NACA

RESEARCH MEMORANDUM

AN ANALYTICAL STUDY OF THE COMPARATIVE PERFORMANCE OF FOUR AIR-INDUCTION SYSTEMS FOR TURBOJET-POWERED AIRPLANES DESIGNED TO OPERATE AT MACH NUMBERS UP TO 1.5

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A study was made to ascertain some of the operational characteristics of four types of air-induction systems for a turbojet-powered airplane intended to operate at Mach numbers from 0.85 to 1.50 at an altitude of 35,332 feet (the lower limit of the stratosphere for standard conditions). Air-induction systems with and without ramps to produce oblique shock waves, with fixed and variable inlet areas, and with divergent diffusers were investigated. The analyses were made on the basis of two-dimensional flow and an angle of attack of 0°. Neither the effects of boundary layer nor the effects accompanying the application of the systems to a three-dimensional body were considered.

For the systems with fixed inlet areas, excess air during supersonic operation was generally assumed to be bypassed internally and exhausted rearward to free-stream static pressure, rather than spilled around the inlet; for the systems with variable inlet areas, an inlet-area variation was calculated which would accommodate the varying air requirements of the assumed engine for as much of the Mach number range as possible.

The four systems were compared on the basis of three drag, or thrust-loss, components. These were the additive drag, the thrust reduction resulting from the total-pressure loss at the entrance to the engine compressor, and the drag resulting from energy losses accompanying the air-bypass process. Since a minimum additive drag was assumed, the most important component was the thrust reduction resulting from total-pressure losses. The differences between the drag forces for the systems resulting from the other two components were small except for the case of the fixed-inlet-area, ramp-type system for Mach numbers approaching 1.31.

In this Mach number range the additive-drag forces attained a magnitude that could cause an important reduction in performance of this system compared with the other three.

For Mach numbers from 1.05 to about 1.37, the systems without ramps had the lowest drag while, for Mach numbers greater than 1.37, the drag of the systems with ramps was lowest. In both cases, the drag of the fixed-inlet-area system was only slightly greater than that of the corresponding variable-inlet-area system.

The air-induction system with a fixed inlet area and no ramp was further analyzed for Mach numbers from 0 to 1.50 and altitudes from sea level to 60,000 feet. The maximum percentage of excess air entering the inlet was shown to increase from about 6 percent for altitudes from 35,332 to 60,000 feet to over 19 percent at sea level. It was also shown that the air-bypass drag force throughout the altitude range at a Mach number of 1.50 would be only 12 to 15 percent of the additive drag that would result if the excess air were spilled around the inlet.

INTRODUCTION

A study of the problems encountered in the design of propulsion systems for turbojet-powered airplanes for the supersonic Mach number range through which turbojet engines are practical has shown that one of the most important problems concerns the matching of an air-induction system with a specific engine. It has been found that, in general, the weight of air that can be supplied by an air-induction system with a fixed-inlet area operating at its optimum efficiency (based on total-pressure recovery and additional considerations of drag characteristics) will not match the corresponding requirements of a turbojet engine over a range of supersonic Mach numbers except at unique points. In the present report, a study is made of the operation of air-induction systems in combination with an assumed turbojet engine for an airplane intended to cruise at a Mach number of 0.85 and having a high speed corresponding to a Mach number of 1.50 at an altitude of 35,332 feet (the lower limit of the stratosphere for standard conditions).

Three methods can be used in designing an air-induction system to operate at supersonic speeds. In the first method, a system with a variable-inlet area can be designed to supply the required weight of air to the engine at all times. In the second, the maximum inlet area required for a variable-area system can be used for a fixed-inlet-area system and internal air bypass can be utilized to remove excess air entering the inlet during off-design operation. The third method is similar to the second except that excess air would be spilled around the inlet, externally, rather than bypassed internally. By utilizing one of the first two methods, optimum flow characteristics for the engine and for the inlet to the air-induction system can be maintained over an extensive supersonic Mach number range. Utilization of the third method, because of the adverse effects accompanying spillage of the excess air around the inlet, causes the flow characteristics to be matched with less than optimum efficiency of operation for the air-induction system.

In the present investigation the first two methods are considered in detail, while the third is considered only to the extent of comparing the additive drag that would result if excess air were spilled around the inlet with the air-bypass drag calculated for a fixed-inlet-area system. The two design methods are exemplified in four air-induction systems with scoop-type inlets which are discussed and are compared on the basis of their drag (or thrust-loss) characteristics.

The four air-induction systems are representative of those which might be used at supersonic speeds. Calculations are made to ascertain the inlet-area variation necessary to insure matching with optimum operation for two types of variable-inlet-area systems in combination with an assumed turbojet engine. The two types of systems, one with and one without a ramp ahead of the inlet, were selected to permit a comparison of their thrust-loss characteristics resulting from total-pressure losses. For corresponding fixed-inlet-area systems, the drag penalty incurred in bypassing excess air is ascertained and, for all four systems, additional calculations are made of additive and scoop-incremental drag.

The calculations are made for an angle of attack of 0° utilizing two-dimensional-flow theory; therefore, the investigation is not intended to give design criteria for supersonic air-induction systems. It is intended, rather, to provide a comparison of some of the geometric and operational characteristics of such systems to serve as a guide for the selection of a type of air-induction system for future installations. The design of boundary-layer removal systems, variable geometry mechanisms, diffusers, and excess-air-bypass systems is beyond the scope of this report.

NOTATION

The following notation is used in the present report:

A area, square feet

A_a area over which additive-drag force acts $(A_c - A_o)$ (See fig. 1(a).)

A_c capture area of inlet (See fig. 1(a).)

A_r reference area for drag factors (assumed to be 1 square foot)

a speed of sound, feet per second

C_D drag coefficient $\left(\frac{D}{q_o S}\right)$

C_p static-pressure coefficient $\left(\frac{p-p_o}{q_o}\right)$

c_p specific heat at constant pressure, Btu per pound

c_v specific heat at constant volume, Btu per pound

D drag, pounds

F_n net thrust of engine, pounds

$F_{n_{100}}$ net thrust of engine for total-pressure recovery, $\frac{H_3}{H_o}$ of 1.00

g acceleration of gravity, feet per second per second

H total pressure, pounds per square foot

J mechanical equivalent of heat, 778 foot-pounds per Btu

K_D drag factor $\left(\frac{D}{q_o A_r}\right)$

ΣK_D $K_{D_a} + K_{D_H} + K_{D_W}$

K_{D_a} additive-drag factor

K_{D_H} drag factor corresponding to thrust loss resulting from total-pressure loss at the entrance to the engine compressor

K_{D_S} scoop-incremental-drag factor

K_{D_W} drag factor corresponding to thrust loss accompanying air-bypass process

M Mach number $\left(\frac{V}{a}\right)$

m mass-flow rate, slugs per second

m_o mass-flow rate through the entrance area in the free stream $(\rho_o V_o A_1)$

m_o'	mass-flow rate through the capture area in the free stream $(\rho_o V_o A_c)$
m_1	mass-flow rate through the entrance area $(\rho_1 V_1 A_1)$
N	engine speed, percent rated revolutions per minute
p	static pressure, pounds per square foot
q	dynamic pressure, pounds per square foot
S	wing area, square feet
T	total temperature, degrees Rankine
t	static temperature, degrees Rankine
V	velocity, feet per second
V_j	theoretical jet-exit velocity of bypassed air, feet per second
W	weight rate of air flow, pounds per second
ΔW	excess weight rate of air flow, pounds per second
Δw	excess weight rate of air flow expressed as percentage of actual weight rate of air flow
γ	ratio of specific heats $\left(\frac{c_p}{c_v}\right)$
δ	ramp angle, degrees (See fig. 1(a).)
δ'	pressure correction for weight rate of air flow required by the engine $\left(\frac{H_s}{p_{sl}}\right)$
η	velocity coefficient of air-bypass exhaust nozzle
θ	oblique shock angle, degrees (See fig. 1(a).)
θ'	temperature correction for weight rate of air flow required by engine $\left(\frac{T_s}{T_{sl}}\right)$
ρ	mass density of air, slugs per cubic foot

Subscripts

o free stream

1 station of inlet plane

s station of compressor entrance

sl standard conditions at sea level

DESCRIPTION OF INLETS

The nomenclature used in the investigation is shown in figure 1(a) for an air-induction system (or inlet, as it will generally be referred to in subsequent sections of this report) with a ramp to produce an oblique shock wave. The four inlets the characteristics of which are analyzed are shown in figure 1(b) along with a basic description of each inlet.

Inlet A, a fixed-inlet-area type, has a ramp angle of 7° and is so designed that at a free-stream Mach number of 1.50 the oblique shock wave from the ramp touches the lip of the inlet. The ramp angle was selected on the basis of a preliminary analysis of the total-pressure ratio across the shock waves induced by a ramp (i.e., an oblique shock wave followed by a normal shock wave or, for the lower supersonic Mach numbers, a normal shock wave alone). The total-pressure ratios across the shock waves with the ramp angle selected are near the maximum ratios possible for free-stream Mach numbers near 1.50.

Inlet B has a variable-angle ramp by which the inlet area is changed. Inlets C and D have no ramps to produce oblique shock waves. Inlet C has a fixed area, while the lip of inlet D is pivoted to permit area variation.

ASSUMPTIONS AND ANALYSES OF GEOMETRIC CHARACTERISTICS

The performance analyses for the inlets were based on two-dimensional-flow theory utilizing the charts and tables of reference 1 in conjunction with the assumed shock-wave patterns shown in figure 2. Abrupt transition from one shock pattern to another was assumed. As a result, abrupt discontinuities occur in the variations of characteristics calculated for the inlets. For the inlets with ramps to produce oblique shock waves (inlets A and B), a normal shock wave was assumed to occur for Mach numbers below that at which an oblique shock wave would detach from the ramp. In all cases for which supersonic flow could enter the inlets, operation with the maximum pressure recovery possible through the subsequent normal shock was insured by assuming that the shock occurred just inside the inlet at a Mach number equal to that at the entrance. Lower pressure recoveries would result if the shock were assumed to occur at some higher Mach number in the diverging portion of the diffuser. Three-dimensional effects that are encountered with actual installations similar to those discussed were not considered. No forebody effects were considered; free-stream conditions were assumed to exist immediately ahead of the ramps or inlets. In addition, the variations of pressure drag on the external surfaces of the inlets were not considered.

The engine characteristics used in the analyses were calculated for a turbojet engine having a static thrust of 4250 pounds at sea level without afterburning. The variation of corrected weight rate of air flow with corrected engine speed shown in figure 3(a) was calculated utilizing the methods developed in references 2 and 3. The variation of net thrust with free-stream Mach number for various total-pressure ratios (fig. 3(b)) was calculated for the engine with afterburning using the methods of references 2, 4, and 5. For the present analysis, the engine was considered to be operating at its rated speed at all times (N = 100).

For the ramp-type inlets (inlets A and B), the curve of total-pressure recovery versus free-stream Mach number shown in figure 4 was assumed. The total-pressure ratio H_3/H_0 was 0.95 for Mach numbers from 0.85 to 1.00 and was about 92 percent of the ratio across the shock waves for inlet A at a Mach number of 1.50. The total-pressure-ratio variation for the inlets without ramps (inlets C and D), also shown in figure 4, was assumed to be the same as that for the ramp-type inlets through the Mach number range for which a shock wave would be detached from the 7° ramp of inlet A (M_0, 1.00 to 1.31). For Mach numbers greater than 1.31, the total-pressure ratio for inlets C and D was assumed to be 95 percent of the total-pressure ratio across a normal shock wave occurring at the free-stream Mach number.

The limiting Mach number for the investigation was selected, primarily, because the total-pressure ratios for inlets C and D were nearly as high as the ratios for inlets A and B for a free-stream Mach number of 1.50. For higher Mach numbers, the total-pressure ratios for inlets C and D decrease rapidly and the resulting decrease in net thrust would be so great as to preclude their use.

For the inlets with air-bypass systems, the excess air was assumed to be exhausted to free-stream static pressure through a nozzle with a velocity coefficient of 0.97.

Maximum Required Entrance Area

The entrance area for the fixed-area inlets (inlets A and C), which was equal to the maximum entrance area for the variable-area inlets (inlets B and D), was calculated for the lower design Mach number 0.85 and a mass-flow ratio of 1.00 for the design altitude, 35,332 feet. The reason for this was that preliminary calculations showed that the area required to supply the weight of air needed by the engine with the assumed variations of total-pressure recovery decreased with increasing Mach number. Therefore, a maximum area based on the air requirement for a design Mach number greater than 0.85 would admit insufficient air for Mach numbers below the design value and operation with the assumed conditions could not be realized.

The maximum entrance area was calculated using the equation

$$A_1 = \frac{W}{\rho_o a_o M_o g} \frac{1}{m_1/m_o} \quad . \tag{1}$$

for which the mass-flow ratio m_1/m_o was assumed to be 1.00, and the weight rate of air flow W was calculated from the basic engine curve (fig. 3(a)) using a total-pressure ratio of 0.95. The maximum entrance area was found to be 1.480 square feet.

Characteristics of the Inlets as Affected by Inlet Geometry

<u>Mass-flow ratio (fig. 5)</u>.- The mass-flow-ratio variations for the inlets were calculated using the equation

$$\left.\begin{aligned} \frac{m_1}{m_o} &= \frac{\rho_1 A_1 V_1}{\rho_o A_1 V_o} \\ \text{or} \qquad \frac{m_1}{m_o} &= \frac{\rho_1 a_1 M_1}{\rho_o a_o M_o} \end{aligned}\right\} \tag{2}$$

Another expression, equivalent to equation (2), is

$$\frac{m_1}{m_o} = \frac{A_o}{A_1} \tag{2a}$$

for which the free-stream area of the stream tube entering the inlets A_o can be calculated using the flow characteristics of the engine (fig. 3(a)) and the assumed variation of total-pressure ratio (fig. 4).

The mass-flow ratios were assumed to be 1.00 for free-stream Mach numbers from 0.85 to 1.00, the subsonic design range. For Mach numbers from 1.00 up to that at which an oblique shock attached to the ramps of inlets A and B, a normal shock was assumed to be ahead of the ramp; therefore, the mass-flow ratio remained 1.00. After the oblique shock attached to the ramps, the mass-flow ratios increased with increasing Mach number to 1.119 for inlet A and 1.132 for inlet B for a free-stream Mach number of 1.50. (The mass-flow ratio and also the entrance area for inlet B depend on the ramp angle; therefore, the variations of these characteristics for inlet B have to be determined simultaneously.) For inlets C and D, the mass-flow ratio remained 1.00 throughout the Mach number range.

An alternative manner of defining the mass-flow ratio is to base it on the capture area of the inlet A_c. (See fig. 1.) The equation for this mass-flow ratio, paralleling equation (2a), is

$$\frac{m_1}{m_o{}'} = \frac{A_o}{A_c} \tag{3}$$

An advantage of this method is that the maximum value attainable with supersonic flow is 1.00 and curves of capture-area mass-flow ratio show, effectively, what proportion of the maximum mass-flow ratio is attained for a given set of conditions. Curves of capture-area mass-flow ratio are presented in figure 5(b) for each of the inlets.

Entrance area (fig. 6).- The entrance area for inlets A and C was 1.480 square feet. For inlet D, the entrance area was 1.480 square feet for a free-stream Mach number of 0.85, but varied with increasing Mach number in such a manner that the air requirement of the engine was always satisfied. The same was true for inlet B except for the small range of Mach numbers from 1.19 to 1.27 for which the required combination of flow conditions and geometry could not be obtained. This discrepancy will be discussed at length in a succeeding section of the report. The areas were calculated using equation (1). The area variation of inlet B was accomplished by varying the ramp angle δ (figs. 1(a) and 1(b)), the minimum area being about 1.282 square feet for a Mach number of 1.50. The area of inlet D was reduced by reducing the inlet height (fig. 1(b)), the minimum area being about 1.390 for a Mach number of 1.17.

Ramp angle (fig. 7).- For inlet A, the ramp angle was 7° as discussed previously and was constant, while inlets C and D had no ramps $\delta = 0^\circ$. For inlet B, the ramp angle increased from 0° for a Mach number of 0.85 to 8° for a Mach number of 1.50 to provide the entrance-area variation discussed above.

DRAG EVALUATION OF THE INLETS

The four inlets were evaluated on the basis of a drag analysis. The factors taken into account were the additive drag, the thrust loss resulting from the total-pressure loss at the engine-compressor inlet, and the energy loss incurred in exhausting excess air. In addition, the scoop-incremental-drag variations for the four inlets were calculated.

Additive- and Scoop-Incremental-Drag Factors

The additive- and scoop-incremental-drag forces were calculated by the method discussed in reference 6 with the flow considered to be two-dimensional.

Additive-drag factor (fig. 8(a)).- The additive-drag factor was calculated using the equation

$$K_{D_a} = \frac{1}{A_r} \int C_p dA_a \tag{4}$$

for which the area A_a was the difference between the capture area of the inlet and the free-stream area of the stream tube entering the inlet as indicated in figure 1(a). The reference area A_r was 1 square foot.

For inlets C and D, there was no additive drag since the conditions at the entrance were the same as in the free stream. For the ramp-type inlets, however, the additive drag was zero for a free-stream Mach number of 1.00, then increased to a maximum for the Mach number for which the oblique shock attached to the ramp. This was primarily the result of the increasing pressure coefficient, since the additive-drag area A_a of inlet A remained constant and that for inlet B changed only slightly. (See equation (4).) After the oblique shock attached to the ramp, the additive-drag factor decreased abruptly, principally because the additive-drag area A_a was decreased. For inlet A, which was so designed that the oblique shock wave intersected the inlet lip for a Mach number of 1.50, the additive-drag area became zero. For inlet B, however, the ramp angle necessary to insure operation with no excess air at a Mach number of 1.50 made it impossible to attain zero additive drag because the resulting oblique shock wave did not intersect the lip.

The relation between additive drag and the capture-area mass-flow ratio, defined by equation (3), can be seen by referring to figure 1(a). The additive-drag area A_a and, therefore, the additive drag, decreases to zero as the capture-area mass-flow ratio increases to 1.00 for supersonic free-stream Mach numbers.

Scoop-incremental-drag factor (fig. 8(b)).- The scoop-incremental-drag factor was calculated using the equation

$$K_{D_s} = \left[C_{p_1} - 2 \frac{m_1}{m_o} \left(\frac{1}{\cos \delta} - \frac{V_1}{V_o} \right) \right] \frac{A_1 \cos \delta}{A_r} \qquad (5)$$

which is based on the total momentum change between stations 0 and 1 in the stream tube entering the inlets. (See fig. 1(a).) Here, again, the reference area A_r has been used as 1 square foot. The scoop-incremental-drag factors were zero for inlets C and D since free-stream and entrance conditions were identical. For the ramp-type inlets, A and B, the scoop incremental drag was negative, as reference 6 reported it should be for this type of inlet. As in the additive-drag-factor curves, sharp discontinuities occurred for the Mach numbers associated with the attachment of the oblique shocks to the ramps because no continuous transition between the shock patterns shown in figure 2 was assumed. The scoop-incremental-drag factor was constant for supersonic Mach numbers below the Mach number for shock attachment. There was an abrupt decrease when the oblique shock attached, and thereafter the scoop-incremental-drag factor decreased continuously with increasing Mach number until the minimum values of -0.050 for inlet A and -0.057 for inlet B were reached for a Mach number of 1.50. This decrease for Mach numbers after shock attachment is associated with the increase in mass-flow ratio for the same Mach number range.

In assessing the effect on the drag of a body caused by the addition of a scoop-type inlet, the criterion which determines whether the scoop incremental drag or the additive drag of the inlet should be used is the definition of the basic body shape. For the case of a scoop-type inlet preceded by a ramp, if the basic body, for which the drag is known, includes the ramp, then the scoop incremental drag of the inlet should be added in calculating the total drag force. On the other hand, if the basic body does not include the ramp, that is, if the ramp and inlet are considered as a unit, then the additive drag of the inlet should be added in calculating the total drag force of the body-inlet combination. For the case of scoop-type inlets without ramps, the scoop-incremental- and additive-drag forces are equal. In the rest of the present investigation, only the additive-drag concept will be considered.

Drag Factor Corresponding to Thrust Loss Resulting From Total-Pressure Loss

The drag factor associated with the total-pressure loss at the engine-compressor inlet, or, in other words, associated with a total-pressure ratio H_s/H_o less than 1.00, was calculated using the equation

$$K_{D_H} = \frac{F_{n_{100}} - F_n}{q_o A_r} \tag{6}$$

The reference area A_r was assumed to be 1 square foot. Net thrusts were calculated utilizing the curve of net thrust versus free-stream Mach number for the assumed engine presented in figure 3(b). Curves of the drag factor K_{D_H} are presented in figure 9.

Drag Factor Corresponding to Energy Loss Incurred in Air-Bypass Process

The drag factor corresponding to the energy loss incurred in expanding excess air to free-stream static pressure through a rearward-facing nozzle was calculated for each of the inlets using the equation

$$K_{D_W} = \frac{\Delta W}{g q_o A_r} (V_o - \eta V_j) \tag{7}$$

in which the reference area A_r was assumed to be 1 square foot and the nozzle velocity coefficient η was assumed to be 0.97 for each of the inlets throughout the Mach number range. The theoretical jet velocity of the bypassed air, expanded from conditions at the entrance to the engine compressor to free-stream static pressure, was calculated using the equation

$$V_j = \sqrt{2gJc_p\, T_s \left\{ 1 - \left[\left(\frac{p_o}{H_o}\right)\left(\frac{H_o}{H_s}\right) \right]^{\frac{\gamma-1}{\gamma}} \right\}} \tag{8}$$

The excess weight of air to be bypassed ΔW was calculated as the difference between the weight of air that could be supplied by the inlet and the weight of air required by the engine.

For the fixed-area inlets, inlets A and C, the weight of air supplied by the inlets was calculated using equation (1) with the mass-flow ratio of figure 5(a) and the entrance area, 1.480 square feet. The excess weight of air was expressed in percent of the weight of air supplied. The variations of percentage of excess air with free-stream Mach number are presented in figure 10. The area variation of inlet D was such that there was no excess weight of air entering the inlet throughout the Mach number range from 0.85 to 1.50. The same was true for inlet B except for Mach numbers from 1.19 to 1.27. In this Mach number range the shock-wave angle θ (fig. 1(a)) was maintained at the maximum value possible for an attached shock wave by the variation of δ shown in figure 7, and the Mach number after the shock wave, which, by the assumptions of the present investigation, was also the entrance Mach number, was such that an excess of air would be supplied. Any attempt to decrease the entrance area by increasing the ramp angle resulted in the shock detaching, and, under the assumptions of the investigation, becoming a normal shock. The subsonic Mach number behind this normal shock was less than was necessary to supply the required air to the engine. On the other hand, decreasing the ramp angle from the value shown by figure 7 for the Mach number range in question would only result in a larger entrance area and a higher entrance Mach number with an increase of excess weight of air over that shown in figure 10. Therefore, the results shown in figure 10 for inlet B were the best possible for a variable area inlet of this type, and the maximum amount of air that would need to be bypassed for the inlet to operate satisfactorily would be about 2.3 percent of the air entering.

For inlets A and C, for the design altitude (35,332 feet), the maximum percentages of excess air entering the inlets, which would have to be bypassed, were, respectively, 12.6 and 6.0. For inlet C calculations were made of the additive-drag penalty that would have to be accepted if the excess air were spilled around the inlet rather than bypassed internally. (The results of this calculation are presented in a subsequent section of this report.) Otherwise, the alternative of spilling the excess air around the inlets was not considered.

The drag factors accompanying the air-bypass process for each of the inlets were calculated using equation (7) and their variations with free-stream Mach number are plotted in figure 11.

Summation of Drag Factors

The comparative drag factor showing, to a limited extent, the relative merit of the four inlets over the design Mach number range was obtained as the summation of the three drag-factor increments calculated:

$$\Sigma K_D = K_{D_a} + K_{D_H} + K_{D_W} \tag{9}$$

The variations of ΣK_D with free-stream Mach number are presented in figure 12.

Study of figures 8(a), 9, 11, and 12 shows that of the three factors affecting the drag considered in the present investigation, by far the most important is total-pressure recovery, while additive drag and air bypass are, in general, of comparatively minor importance. An exception to this conclusion occurs for inlet A for supersonic Mach numbers up to about 1.31 (the Mach number at which an oblique shock attaches to the 7° ramp). In this range the additive-drag factor increases to the extent that the performance of inlet A is impaired compared with the other three inlets.

Additionally, the figures show that for Mach numbers from 1.05 to about 1.37 the inlets without ramps, C and D, have slightly less drag than the ramp-type inlets, primarily because they have essentially the same total-pressure recovery but have no additive drag. In this Mach number range inlet C would be nearly as satisfactory as inlet D, its drag being only about 1.5 percent higher because of air-bypass losses. For Mach numbers above 1.37, up to 1.50, either of the ramp-type inlets, A or B, would have lower drag than would the inlets without ramps because of the difference in total-pressure recovery assumed. In this range inlet B has the lowest drag but inlet A has only about 2.0- to 2.5-percent higher drag, the increase being the result of air-bypass losses and differences in additive drag.

The drag of the inlets (which includes the thrust loss resulting from total-pressure loss at the entrance to the engine compressor) is of sufficient magnitude to have a significant effect on airplane performance. The magnitude of the drag-factor summation, in terms of total airplane drag coefficient, can be calculated in an example which will also illustrate the utility of the drag factors as they are presented in the present report, based on a reference area of 1 square foot. For this example an airplane with a wing area of 300 square feet and a turbojet power plant requiring twice the weight rate of air flow of the engine of the present investigation has been assumed. In other words, the assumed power plant and inlet are the equivalent of two engines and two inlets of the present investigation. The drag factors ΣK_D can be expressed in terms of airplane drag coefficient, based on wing area, by use of the following equation:

$$C_D = \left(\frac{\text{number of equivalent engines}}{S}\right) \Sigma K_D \tag{10}$$

or, for this example,

$$C_D = \frac{2}{300} \Sigma K_D$$

The drag coefficients calculated in this manner for each of the inlets for a free-stream Mach number of 1.50 are shown in the following table:

Inlet	C_D, 2 inlets based on wing area
B	0.0050
A	.0051
D	.0061
C	.0062

The differences between the drag factors for a fixed- and a variable-area inlet for a given type of installation (with or without a ramp), which are a measure of the additive-drag and air-bypass losses, can be seen to be negligible compared to the order of magnitude of the drag factor which is governed by the total-pressure recovery. Obviously, any improvement in pressure recovery in an actual installation over that assumed in the present investigation would be of major importance in reducing the order of magnitude of these drag factors. Similar calculations for Mach numbers below 1.50 show that the drag reduction obtained by the use of a variable-area inlet rather than a fixed-area inlet of the same type is so small as to be nearly negligible throughout the Mach number range of the present study.

Discussion of Factors Which Could Affect Drag Evaluation

The results of the analysis presented depend to a great extent on the assumptions made, and any change in the assumptions would, of course, affect the drag-factor variations calculated. A brief discussion of some of the effects anticipated for conditions other than those assumed is, therefore, necessary to complete the analysis.

The flow was considered to be two-dimensional. The actual existence, in a practical installation, of three-dimensional flow would modify the assumptions of the shock-wave patterns (and, therefore, the mass-flow ratios) shown in figure 2 for the ramp-type inlets, A and B. The shock-wave patterns assumed for the inlets without ramps, inlets C and D, should not be affected. With the possible exception of the effects of differences of inlet aspect ratio which might exist, other three-dimensional effects resulting from the combination of the inlets with bodies would probably affect all the inlets to the same degree, without affecting the differences in ΣK_D between inlets.

As was pointed out previously, deviations of the total-pressure recoveries from those assumed would have an important effect on ΣK_D. Of the four inlets analyzed, however, only the ramp-type inlets, A and B, would be likely to have better pressure recovery in an actual installation than was assumed.

Insofar as off-design operating conditions are concerned, that is, operation with subsonic velocities below a Mach number of 0.85, or operation at altitudes other than 35,332 feet, any extensive evaluation of inlet characteristics would have to be based on the tactical requirements for a given airplane. In general, for a fixed-area inlet, the mass-flow ratio would have to increase with decreasing subsonic Mach numbers if the required weight of air were to be supplied at all times. The maximum percentage of air to be bypassed at supersonic Mach numbers for this type of inlet would increase with decreasing altitude. Above 35,332 feet, as high as 60,000 feet, both the air requirement and supply for a given free-stream Mach number decrease at about the same rate, so that the percentage of air to be bypassed would remain nearly constant. A variable-area inlet to supply the proper weight of air for altitudes from sea level to 35,332 feet and above and for Mach numbers from 0 to 1.50 would have to have a considerably greater range of entrance-area variation than either inlet B or D of the present investigation. For Mach numbers below 0.85 at altitudes of 35,332 feet or greater, the operation of inlets B and D with their maximum entrance areas of 1.480 square feet should be no better than that of the fixed-area inlets with the same entrance area. Inlets B and D would have advantages for altitudes below 35,332 feet since their area variations would be sufficient either to maintain the proper weight rate of air flow, or at least to permit operation with a smaller percentage of excess air than would be the case for the fixed-area inlets, A and C.

DETERMINATION OF OPERATIONAL CHARACTERISTICS OF INLET C FOR FREE-STREAM MACH NUMBERS FROM 0 TO 1.50 FOR ALTITUDES FROM SEA LEVEL TO 60,000 FEET

The analysis of the operational characteristics of inlet C was extended to include flight Mach numbers from 0 to 1.50 at altitudes from sea level to 60,000 feet. For subsonic operation, with the required weight of air entering the inlet at all times, the variations of mass-flow ratio and entrance Mach number with altitude and free-stream Mach number shown by figure 13 were calculated. The total-pressure recovery was assumed to be 0.95 for all subsonic velocities and altitudes. For much of the low-velocity, or high-mass-flow-ratio, range included in figure 13, this assumption of high total-pressure recovery would be quite optimistic because of the detrimental effects of internal separation from the inlet lips. The curves are presented, primarily, to serve as a basis in evaluating or planning subsonic experimental research on the effects of inlet lip shape on inlet performance and, additionally, to aid in the analysis of the efficacy of possible flight plans. The data presented in figure 13 indicate that for operation with Mach numbers from 0 to 0.4, the mass-flow ratio varies from infinity down to about 1.50. For this range of high mass-flow ratios, separation and choking would be likely to occur in the inlet and the attainment of the assumed total-pressure ratio, 0.95, would be doubtful. Therefore, critical design problems of an actual installation for this range would be the extent to which auxiliary air intakes, separation control by suction on the inner surface of the inlet, or similar artifices, would be able to insure adequate performance during take-off.

For the range of Mach numbers from about 0.4 to 0.6, the mass-flow ratios are low enough that separation and choking in the inlet should be less severe and possibly could be alleviated by maintaining flight at relatively low altitudes where the entrance Mach number would not be excessive. Under these conditions the assumption of a total-pressure recovery of 0.95 should prove to be reasonable and inlet design problems for this Mach number range should not be critical. For the subsonic Mach number range above 0.6, the problem of internal separation and choking for the inlet becomes negligible and the efficient operation of the inlet would not be limited to the lower altitudes. In this Mach number range the drag penalty, or, more correctly, the thrust loss attributable to the inlet and methods of reducing it, would appear to be the critical design problem.

For operation at Mach numbers from 0.85 to 1.50, with a constant mass-flow ratio of 1.00, the variations of excess weight of air with free-stream Mach number shown in figure 14 were calculated. For low altitudes, the excess weight of air was quite large (about 13 to 19 percent of the air entering the inlet at sea level) over the Mach number range. However, the percentage of excess weight of air decreased rapidly with increasing altitude up to 35,332 feet, above which there was no change up to 60,000 feet. The significance of these excess weights of air can be realized by calculating and comparing the additive-drag factors that would exist if the excess air were spilled around the inlet (with the normal shock being forced out ahead of the inlet) with the air-bypass drag factors resulting when the excess air is bypassed internally and exhausted to free-stream static pressure. Representative drag factors for both conditions are presented in the following table for a free-stream Mach number of 1.50:

Altitude	Air-bypass drag factor (additive-drag factor zero)	Additive-drag factor with excess air spilled ahead of the inlet
Sea level	0.039	0.32
10,000 feet	.031	.24
20,000 feet	.022	.18
30,000 feet	.014	.10
35,332 feet	.009	.06

These figures indicate that the drag penalty incurred by spilling excess air may be much greater than the penalty incurred in bypassing the excess air in the manner assumed in the present investigation, and that the drag reduction possible with the air-bypass system increases with decreasing altitude. The percentage of air to be bypassed, however, increases with decreasing altitude, as shown in figure 14, and the design of an adequate air-bypass system would become increasingly difficult for the lower altitudes. On the basis of this analysis and the excess weight of air shown in figure 10, it is obvious that the use of inlet A at Mach numbers near 1.50 at altitudes below 35,332 feet would require an air-bypass system of much greater capacity than would the use of inlet C, and, lacking an adequate air-bypass system, greatly increased additive-drag forces could result.

Considering both figures 13 and 14, possible flight plans for an airplane with inlet C can be studied. In general, all flight for Mach numbers up to about 0.5 should be accomplished without exceeding an altitude of 5,000 feet. Acceleration to a Mach number of 0.85 could be accomplished while climbing to the design altitude, 35,332 feet, and subsequent flight through the supersonic range should be at the design altitude or above.

CONCLUSIONS

Based on the assumptions and limitations of the present study, the following conclusions appear to be justified by the drag evaluation of four air-induction systems:

1. The thrust loss accompanying the total-pressure loss is by far the most important of the three drag factors for the Mach number range considered. The additive-drag forces are small in comparison because

excess air was assumed to be bypassed internally rather than spilled around the inlet.

2. The difference between the drag forces for a fixed-inlet-area system with internal air bypass and a similar variable-inlet-area system is so small that a variable-inlet-area system should not be necessary for Mach numbers up to 1.50.

3. The systems without ramps ahead of the inlets had slightly lower drag for Mach numbers from 1.05 to about 1.37. For higher Mach numbers, up to 1.50, the drag of the systems with ramps was lower.

4. The weight of air which must be bypassed by a fixed-inlet-area system and, therefore, the drag penalty incurred in an internal air-bypass system, decreases markedly with increasing altitude up to an altitude of 35,332 feet.

5. The drag forces incurred in bypassing excess air internally in the manner assumed in the present study may be only 12 to 15 percent of the additive-drag forces that would exist if the excess air were spilled around the inlet at a Mach number of 1.50 for altitudes from sea level to 35,332 feet.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., March 14, 1952

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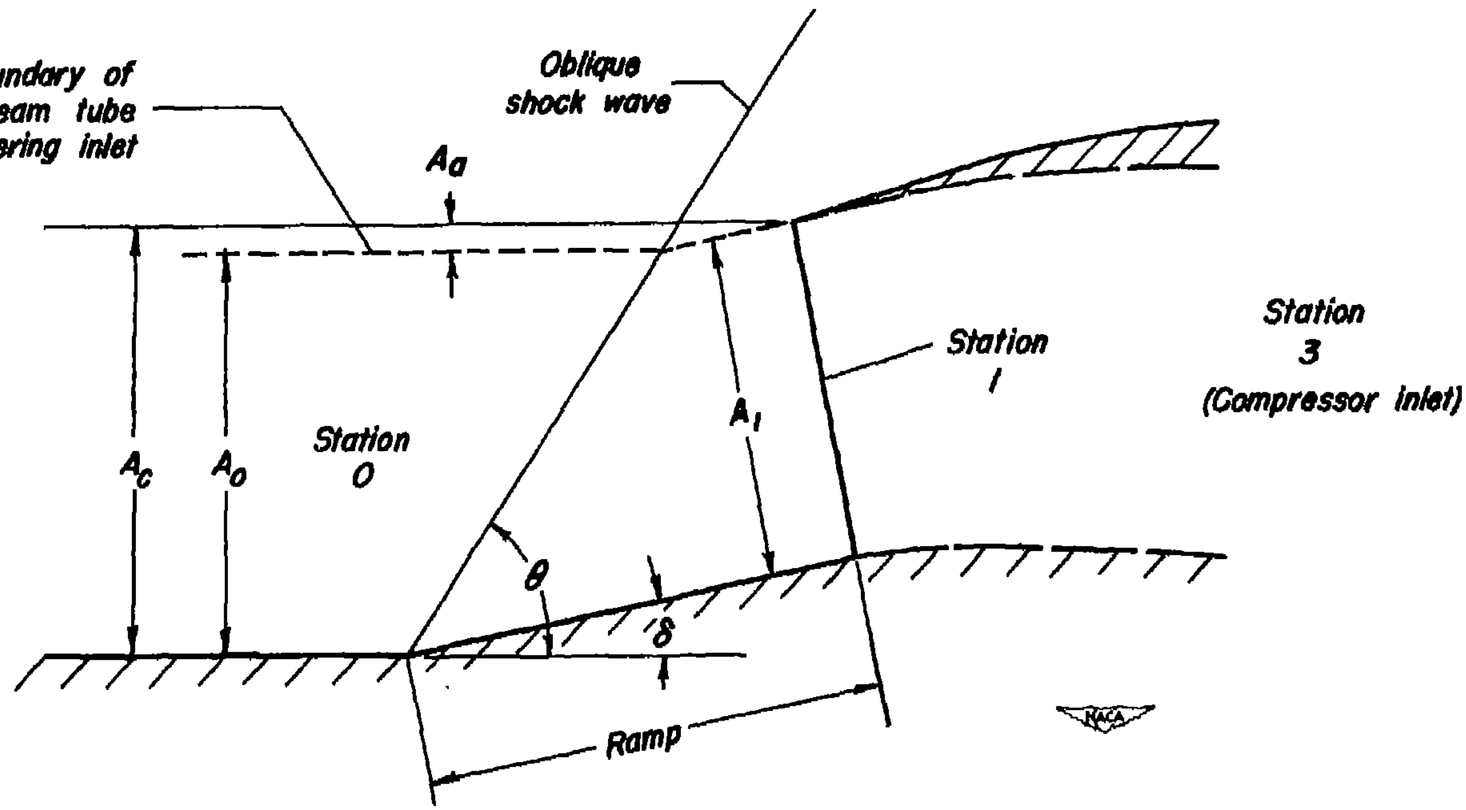
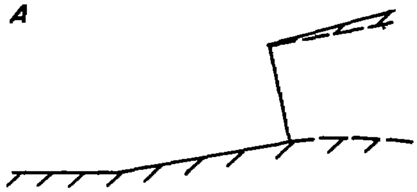
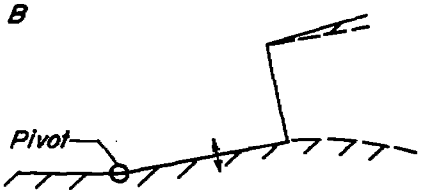
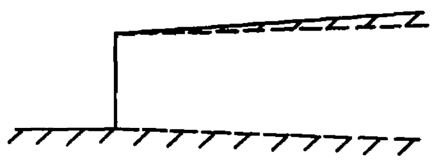
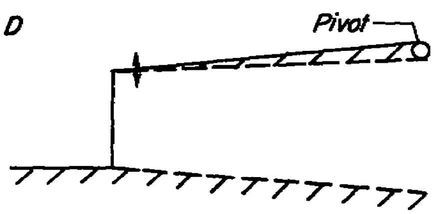


(a) Nomenclature for inlet operating with an oblique shock.

Figure 1.—Nomenclature, diagrammatic representation, and description of the inlets.

Inlets	Description
A 	Ramp angle — Constant, 7 deg Entrance area — Constant, 1.480 sq ft Diffuser — Divergent
B 	Ramp angle — Variable 0–8 deg Entrance area — Variable 1.480–1.282 sq ft Diffuser — Divergent
C 	Ramp angle — Constant, 0 deg Entrance area — Constant, 1.480 sq ft Diffuser — Divergent
D 	Ramp angle — Constant, 0 deg Entrance area — Variable, 1.480–1.416 sq ft Diffuser — Divergent

(b) Inlet designations.

Figure 1.—Concluded.

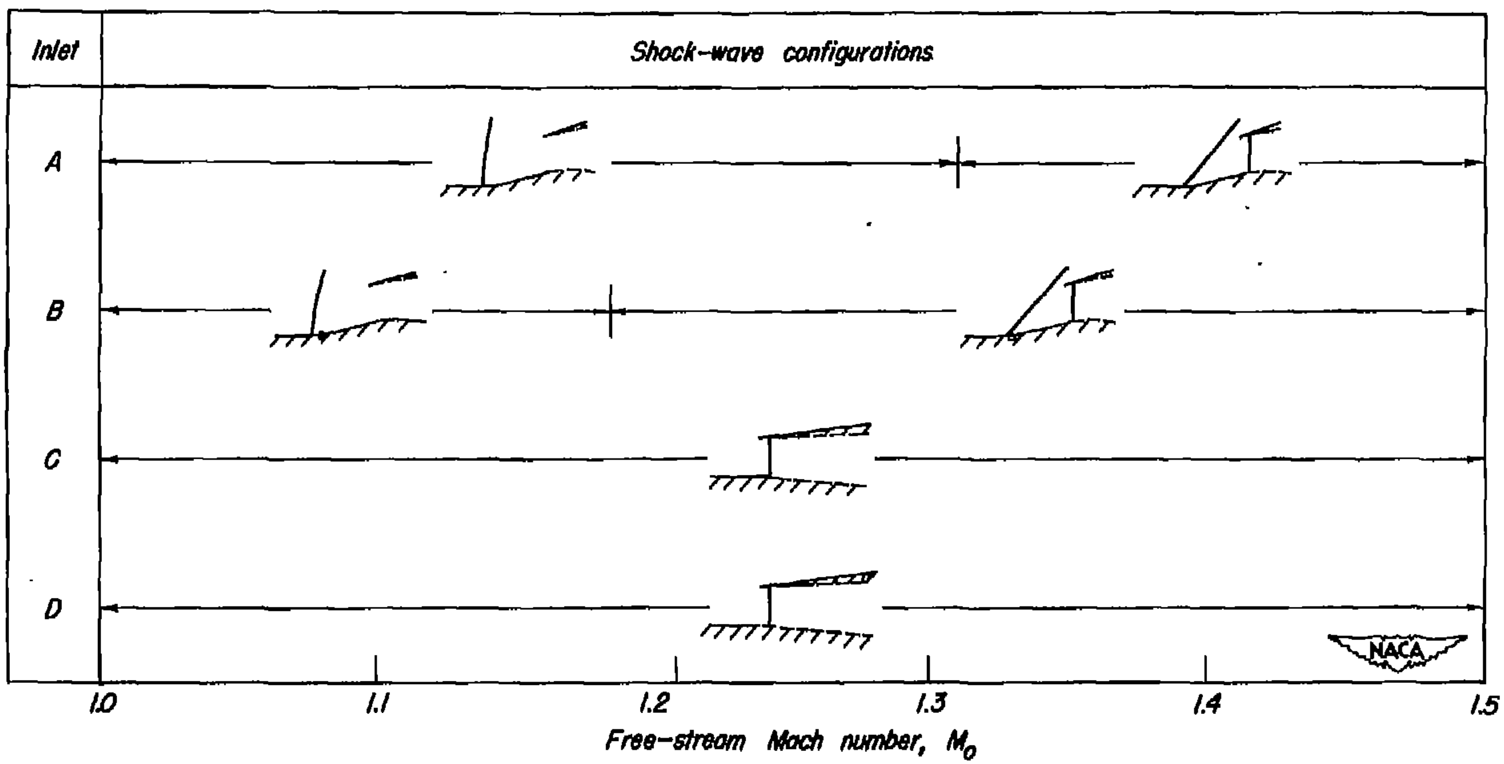
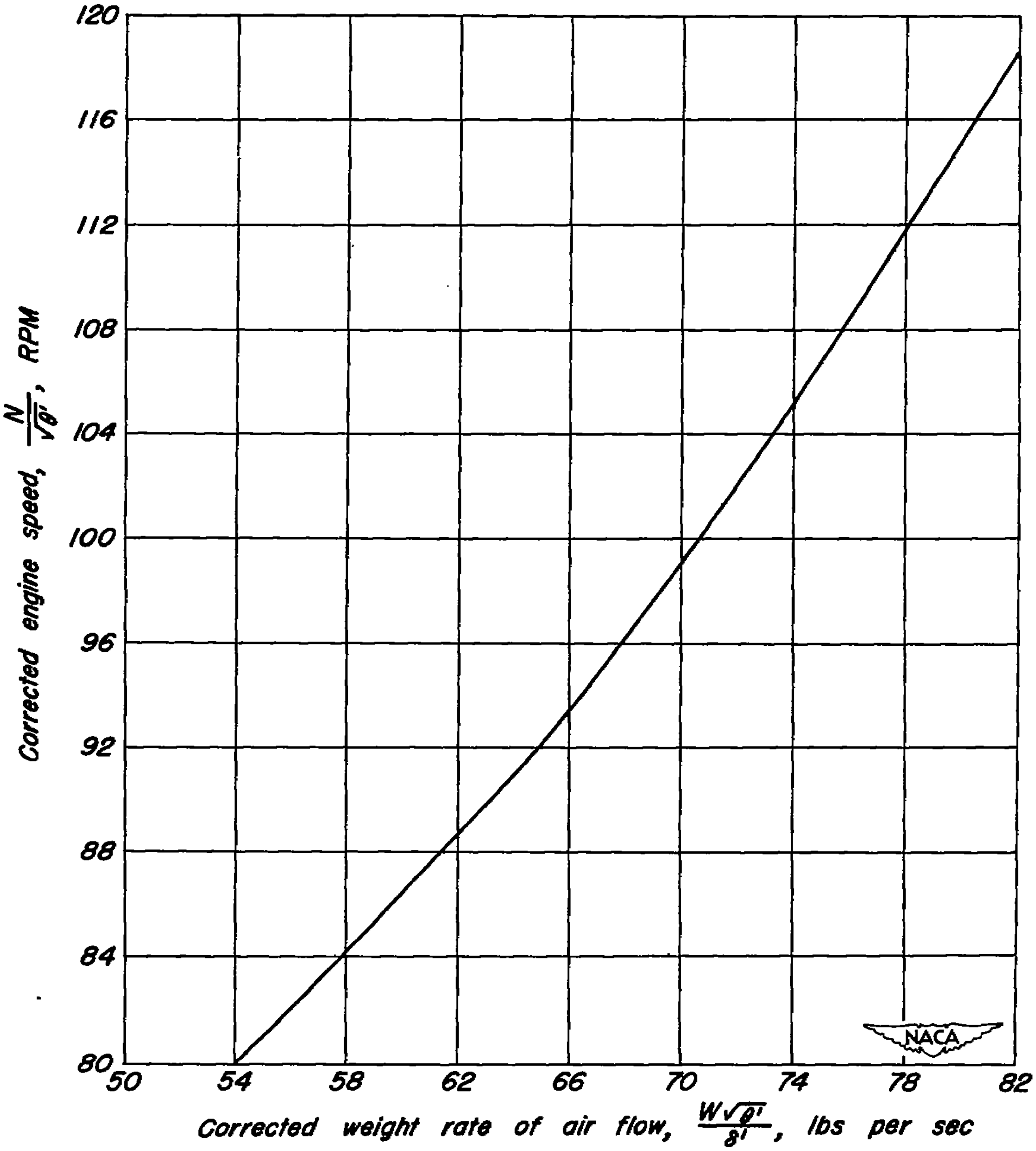
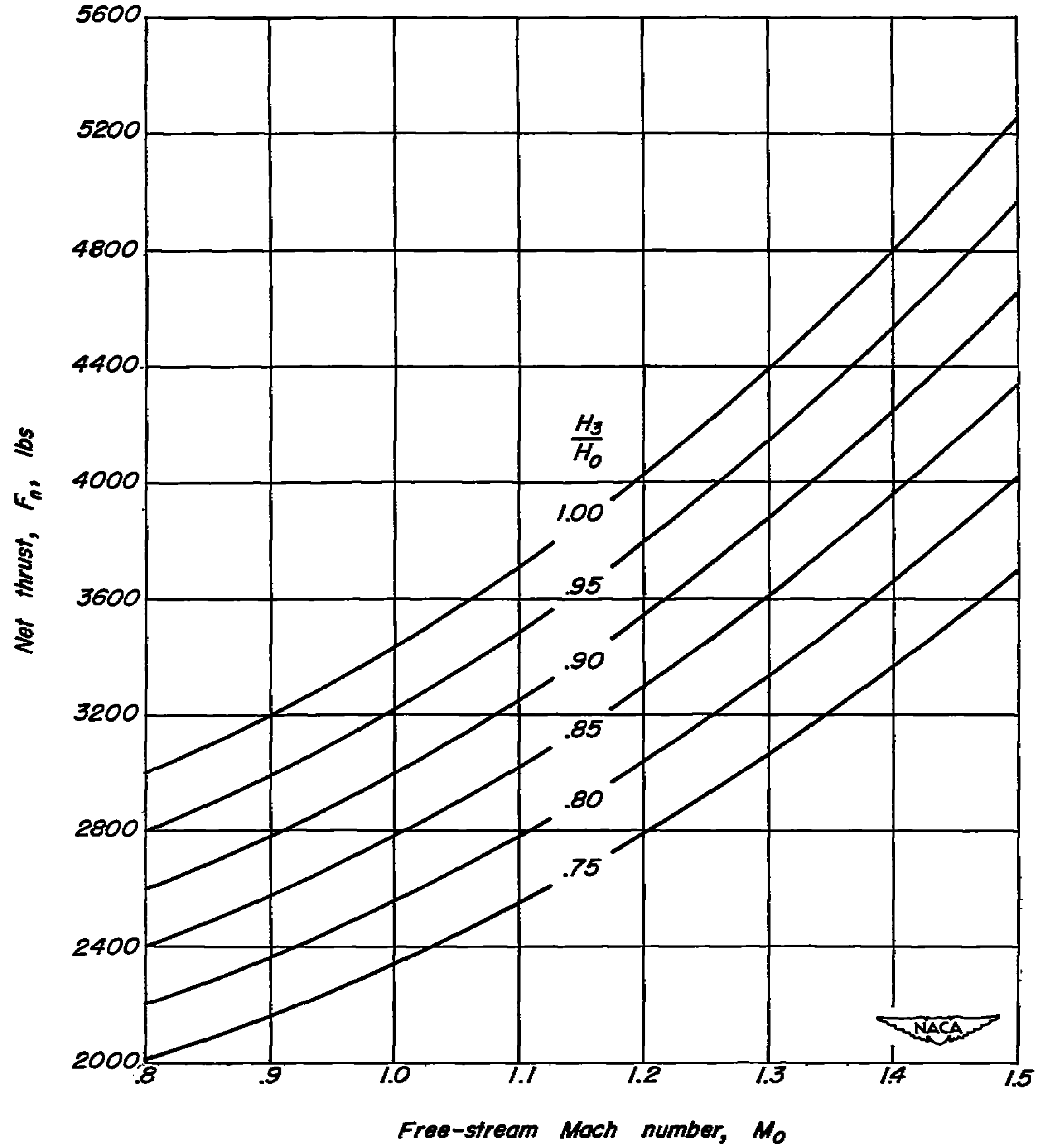


Figure 2.—Diagrammatic representation of assumed locations and types of shock waves for each of the inlets for free-stream Mach numbers from 1.00 to 1.50.



(a) Corrected weight rate of air flow.

Figure 3.— Corrected air requirements and thrust characteristics of the assumed turbojet engine.



(b) Net thrust, 35,332 feet.

Figure 3.—Concluded.

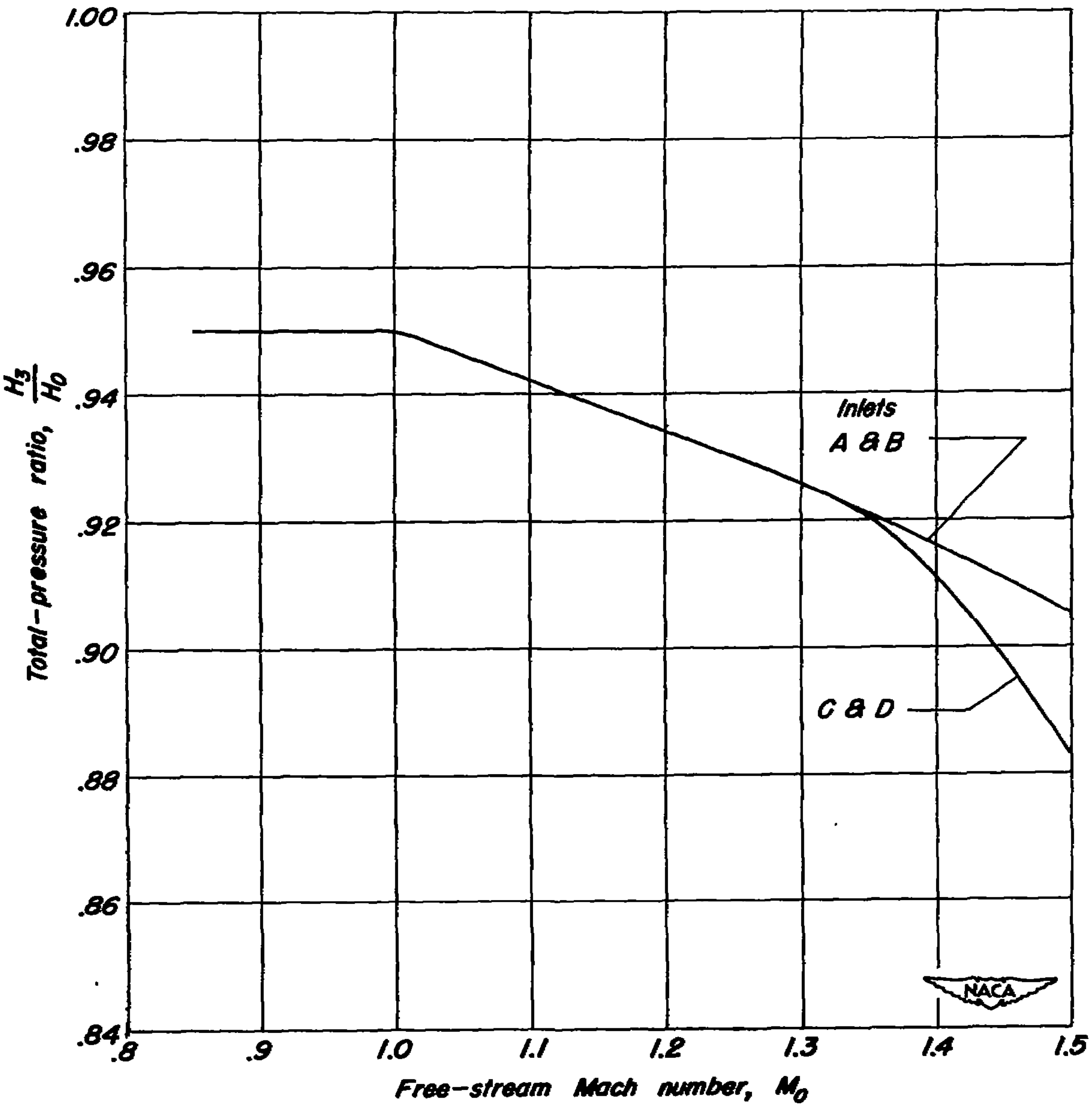
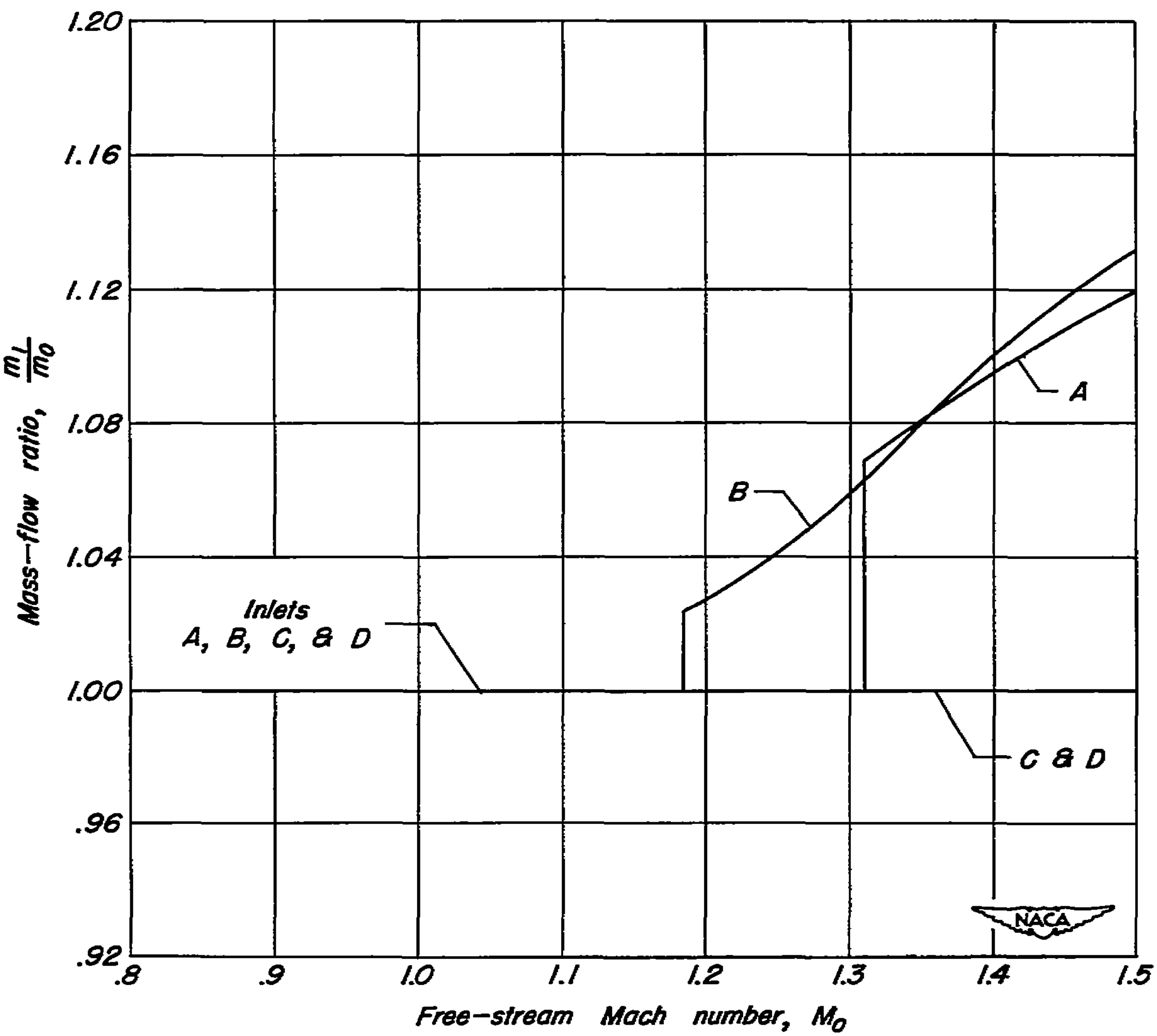
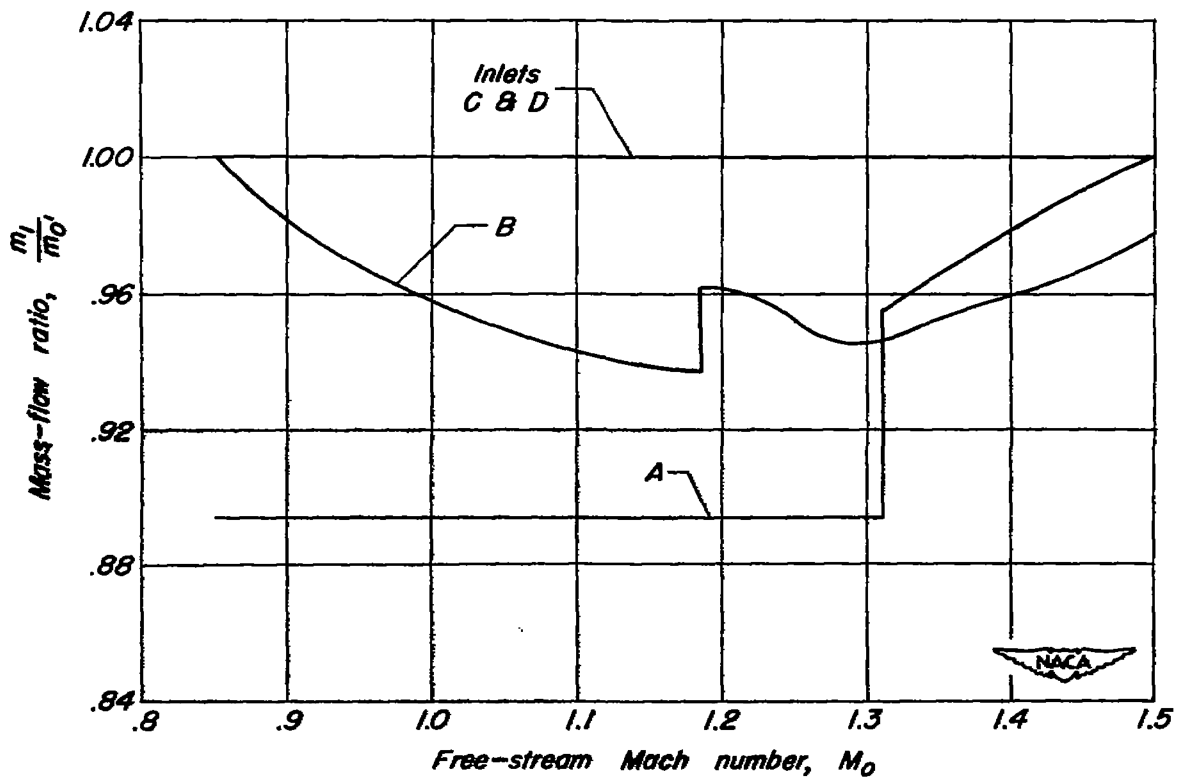


Figure 4.—Assumed variation of total-pressure ratio with free-stream Mach number for each of the inlets. M_0, 0.85 to 1.50.



(a) Entrance-area mass-flow ratio.

Figure 5.—Variation of mass-flow ratio with free-stream Mach number for each of the inlets. M_0, 0.85 to 1.50; altitude, 35,332 feet.



(b) Capture-area mass-flow ratio.

Figure 5.—Concluded.

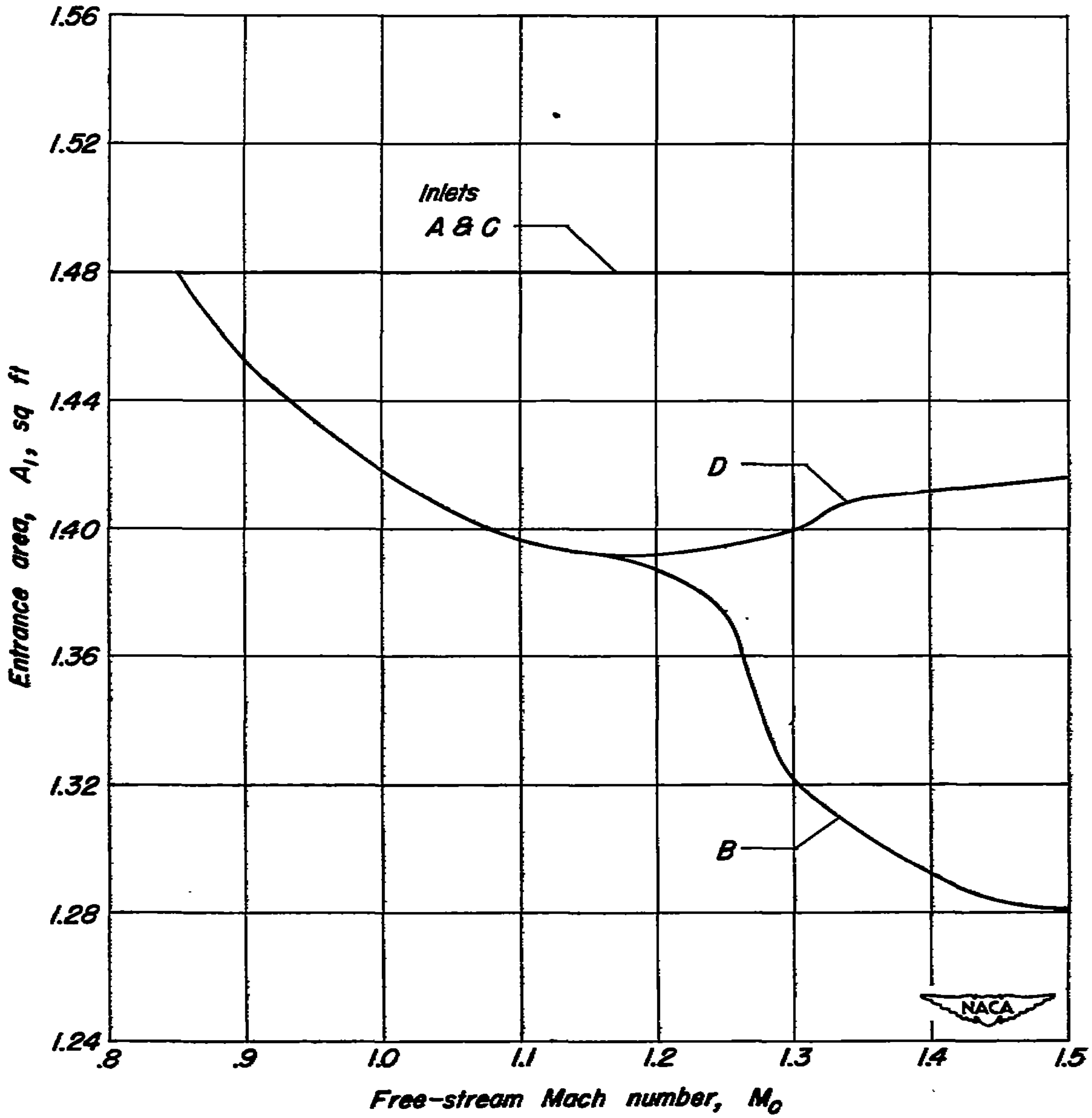


Figure 6.—Variation of entrance area with free-stream Mach number for each of the inlets. M_0, 0.85 to 1.50; altitude, 35,332 feet.

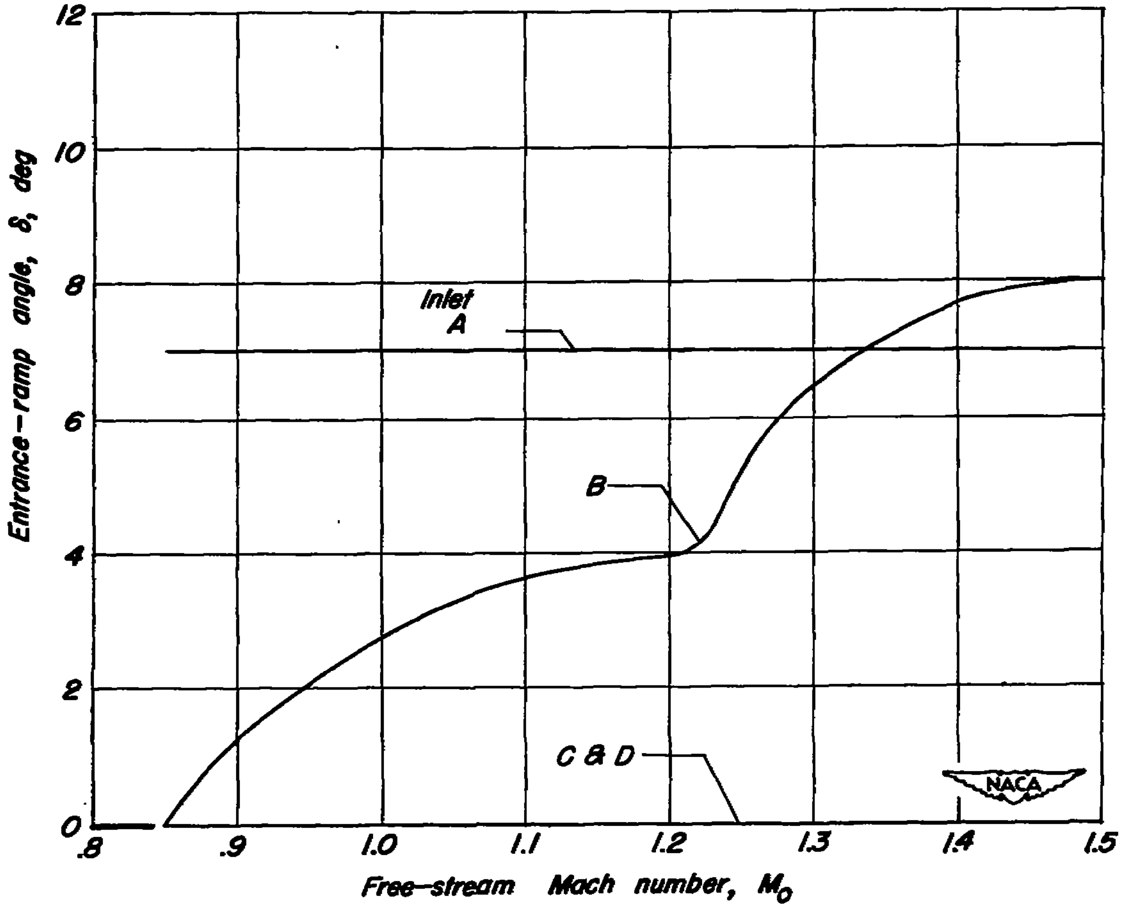
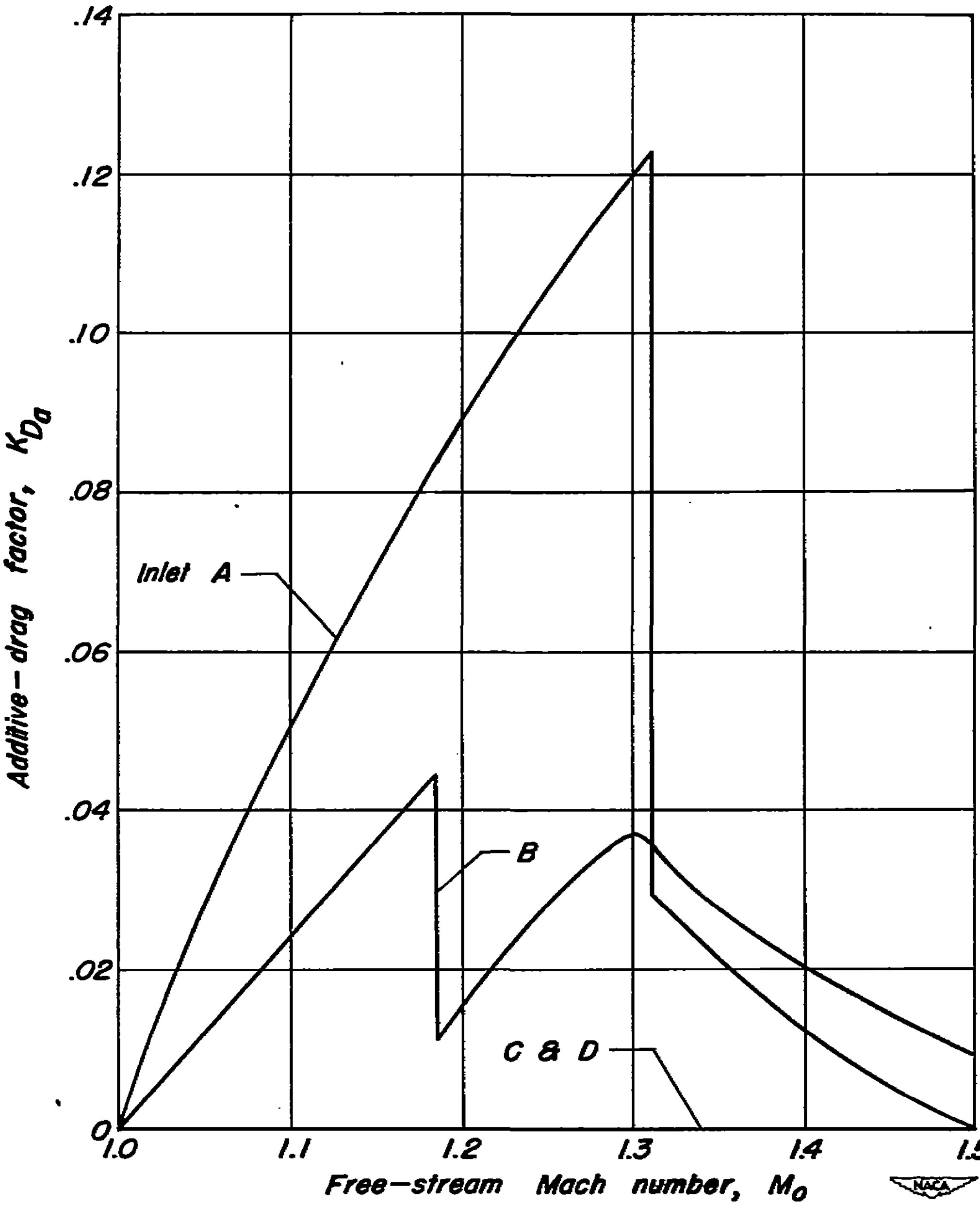
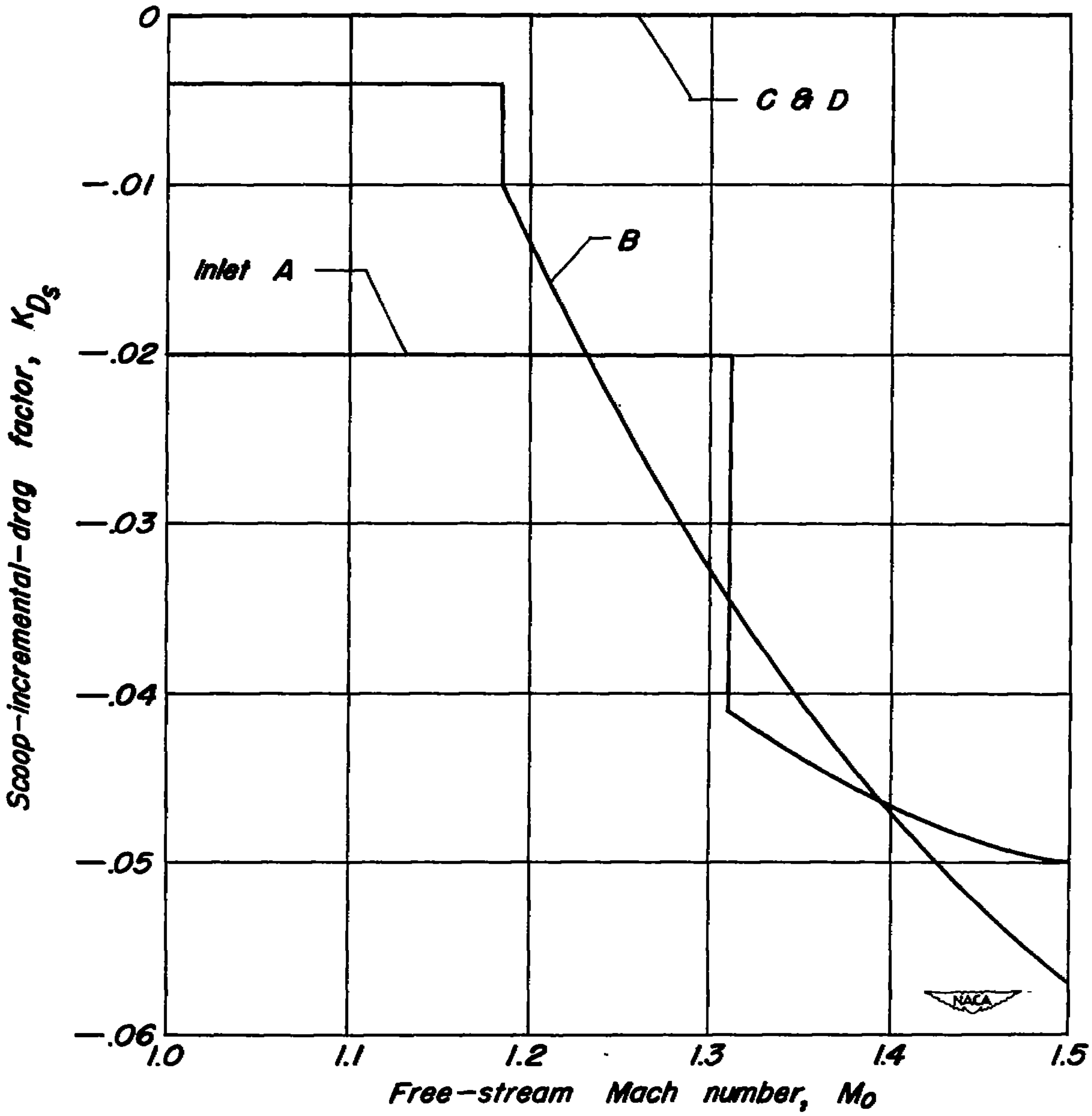


Figure 7.—Variation of entrance-ramp angle with free-stream Mach number for each of the inlets. M_0, 0.85 to 1.50; altitude, 35,332 feet.



(a) Additive-drag factor.

Figure 8.—Variation of additive-and scoop-incremental-drag factors with free-stream Mach number for each of the inlets. M_o, 1.00 to 1.50; altitude, 35,332 feet.



(b) Scoop-incremental-drag factor.

Figure 8.—Concluded.

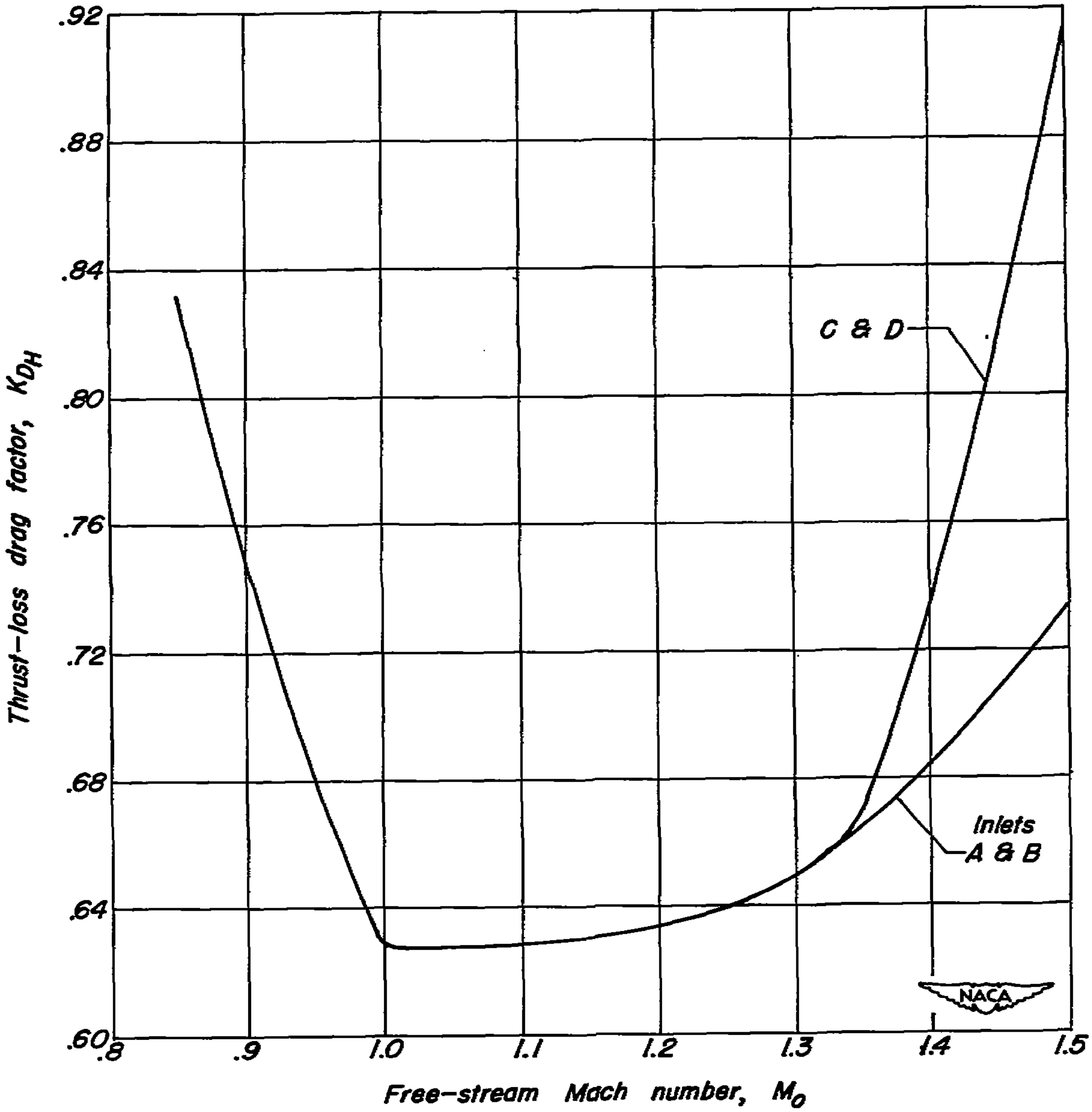


Figure 9.—Variation of thrust-loss drag factor with free-stream Mach number for each of the inlets. M_0, 0.85 to 1.50; altitude, 35,332 feet.

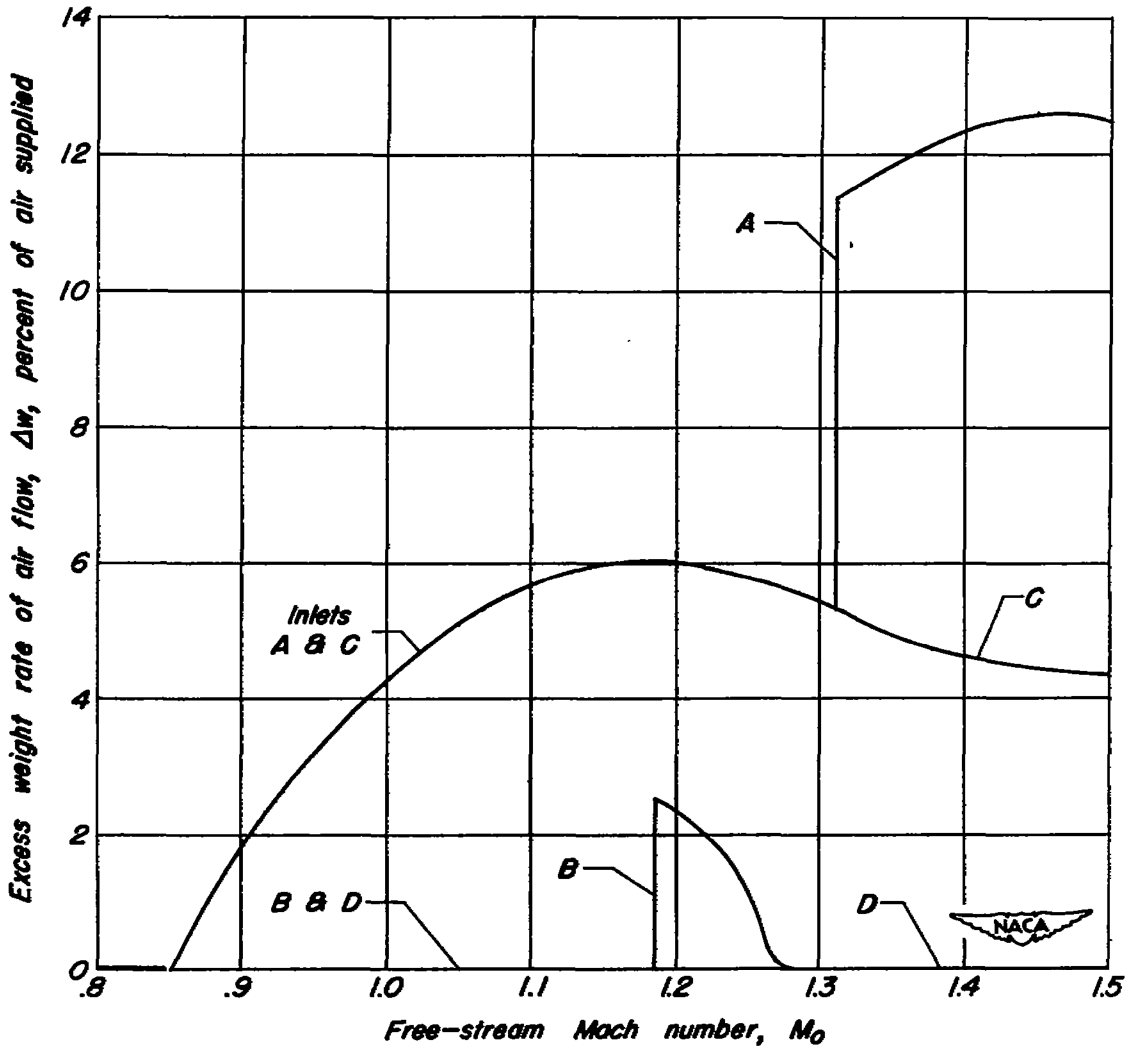


Figure 10.—Variation of excess weight rate of air flow with free-stream Mach number for each of the inlets. M_0, 0.85 to 1.50; altitude, 35,332 feet.

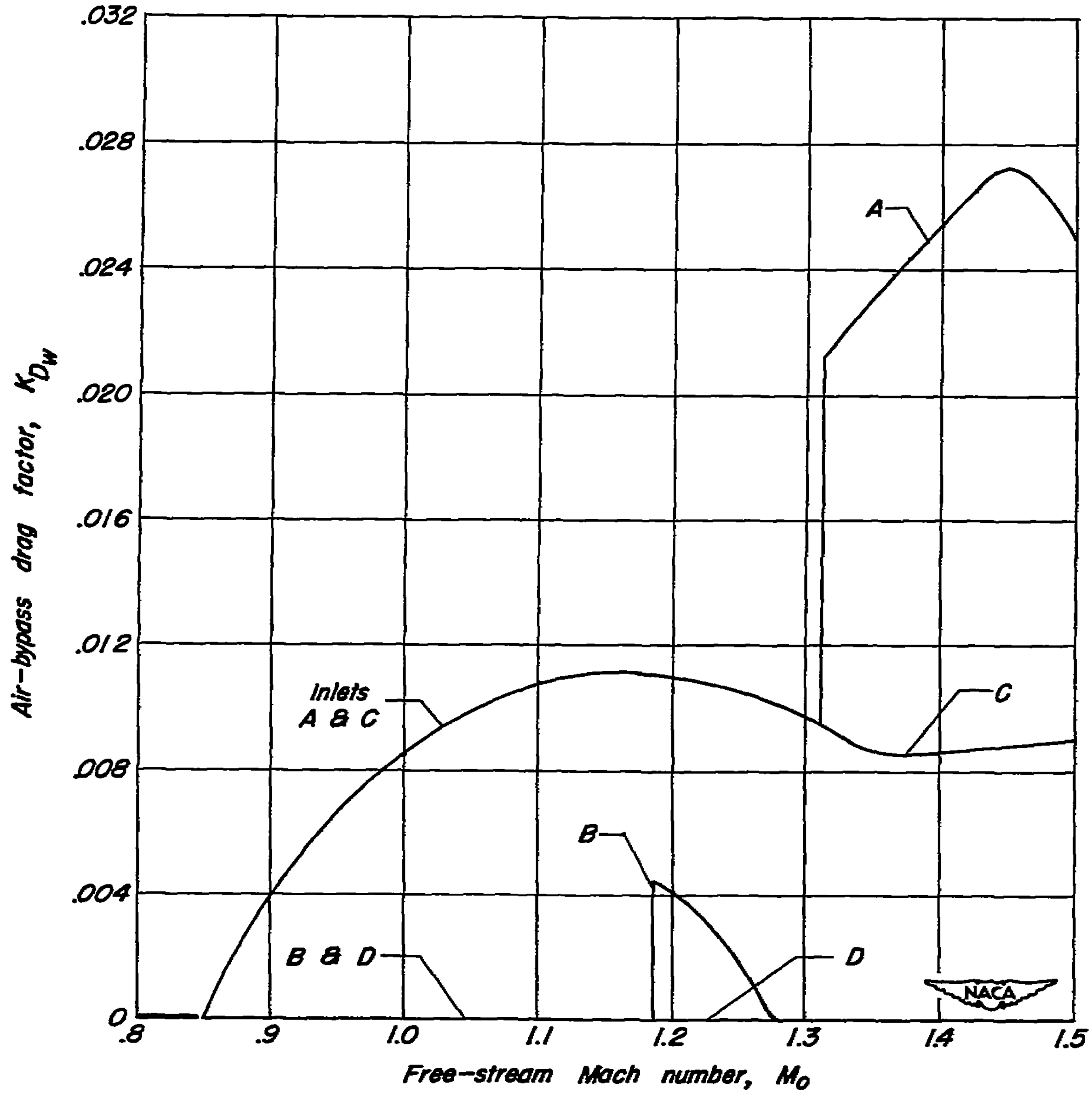


Figure 11.—Variation of air-bypass drag factor with free-stream Mach number for each of the inlets. M_0, 0.85 to 1.50; altitude, 35,332 feet.

[redacted]

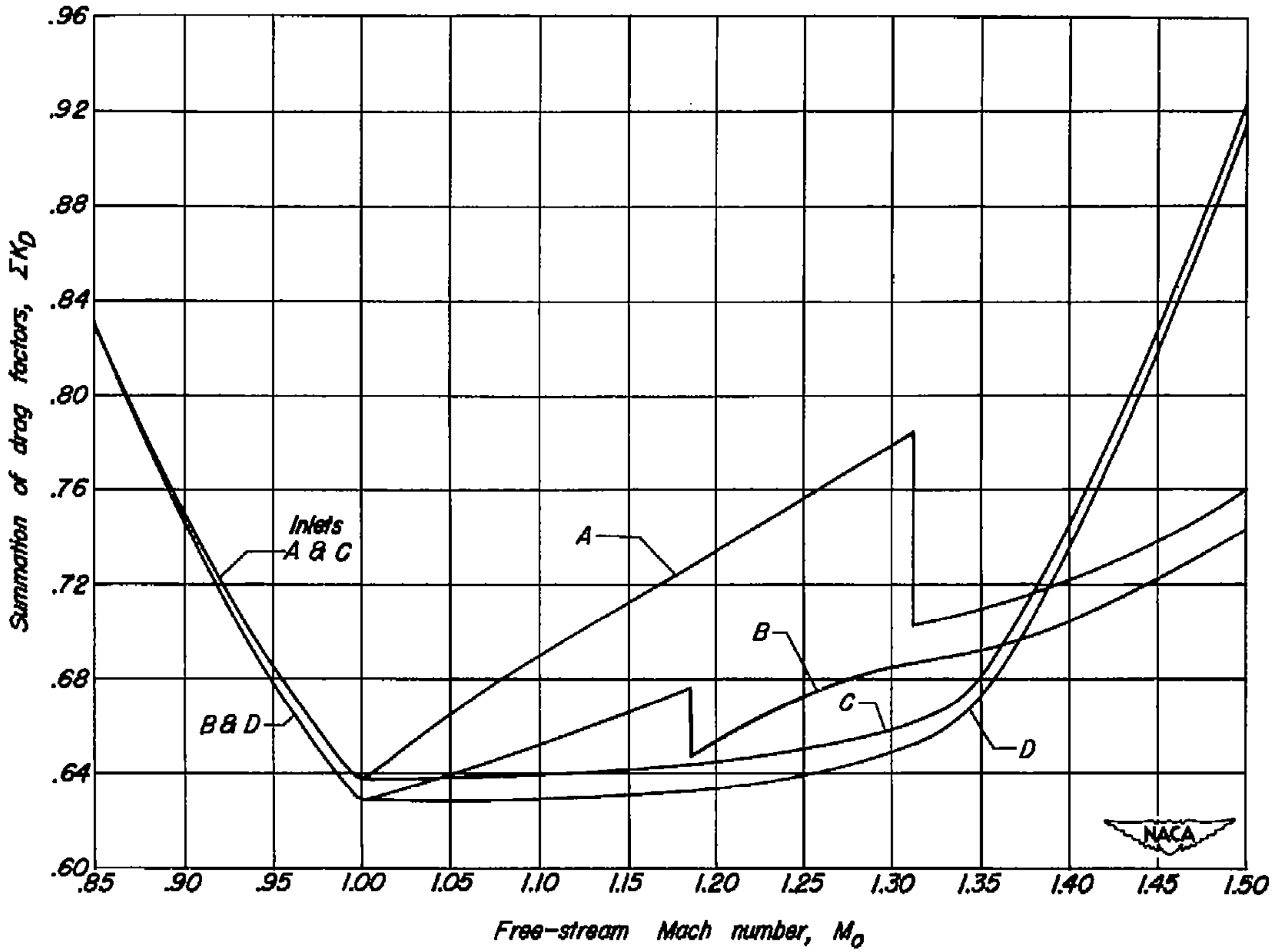


Figure 12.—Variation of drag-factor summation with free-stream Mach number for each of the inlets. M_0, 0.85 to 1.50; altitude, 35,332 feet.

[redacted]

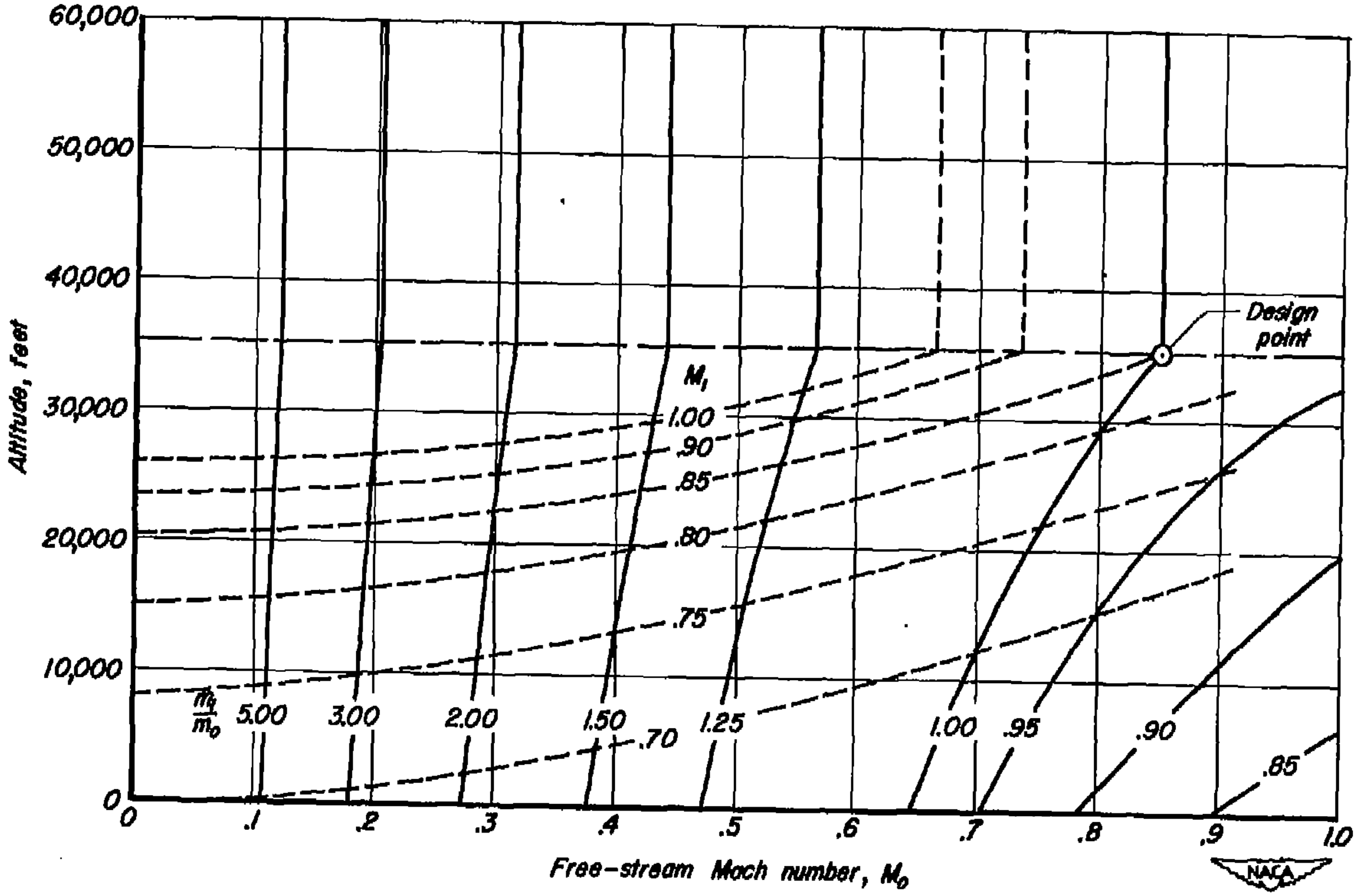


Figure 13.—Effect of altitude on the mass-flow ratio and entrance Mach number for subsonic operation of inlet C. M_0, 0 to 1.00; H_3/H_0, 0.95.

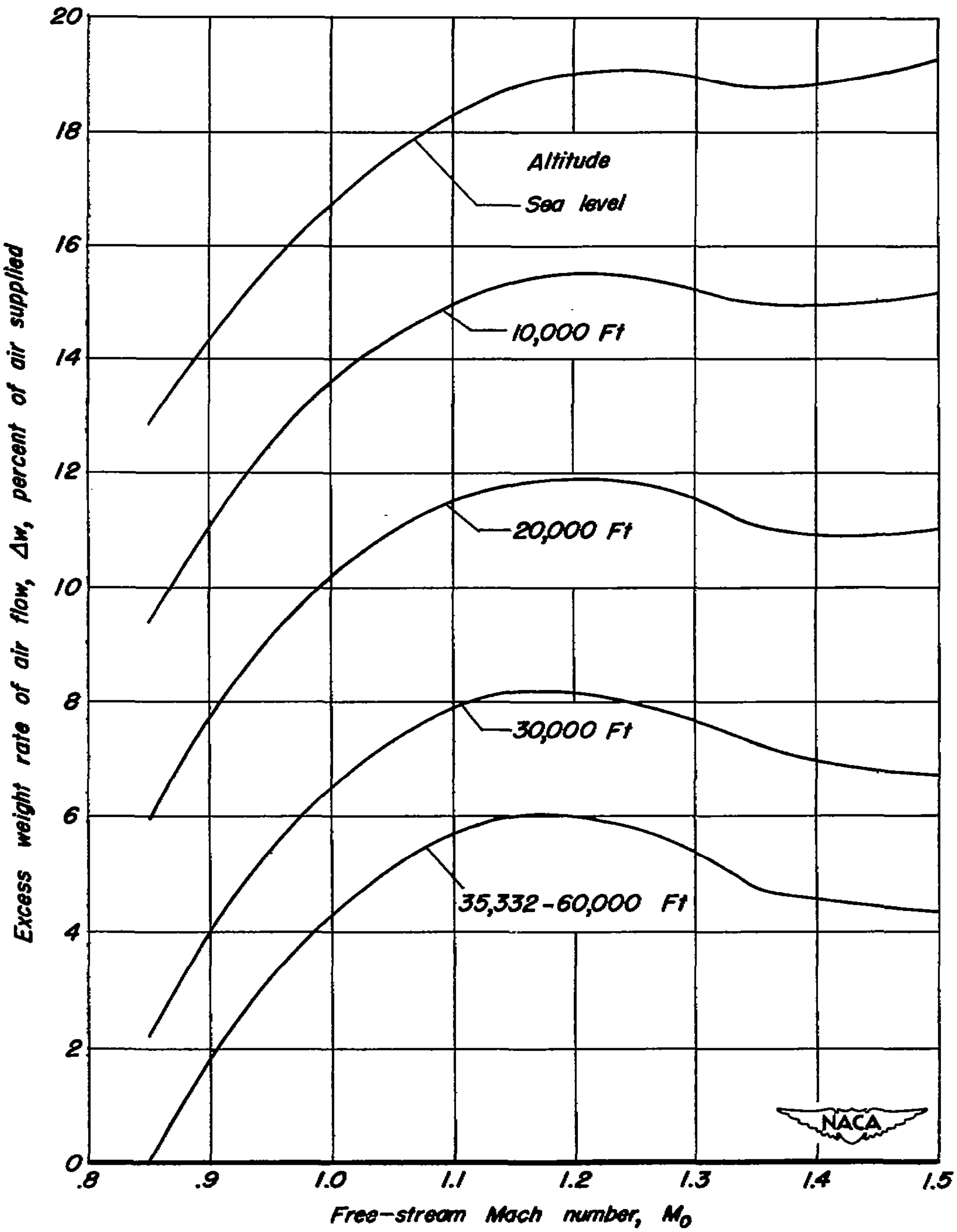


Figure 14.—Effect of altitude on the excess weight rate of air flow for inlet C. M_0, 0.85 to 1.50.

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