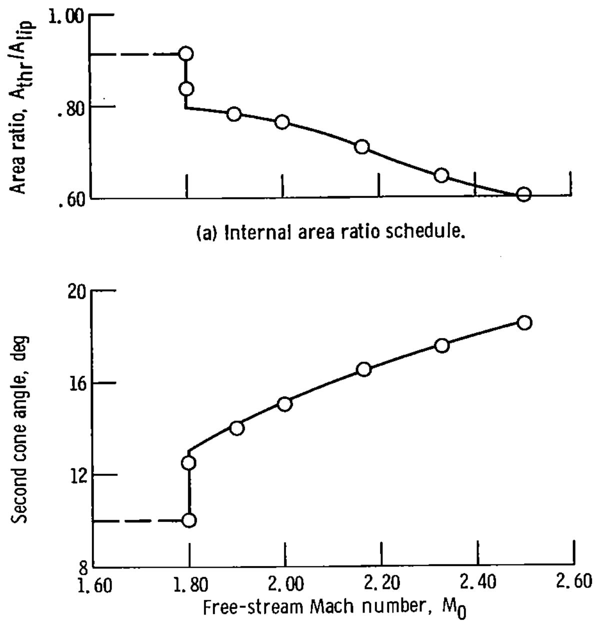


Figure 2. - Inlet contours for off-design operation of basic inlet.



(a) Internal area ratio schedule.

(b) Second cone angle schedule.

Figure 3. - Off-design schedule of second cone angle and resultant internal area ratio for basic inlet.

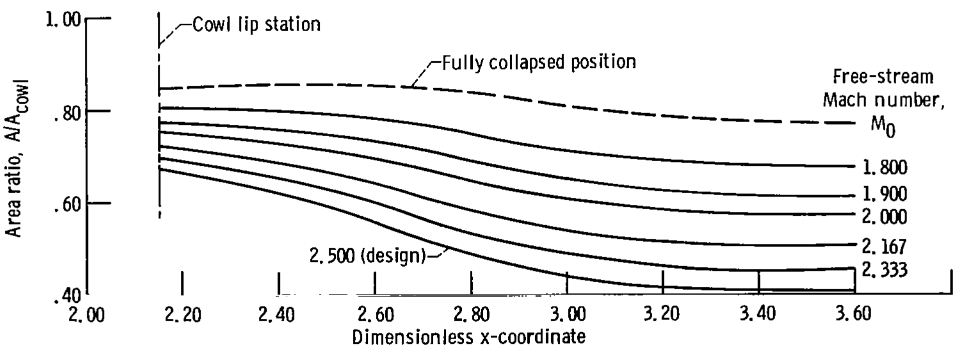


Figure 4. - Internal area variation for basic inlet.

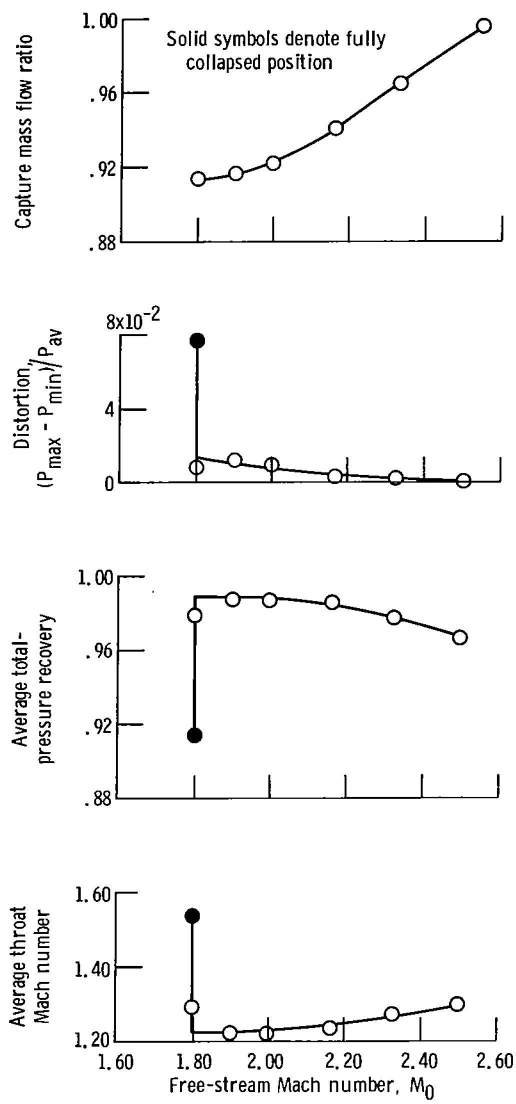
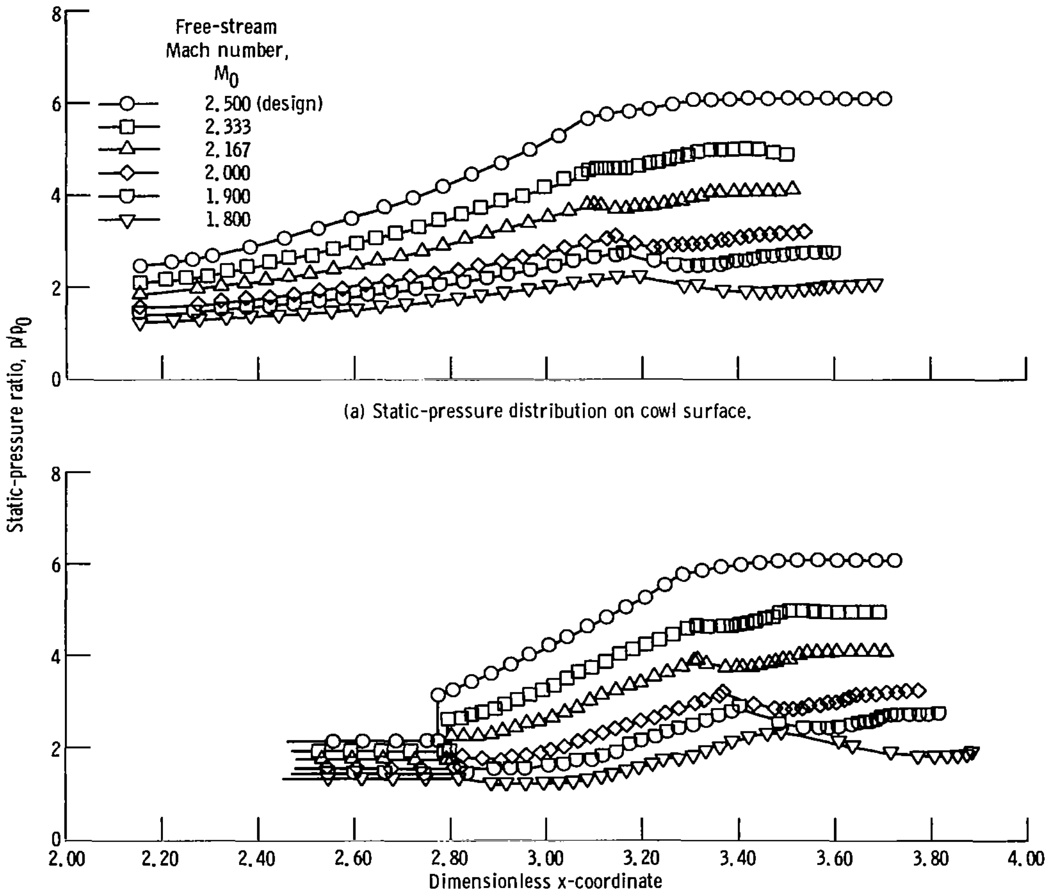


Figure 5. - Summary of performance for basic inlet.



(a) Static-pressure distribution on cowl surface.

(b) Static-pressure distribution on centerbody surface.

Figure 6. - Effect of free-stream Mach number on internal static-pressure distribution for basic inlet.

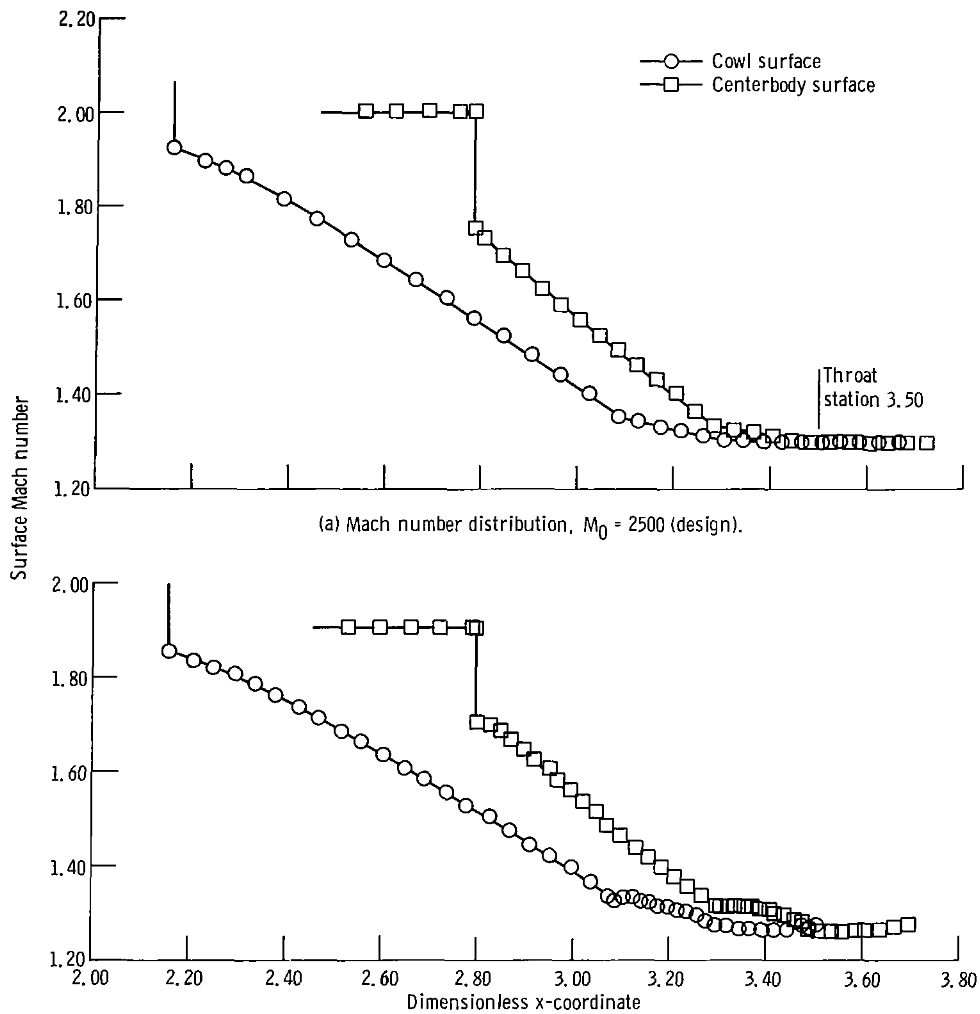
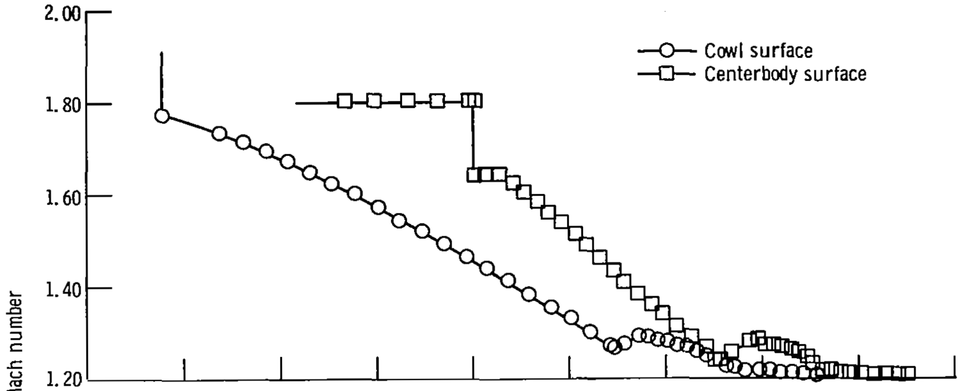
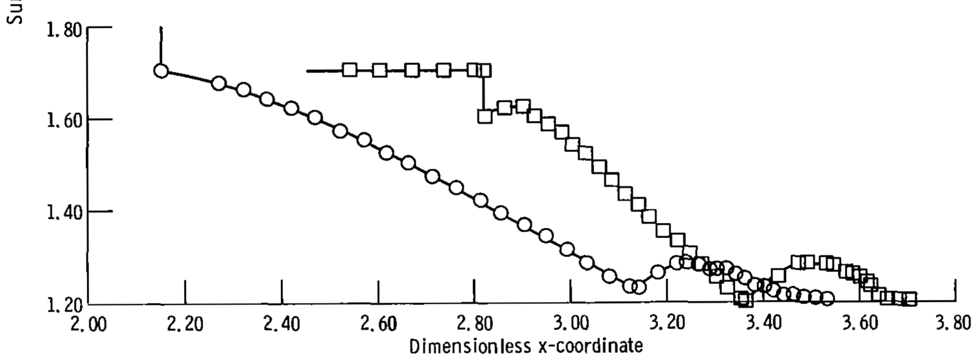


Figure 7. - Comparison of Mach number distribution on cowl and centerbody for basic inlet.

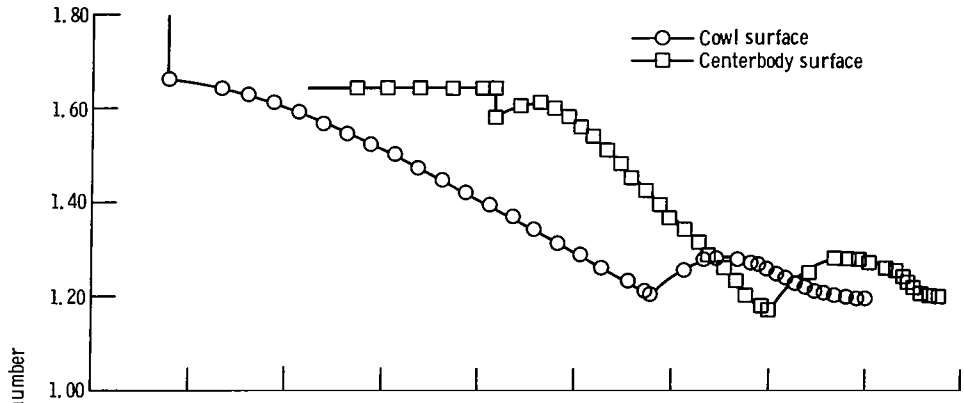


(c) Mach number distribution, M_0 = 2.167.

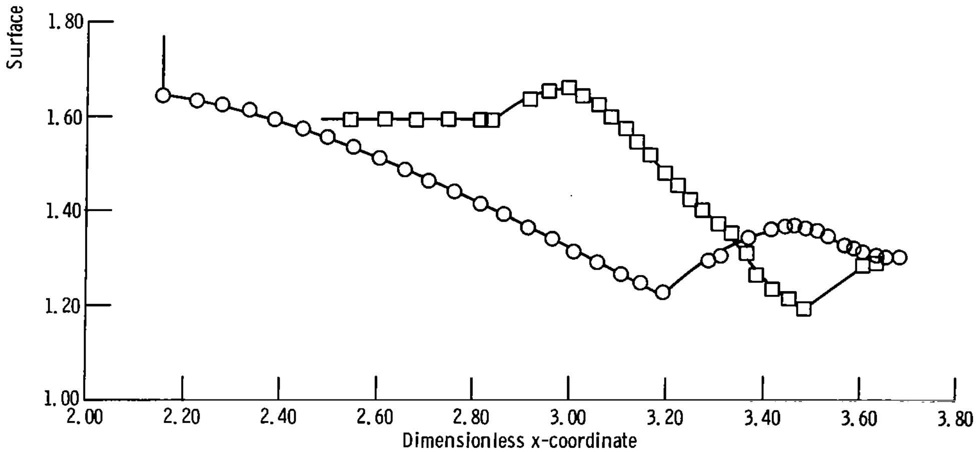


(d) Mach number distribution, M_0 = 2.000.

Figure 7. - Continued.

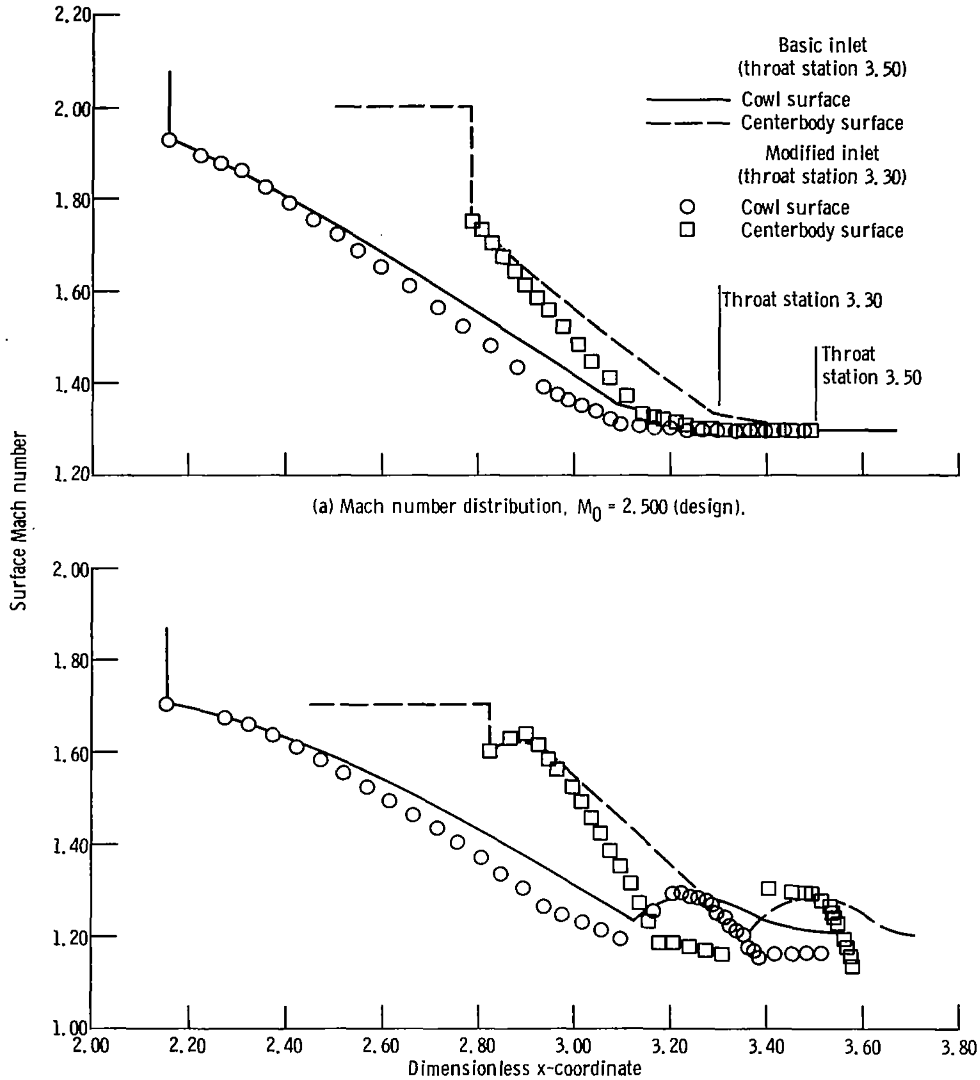


(e) Mach number distribution, M_0 = 1.900.



(f) Mach number distribution, M_0 = 1.800.

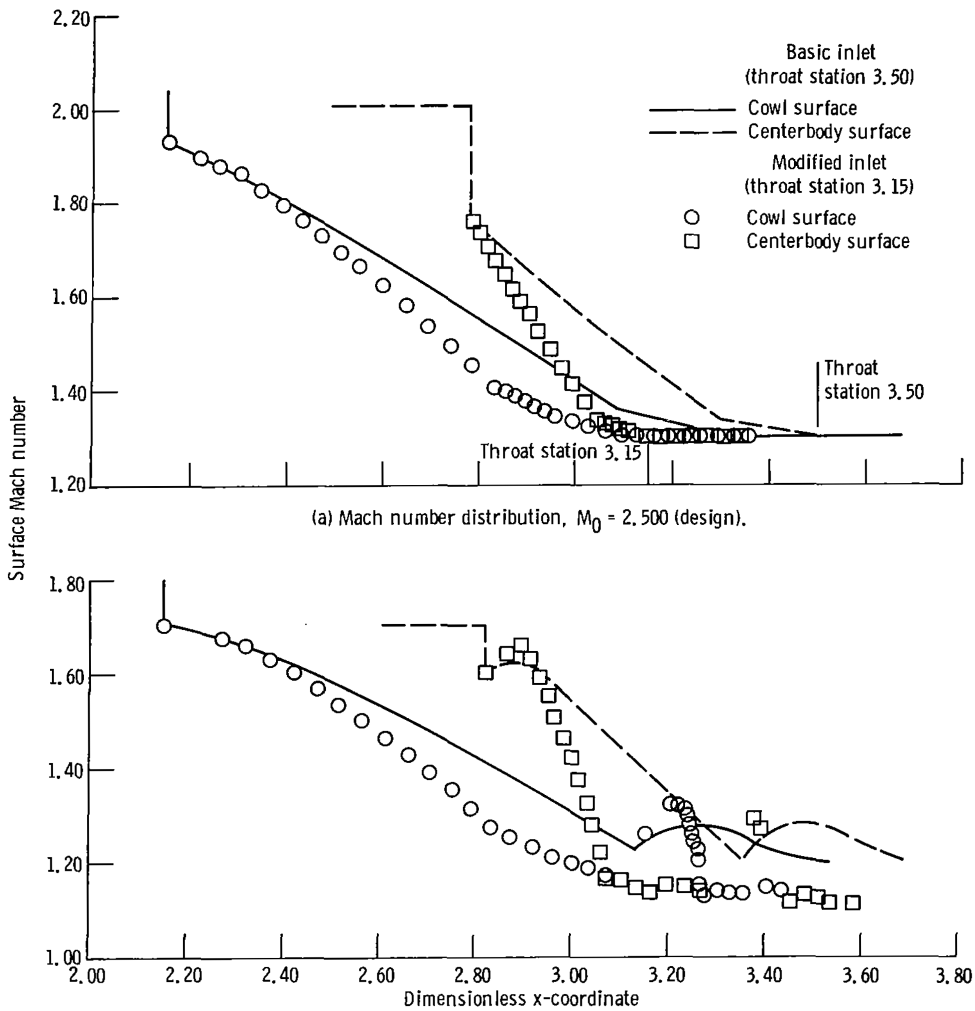
Figure 7. - Concluded.



(a) Mach number distribution, $M_0 = 2.500$ (design).

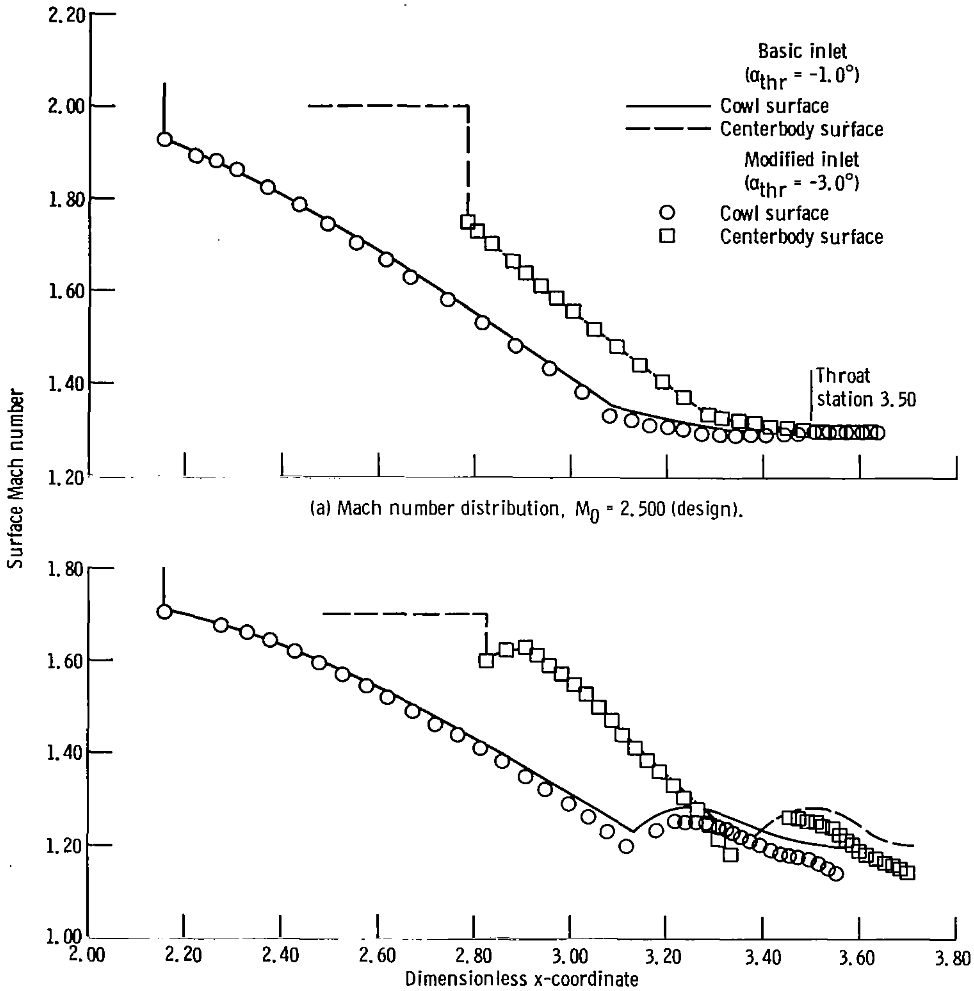
(b) Mach number distribution, $M_0 = 2.000$.

Figure 8. - Effect of decreasing internal compression length from 3.50 to 3.35.



(b) Mach number distribution, M_0 = 2.000.

Figure 9. - Effect of decreasing internal compression length from 3.50 to 3.15.



(a) Mach number distribution, M_0 = 2.500 (design).

(b) Mach number distribution, M_0 = 2.000.

Figure 10. - Effect of decreasing throat flow angle from -1.0° to -3.0°.

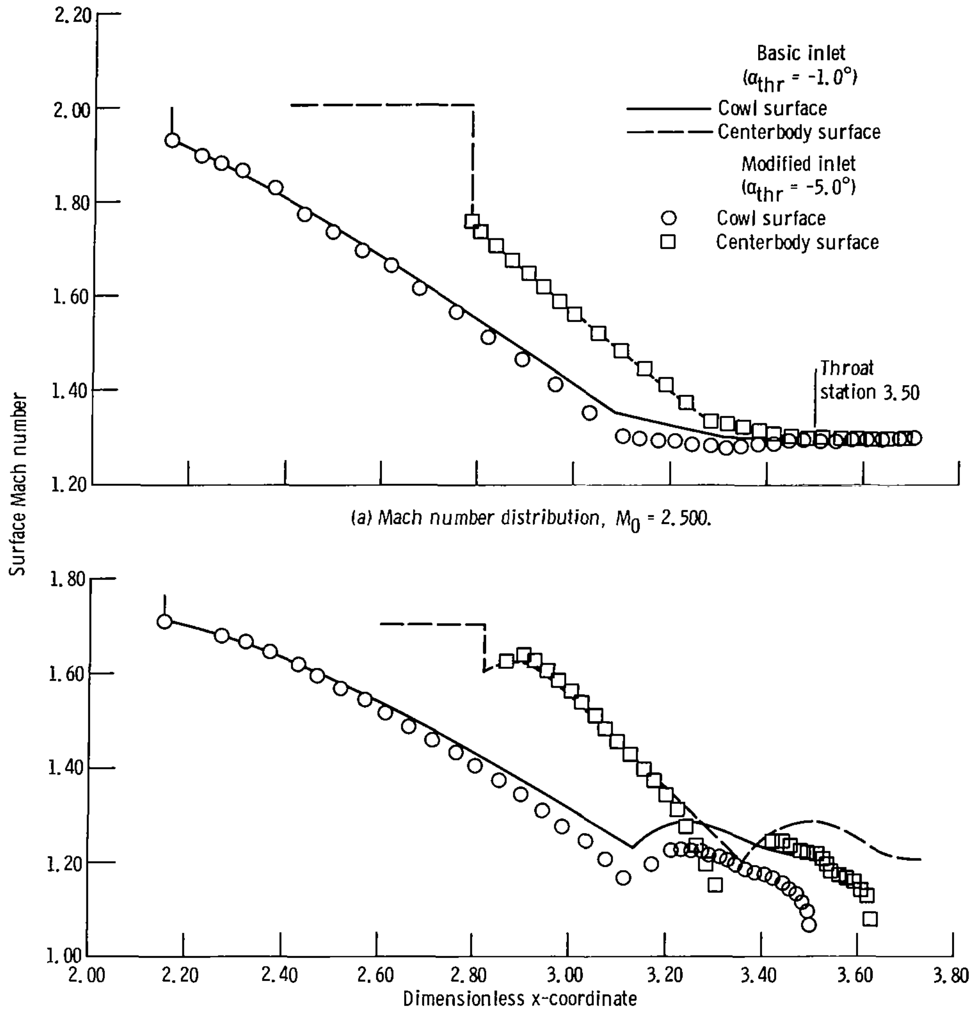
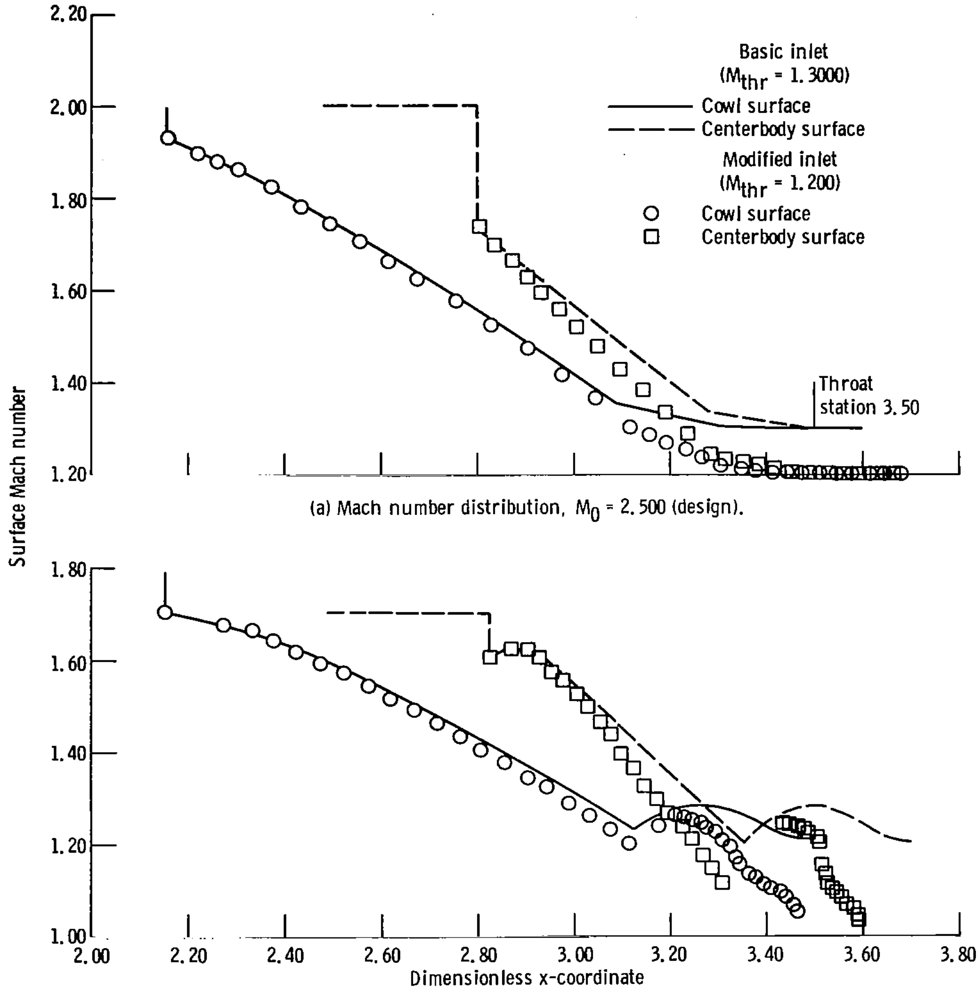


Figure 11. - Effect of decreasing throat flow angle from -1.0° to -5.0°.



(a) Mach number distribution, M_0 = 2.500 (design).

(b) Mach number distribution, M_0 = 2.000.

Figure 12. - Effect of decreasing throat Mach number from 1.300 to 1.200.

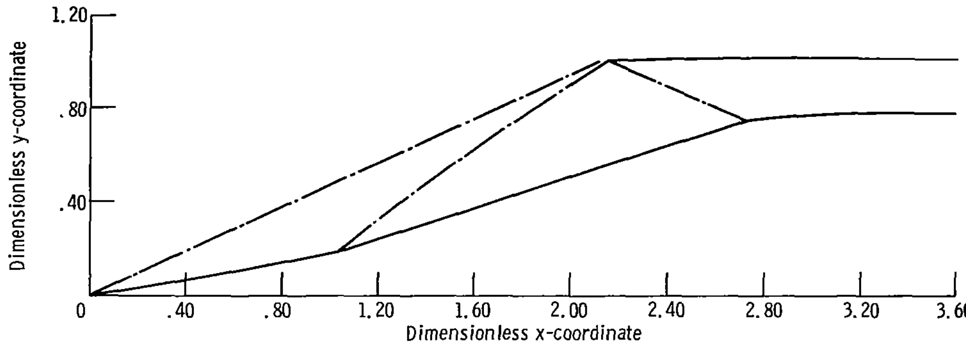
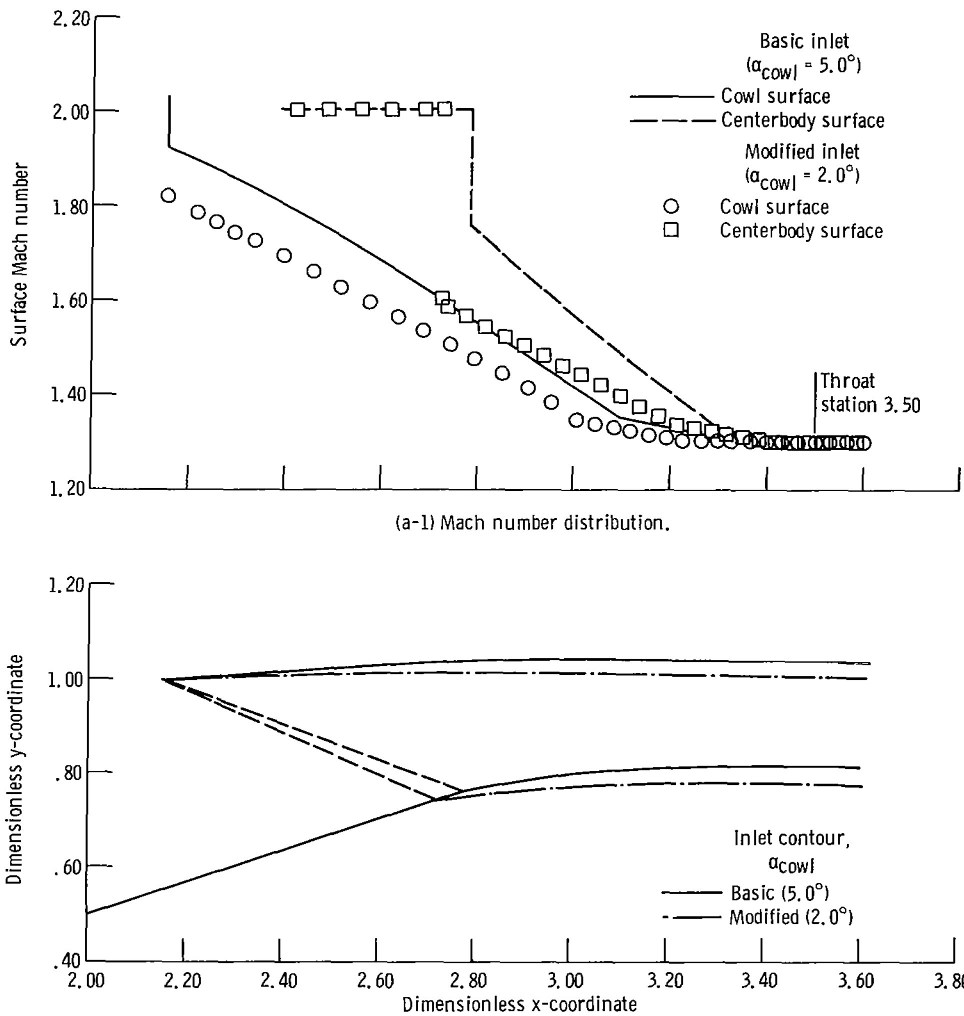


Figure 13. - Bicone inlet (10° to 18.5°) designed for Mach 2.500. Initial cowl angle, 2.0°; design throat Mach number, 1.300; total-pressure recovery, 0.959.

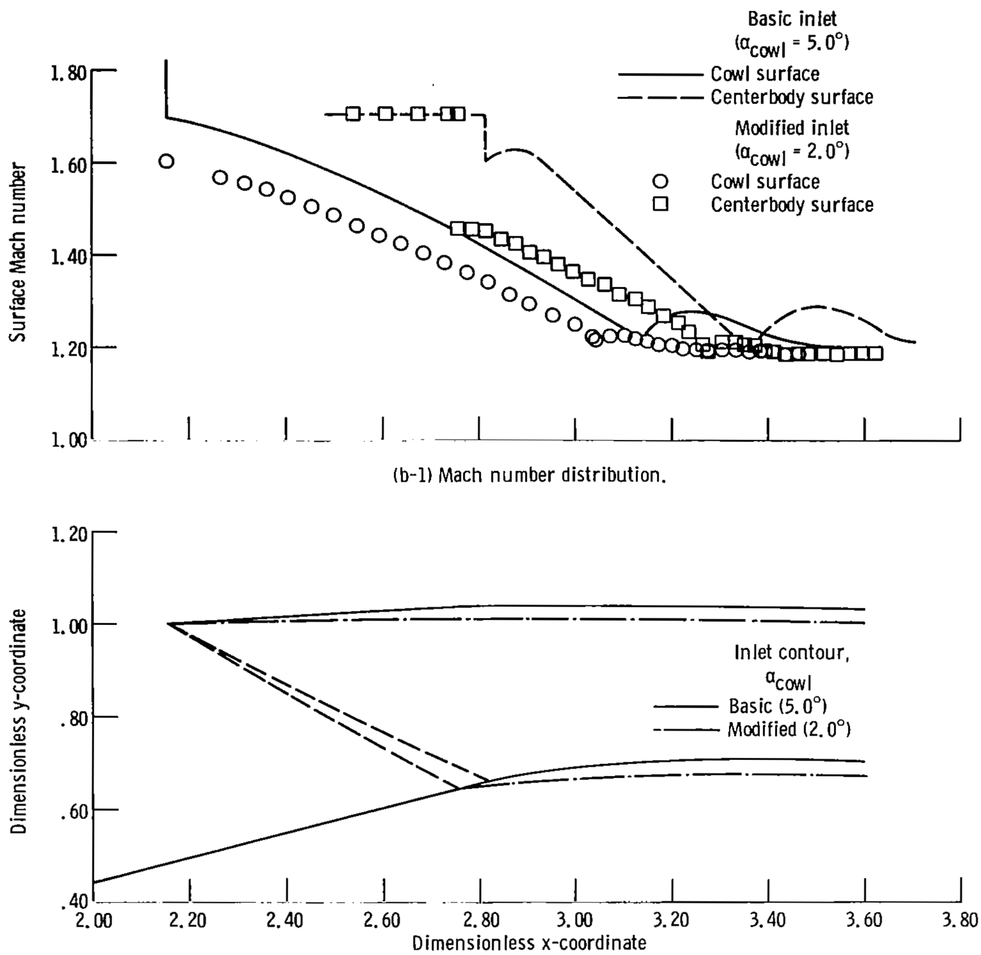


(a-1) Mach number distribution.

(a-2) Inlet contour.

(a) Free-stream Mach number, M_0 = 2.500 (design).

Figure 14. - Effect of reducing initial cowl angle from 5.0° to 2.0°.

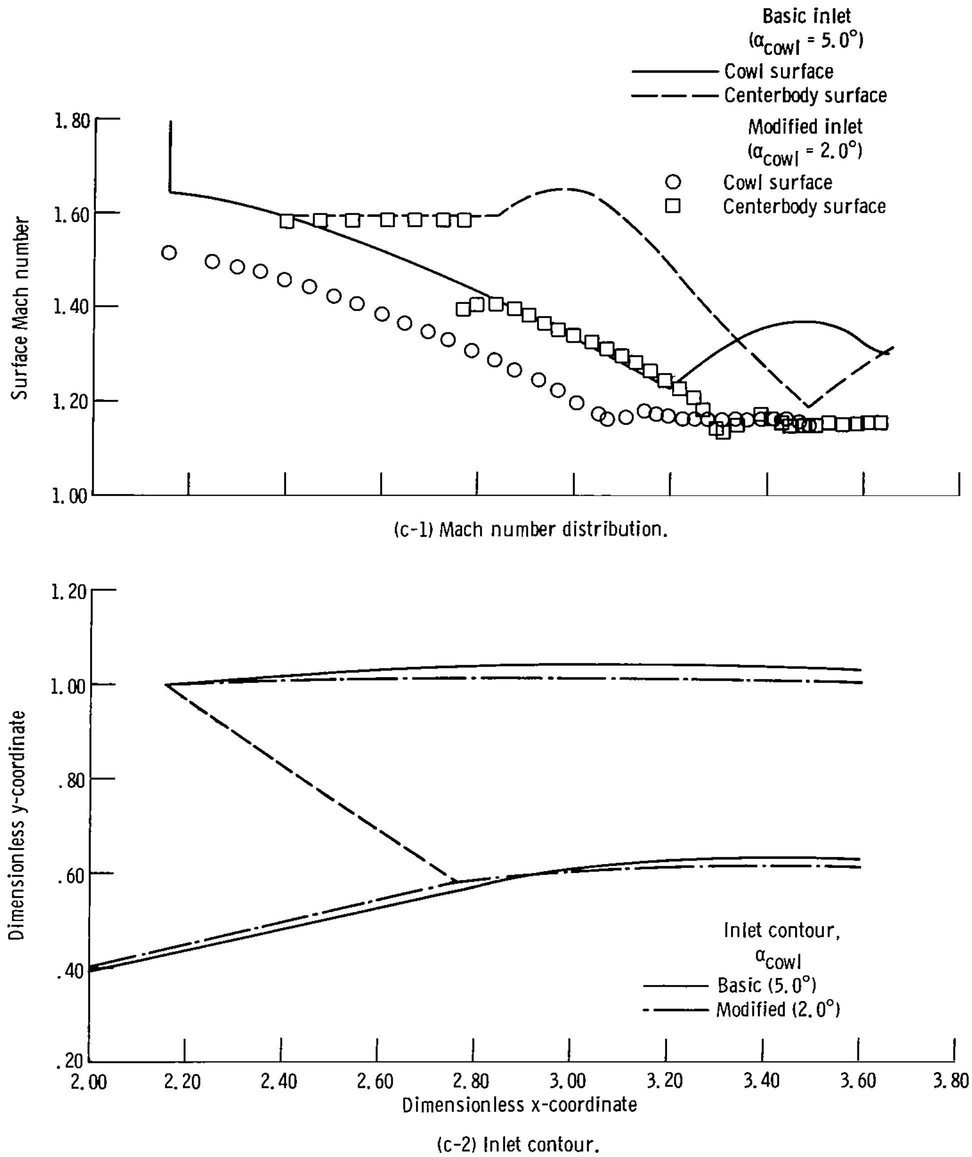


(b-1) Mach number distribution.

(b-2) Inlet contour.

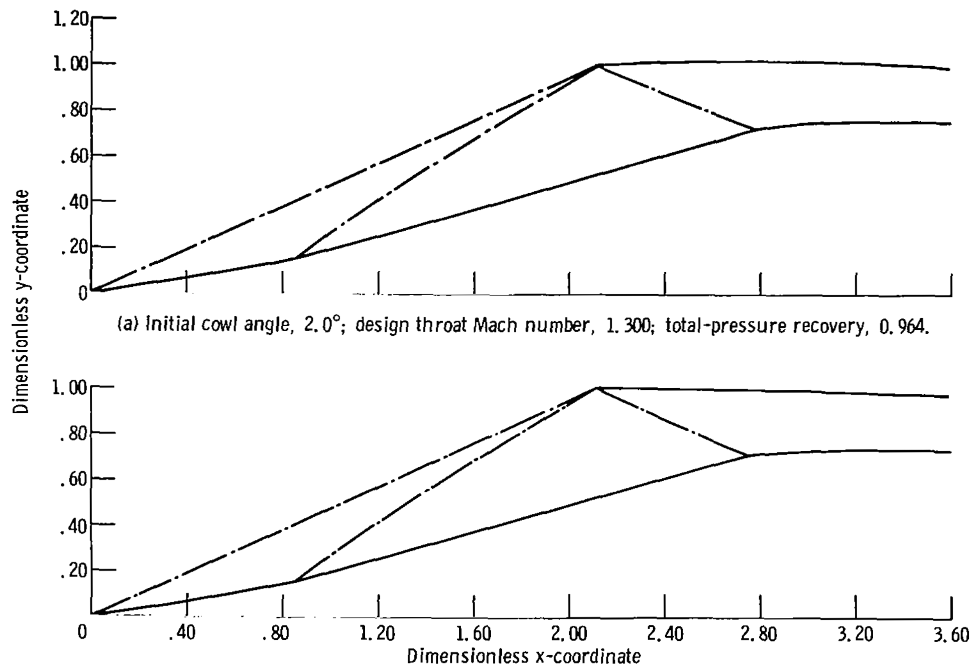
(b) Free-stream Mach number, M_0 = 2.000.

Figure 14. - Continued.



(c) Free-stream Mach number, M_0 = 1.800.

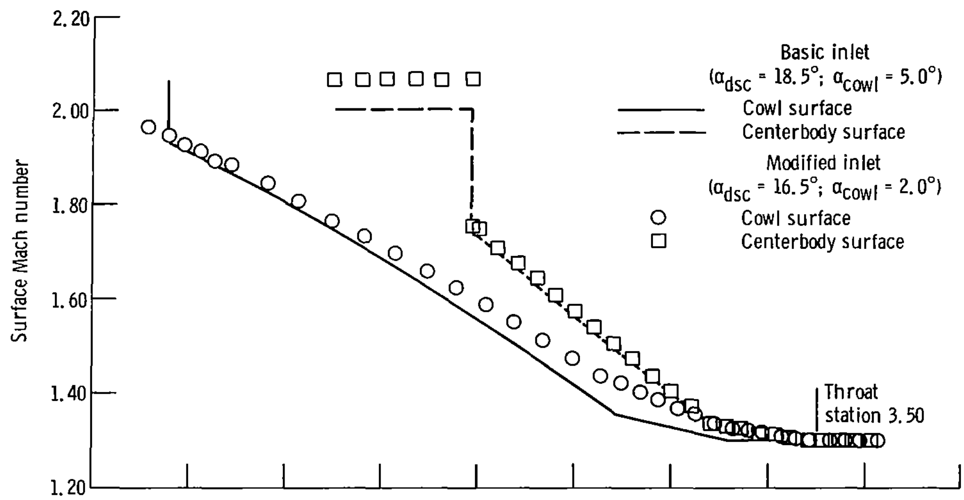
Figure 14. - Concluded.



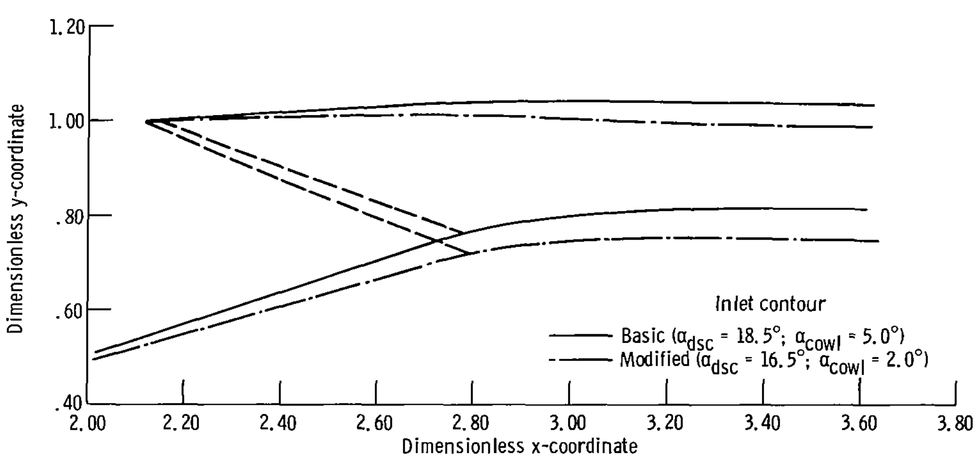
(a) Initial cowl angle, 2.0°; design throat Mach number, 1.300; total-pressure recovery, 0.964.

(b) Initial cowl angle, 0°; design throat Mach number, 1.300; total-pressure recovery, 0.962.

Figure 15. - Bicone inlet (10° to 16.5°) designed for Mach 2.500.



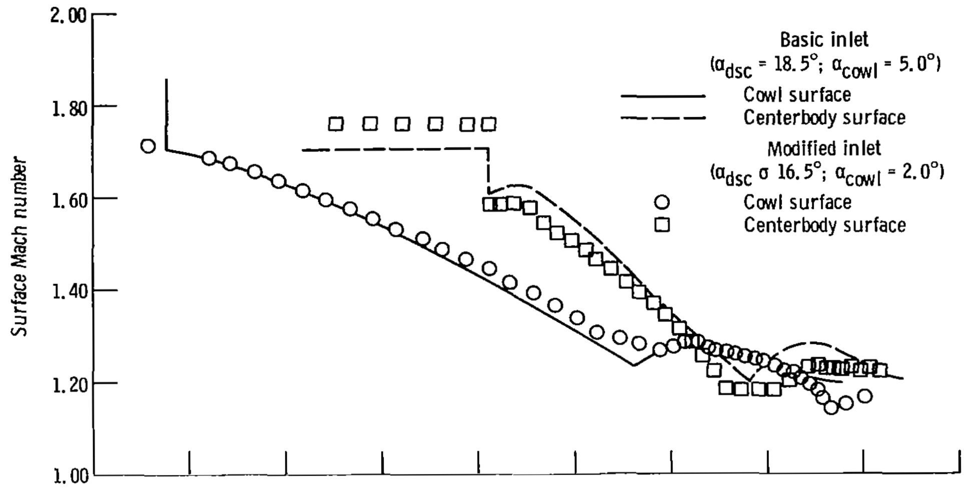
(a-1) Mach number distribution.



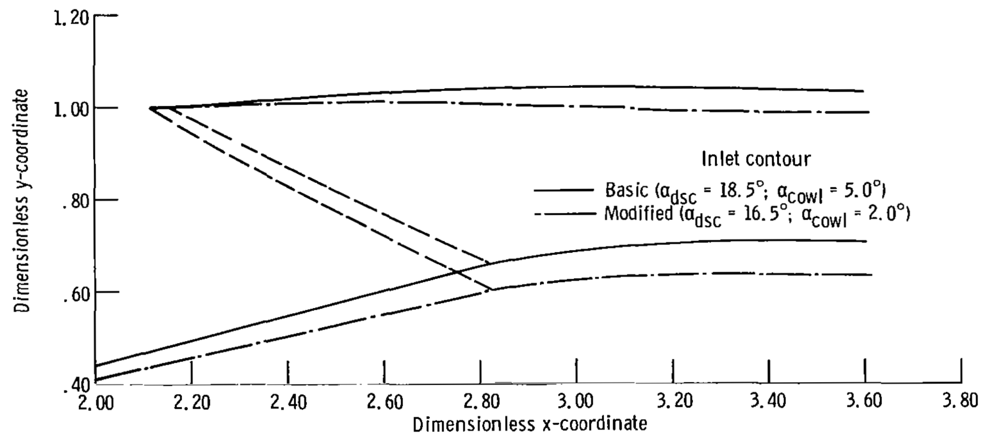
(a-2) Inlet contour.

(a) Free-stream Mach number, M_0 = 2.500 (design).

Figure 16. - Effect of reducing design second cone angle from 18.5° to 16.5° and initial cowl angle from 5.0° to 2.0°.



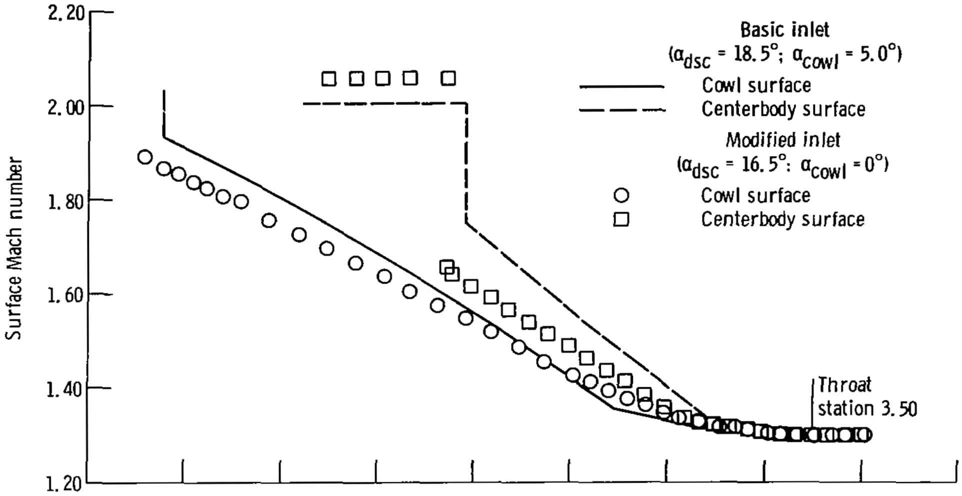
(b-1) Mach number distribution.



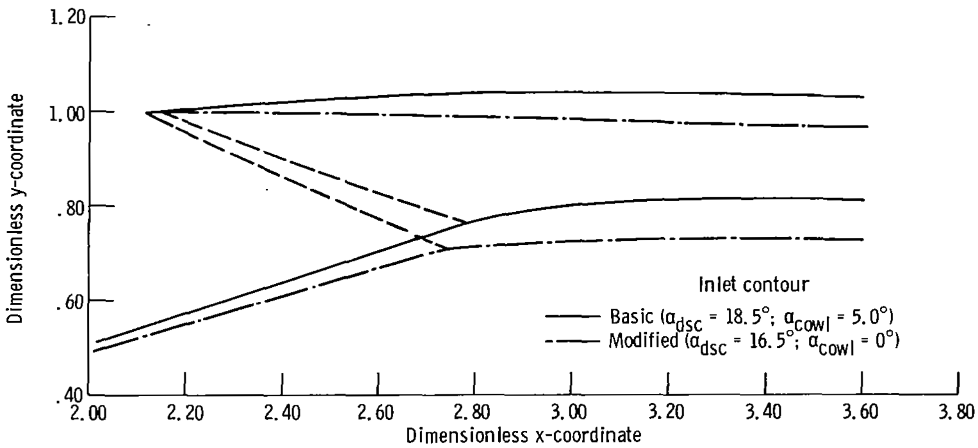
(b-2) Inlet contour.

(b) Free-stream Mach number, $M_0 = 2.000$.

Figure 16. - Concluded.



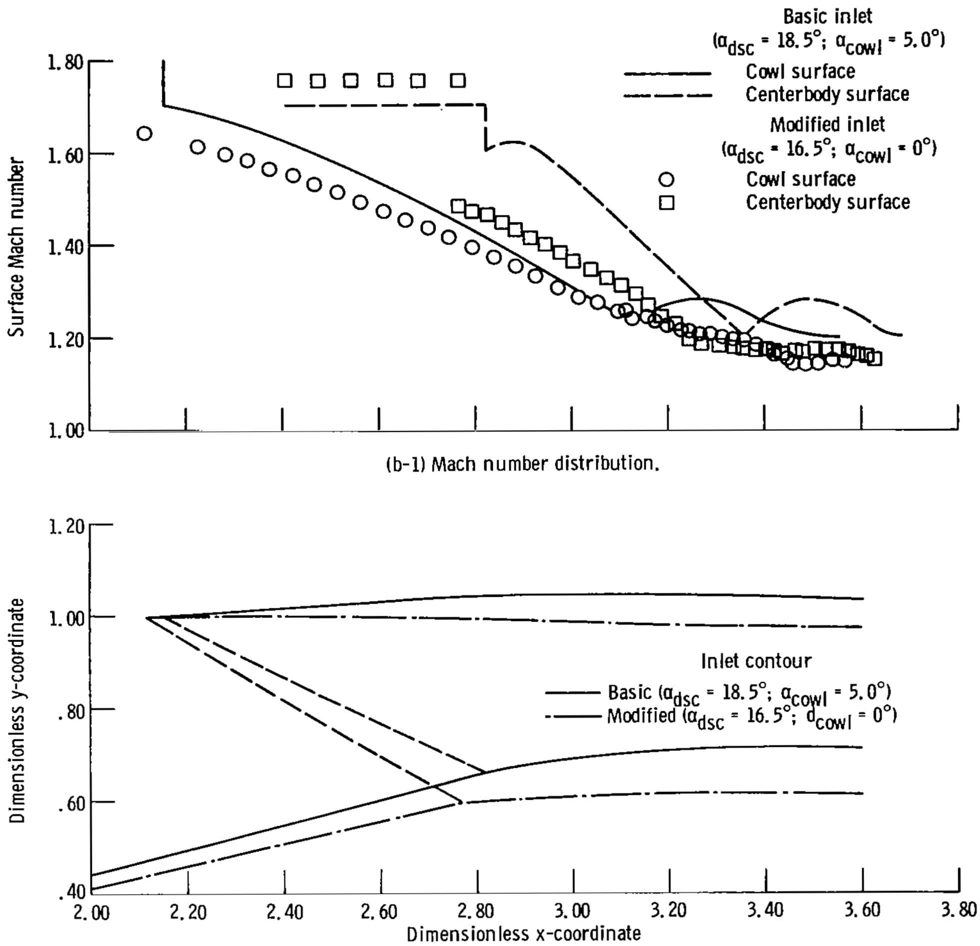
(a-1) Mach number distribution.



(a-2) Inlet contour.

(a) Free-stream Mach number, M_0 = 2.500 (design).

Figure 17. - Effect of reducing design second cone angle from 18.5° to 16.5° and initial cowl anlge from 5.0° to 0°.



(b-1) Mach number distribution.

(b-2) Inlet contour.

(b) Free-stream Mach number, M_0 = 2.000.

Figure 17. - Concluded.