pressure ratio. Additional information is required to characterize the distribution of thrust between the primary and bypass flows. The analysis presented herein illustrates that the use of a theoretical expression for gross thrust that accounts for the influence of engine bypass ratio permits the definition of a gross thrust coefficient that is found to be primarily a function of the nozzle pressure ratio. The results of the subject investigation also indicate the potential of the relatively simple compound flow model for use in the development of improved gross thrust coefficient correlations when the availability of full scale engine test data is less extensive.

It should be emphasized that the compound nozzle flow theory employed herein provides only an approximate representation of the flow in a single nozzle turbofan engine exhaust. It can be expected that variations in the degree of mixing between the primary and secondary streams may be of considerable importance. Nevertheless, the application of this rather simplified theoretical model provides added insight into the parameters of importance that are likely to influence the gross thrust of a turbofan engine. It emphasizes the need for accurate data on the engine bypass ratio and the properties of the primary and bypass flows at the nozzle inlet to be obtained in future engine tests or included in the information supplied by the engine manufacturer. Moreover, the importance of proper simulation of the turbofan nozzle flow (pressure ratio, bypass ratio, mixing characteristics, ...) in the experimental determination of the gross thrust coefficient cannot be overemphasized.

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A Comparative Study of Three Axisymmetric Inlets for a Hypersonic Cruise Mission

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The relative merits of three different axisymmetric inlet systems suitable for turboramjet-powered hypersonic cruise vehicles are examined. The differences among the three inlets were centered in their off-design airflow characteristics, and these differences were in turn reflected in the spillage and cowl drags of each inlet. To achieve these different airflow characteristics, two of the configurations utilized a forward translating cowl to achieve a reduction in contraction ratio, and the third utilized a forward translating centerbody. The comparisons were based on the range performance of a blended-body, hydrogen-fueled, Mach number 6.0 cruise vehicle. The forward translating centerbody system was found to be superior. With this system, the vehicle achieved 13.6% greater range than with either of the two forward translating cowl systems. A parametric study was then performed to determine the vehicle's range sensitivity to various inlet performance parameters for the vehicle configured with the forward translating centerbody inlet. The parameters investigated included the inlet total-pressure recovery, the performance of the boundary-layer bleed system, the inlet transonic airflow capability, and the cowl pressure drag. Although no single inlet performance item had a dominant influence on the vehicle's range capability, taken collectively, the effect of improving the various aspects of inlet performance can be substantial.

Nomenclature

A = cross-sectional area
C_{D_a} = additive drag coefficient, D_{add}/q_0A_c
C_{D_c} = cowl drag coefficient, D_{cowl}/q_0A_c
C_{D_s} = spillage drag coefficient, D_{spill}/q_0A_c
D = drag or inlet diameter
L/D = lift to drag ratio
M = Mach number
m = mass flow rate
P_t = total pressure
P_{t_2}/P_{t_0} = inlet total-pressure recovery
q = dynamic pressure
R = range
TOGW = takeoff gross weight
δ = initial exterior cowl angle

Subscripts

bl = bleed
c = cowl or capture
0 = local conditions

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t = inlet throat
2 = engine face

Introduction

STUDIES[1,2] of hypersonic airbreathing vehicles have shown that the attainment of reasonable payload and range is critically dependent on the achievement of low structural weight and high aerodynamic performance throughout the flight envelope. This is equally true for the vehicle's propulsion system and, in particular, the air induction system. For hypersonic cruise missions, the climb and acceleration phase accounts for a substantial fraction of the total fuel consumed during the mission; and even more important, the critical thrust requirements, which dictate the size of the propulsion system, may occur during this phase of the mission. In view of this, the off-design performance of the inlet system acquires added importance and demands the necessary attention to ensure the optimum performance of the propulsion system for the entire mission.

Maximum inlet performance is characterized by the attainment of the maximum internal and external aerodynamic performance at the minimum possible structural weight and cooling requirements. To obtain maximum internal performance, the inlet must provide maximum pressure recovery and minimum flow distortion at the engine face while utilizing a minimum of boundary-layer bleed and matching the airflow requirements of the engine cycle. Maximum external aerodynamic performance requires the minimum possible spillage and cowl drags. Minimum inlet weight and cooling are achieved primarily through reductions in inlet length. Unfortunately, many of these design criteria conflict with one another, and the optimum inlet system is necessarily a compromise among them. Since the off-design performance may be critical for systems required to operate over a broad range of Mach numbers, the criteria for assessing the merits of an inlet and defining the optimum must be based on the over-all performance of the vehicle for the design mission.

Based on these considerations, a comprehensive computer program designed to analyze the propulsion system aspects of mission performance was used to study three different axisymmetric inlet systems designed for a Mach number 6.0 cruise vehicle. The objectives of this study were first to investigate the relative merits of the three inlet systems based on the mission performance attainable with each, and secondly, to evaluate the sensitivity of the vehicle's range performance to variations in the aerodynamic performance of the inlet and thereby obtain tradeoff information between the various inlet performance parameters.

Inlet Designs

The three axisymmetric inlet designs studied are shown in Fig. 1, and are designated for reference purposes, inlets A, B, and C. These are conceptual designs based primarily on one-dimensional flow considerations and the inlet contraction ratio requirements and are not intended to represent final detailed designs. The study concentrated on the aerodynamic performance characteristics of the inlet system. It did not attack the area of inlet cooling and included only a preliminary estimate of the inlet weight. Although the effects of inlet weight and cooling on the final design can be important in the initial investigation of inlet systems for this Mach number regime, a knowledge of the relative importance of the various aerodynamic performance parameters can aid in defining those areas of research that have a significant potential for substantially increasing the over-all performance of the propulsion system.

The design Mach number for the three inlets is 5.2, which is the local Mach number under the wing at the inlet face during cruise at Mach number 6.0. The initial centerbody angle was 10° for all three systems, whereas the initial external

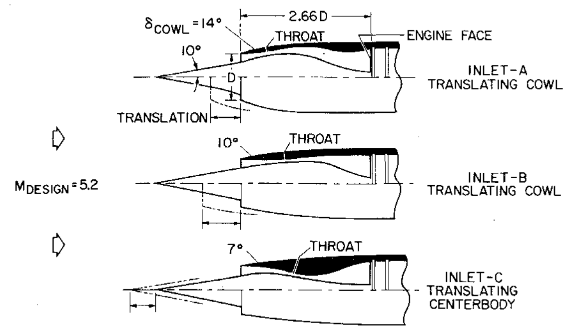


Fig. 1 Axisymmetric inlet designs.

cowl angles, dictated by the internal geometry and maximum engine face diameter, were 14°, 10°, and 7° for inlets A, B, and C, respectively. At the design Mach number the initial shock generated by the center-body intersects the cowl lip. Each inlet system is 2.66 capture diameters long from the cowl lip to the engine face. This is felt to be near the minimum possible length of these inlets. However, a detailed design study would reveal some differences in length, but the differences are believed to be relatively small. Because of their similar geometric and identical operating environments, the structural loads expected for each would be essentially identical. Thus each inlet was assumed to have the same specific weight per unit capture area (250 lb/ft^2). This eliminated the need for extremely accurate weight estimates which, as previously mentioned, were only preliminary in nature.

The design differences among the three inlets were centered in their off-design airflow characteristics and the manner in which the relative translation of the cowl and centerbody was employed to achieve variable gometry. Inlets A and B were designed with a cowl that translated forward from the design operating condition, thus allowing the inlet to capture more flow at the high off-design Mach numbers. To provide the required internal flow area at these lower Mach numbers, the inlet throat area must increase with decreasing Mach number. This combination of a forward translating cowl and the requirement for an increasing throat area with translation dictates that the internal contours in the throat region have a positive slope; i.e., the flow direction must be away from the axis of the inlet. Inlets A and B were designed in this manner as illustrated in Fig. 1. Specifically, the design criteria for inlet A was to achieve a high transonic air flow capability, whereas inlet B was designed to maintain a mass-flow ratio of unity from the design Mach number of 5.2 to 4.5. In contrast to the translating cowl designs, inlet C utilizes a forward translating centerbody to reduce the contraction ratio as the Mach number is decreased from the design value. In this case, to satisfy the requirements of an increasing throat area with a forward translating centerbody, the internal contours in the throat region were required to have a negative slope as shown in Fig. 1.

These design differences among the three inlets led to considerable differences in their spillage and cowl drags. The cowl pressure drag and the transonic spillage drag of the translating cowl systems were substantially greater than those of the translating centerbody system. The high transonic spillage drags of the translating cowl inlets resulted from the relatively large internal contraction (between the cowl lip and throat stations) that exists with the cowl in the most forward position as required to achieve the maximum transonic airflow. The higher cowl pressure drags stem directly from the larger external cowl angles required to provide the cross-sectional area necessary to incorporate the positive sloping throat contours of these systems.

The internal performance parameters of engine face total-pressure recovery and boundary-layer bleed were assumed identical for the three systems. This assumption may not be

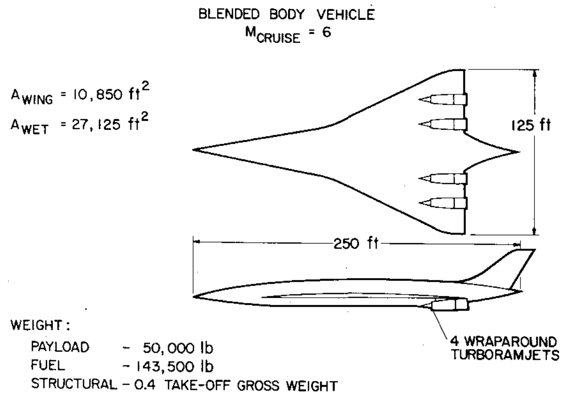


Fig. 2 Vehicle configuration.

entirely correct, but the presently available prediction techniques are not believed to be accurate enough to reliably determine the differences in the internal performance. However, the assumption of identical internal performance formed a basis for evaluating the other design differences. The effects of pressure recovery and boundary-layer bleed on the vehicle performance were determined by perturbating these parameters. A detailed description and further discussion of both the internal and external performance of all three inlets are presented in the Appendix.

Vehicle Configuration and Mission

The only realistic way of evaluating the relative merits of these three inlet systems is on the basis of the over-all mission performance attainable with each system. Therefore, a suitable aerodynamic vehicle and mission were required. Since axisymmetric propulsion system adapt well to podded installations located in the wing flowfield, the blended-body configuration shown in Fig. 2 was chosen. It is a hydrogen-fueled Mach number 6 cruise vehicle powered by four podded wraparound turboramjet engines. The vehicle has a payload of 50,000 lb and carries a fixed fuel load of 143,500 lb. With the payload and fuel capacity fixed, the figure of merit used in the study was the range attained at the end of cruise. The structural weight excluding the weight of the propulsion pods was assumed to be 40% of the takeoff gross weight. The weight of the propulsion system was dictated by the thrust requirements, with the basic engine weights derived from Ref. 3. The takeoff gross weight of the vehicle was nominally 450,000 lb, but varied slightly depending upon the weight of the required propulsion system. The cruise and off-design aerodynamics used in the analysis were developed from other studies.[4]

The performance of the propulsion system was based on a thermodynamic cycle analysis of the turbojet and ramjet cycles. The thermodynamic properties of the working fluid were obtained from an equilibrium combustion model given in Ref. 5. The combustion was assumed stoichiometric with a combustion efficiency of 95%. The exhaust process was assumed to be in equilibrium. The turbojet and ramjet exhaust streams for each engine were handled by a common exhaust nozzle with variable throat and exit areas to minimize the expansion losses. A thrust coefficient, which was a function of the nozzle pressure and expansion ratios, was applied to the ideal gross thrust of both exhaust streams. The turbojet was used from takeoff to Mach number 3.2, whereas the ramjet was utilized for all Mach numbers greater than 0.9.

The mission was a Mach number 6 cruise at the maximum Breguet range factor of the vehicle. The climb portion of the trajectory used after takeoff consisted of a 2 psf sonic boom trajectory followed by a constant dynamic pressure (q = 1000 psf) trajectory to Mach number 6.0 and terminated with a constant Mach number climb to the altitude corresponding to the maximum range factor of the vehicle. During cruise, the engines were throttled to maintain the maximum range factor. No consideration was given to the letdown and landing phases of the trajectory since the incremental effects on range were practically identical for all three systems.

Results and Discussion

Mission Performance of the Three Inlets

The initial objective of the study was to determine the relative merits of the three preliminary inlet designs from an over-all mission point of view. To accomplish this, the inlet performance characteristics presented in the Appendix were combined with the propulsion characteristics of the wraparound turboramjet engine and the aerodynamics of the blended-body configuration; the optimum mission performance was then determined for each inlet-vehicle combination. The optimization process determined the combination of turbojet and ramjet size that yielded the maximum range at the end of cruise. The size of the turbojet and ramjet were varied parametrically to determine the maximum range. The results of the study are shown in Fig. 3 in terms of range as a function of inlet capture area per engine, which is in essence the size of the ramjet. The curves shown are the envelopes of similar curves for constant size turbojets, and hence, indicate the maximum range attainable for each value of inlet capture area. A typical curve for a constant size turbojet is shown for the inlet C configuration. The flatness of these curves indicates that the exact size of the propulsion system was not critical, since for each configuration, a 10% change in the optimum capture area resulted in only a 1% change in the maximum range. On the other hand, a significant improvement did result from the performance of the inlet through reductions in total propulsion system weight and drag as illustrated by the fact that the translating centerbody configuration was found to be superior to both translating cowl configurations. The translating centerbody configuration attained a maximum range of 4750 naut miles compared to 4200 naut miles for both translating cowl configurations.

The primary reason for the higher over-all performance of the translating centerbody configuration was its significantly lower drag over the entire Mach number range as compared to that of the translating cowl configurations. The percentages of fuel required to overcome the various components of inlet drag for the entire mission are compared in Fig. 4 for the three inlet systems. The total fuel accountable to the inlet drags represents 14.9, 13.3, and 8.4% of the total fuel load of the vehicle for inlets A, B, and C, respectively. The cowl drag has the greatest effect in all three cases representing 50% or more of the fuel accountable to the entire inlet. With the bleed and skin friction percentages nearly identical for the three inlets, the difference in range between the translating centerbody configuration and the translating cowl configurations is directly attributable to the incremental differences in the cowl and spillage drags. The lower cowl and spillage

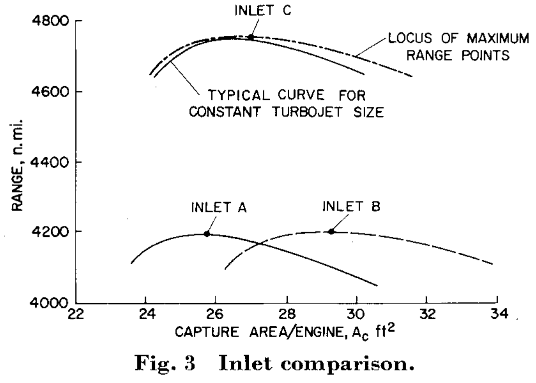


Fig. 3 Inlet comparison.

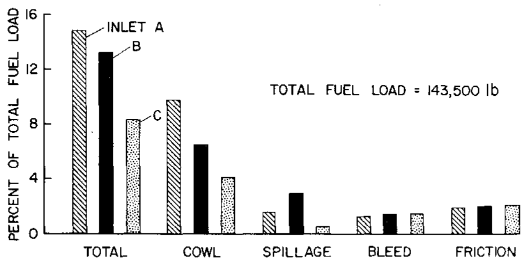


Fig. 4 Fuel accountable to inlet drag.

drags during the climb portion of the mission resulted in more fuel being available for the cruise leg, whereas the lower cowl drag during cruise allowed the vehicle to fly at a higher cruise L/D. Therefore, these results indicate that the apparent advantage of the translating cowl inlets in achieving high inlet mass-flow ratios at the high off-design Mach numbers does not compensate for the increase in transonic spillage drag and over-all cowl pressure drag associated with this capability.

Range Sensitivity to Inlet Performance

The second objective of the study was to evaluate the sensitivity of the vehicle's range to variations in the aerodynamic performance of the inlet system. Since the translating centerbody system appeared to be superior, it was chosen as a basis for the sensitivity study. The inlet performance parameters considered included the engine face total-pressure recovery, the performance of the boundary-layer bleed system, the transonic airflow capability of the inlet, and the cowl pressure drag. The results of the sensitivity study are presented in terms of incremental variations about the translating centerbody configuration that yielded the maximum range as determined in the comparative study of the three inlets.

The isolated effects of pressure recovery and boundary-layer bleed are presented in Figs. 5 and 6, respectively. The pressure recovery and bleed mass-flow were varied about their reference values which are described in the appendix. The actual increments shown in Figs. 5 and 6 refer to the increments assumed at the design condition of Mach number 5.2. For Mach numbers less than design, these increments were reduced in a linear fashion from their initial values at Mach number 5.2 to zero at Mach number 1.0. The range sensitivity to inlet pressure recovery, as shown in Fig. 5 for the reference bleed schedule, was an 18.0-naut mile increase per percentage increase in pressure recovery at Mach number 5.2. Similarly, as presented in Fig. 6, the range sensitivity to boundary-layer bleed, for the reference pressure recovery schedule, was a 31.0-naut mile increase per percentage decrease in bleed mass-flow ratio at Mach number 5.2. This latter result was determined assuming the bleed exit flow was fully expanded to the local static pressure throughout the mission. As shown in Fig. 6, discharging the bleed mass flow through a sonic exit resulted in a decrease of 250 naut miles in

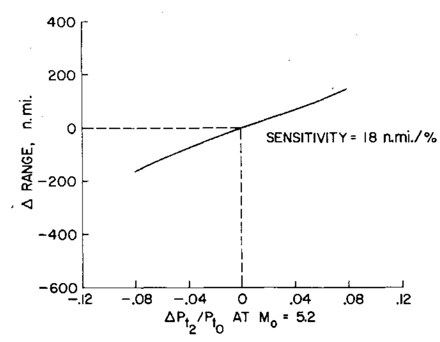


Fig. 5 Influence of inlet pressure recovery.

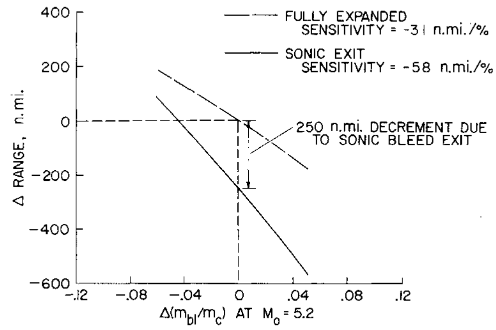


Fig. 6 Influence of bleed mass-flow ratio.

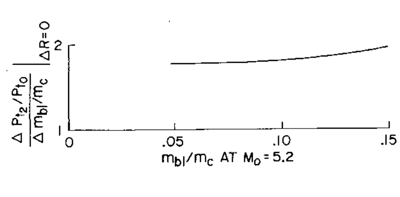
the maximum range. For this sonic exit condition, the effect of bleed mass-flow ratio was increased and resulted in a range sensitivity of a 58.0-naut mile increase per percent decrease in bleed mass-flow ratio at Mach number 5.2.

More interesting than the isolated effects of boundary-layer bleed and pressure recovery was the actual tradeoff between these two performance parameters for no change in the range of the vehicle. Figure 7 shows the required percentage increase in pressure recovery per percentage increase in bleed mass-flow ratio for constant range as a function of bleed mass-flow ratio for the case in which the bleed mass flow is fully expanded. This ratio relates the required increase in pressure recovery to offset a unit increase in bleed mass flow to ensure no decrement in range. Since this ratio is greater than unity, the boundary-layer bleed has the dominating effect, indicating that greater gains can be achieved by reducing the bleed flow than by increasing the pressure recovery. The dominance of the bleed flow is further substantiated by the fact that this ratio increases slightly with bleed mass-flow ratio.

Another aspect associated with boundary-layer bleed is the effect of the discharge conditions. These include the pressure recovery of the bleed flow, the average discharge angle, and the degree of expansion. Figure 8 shows the incremental effects of the average discharge angle and bleed pressure recovery on the range of the vehicle for the fully expanded and sonic exit conditions. For the range of discharge angles presented in Fig. 8a, the difference between the fully expanded and sonic exit conditions remained approximately constant at 250 naut miles. The resulting average range sensitivity for both exit conditions was an 11.0-naut mile increase per degree decrease in average discharge angle. In the case of the bleed pressure recovery, the range sensitivity is considerably greater for the fully expanded condition than for the sonic exit, as shown in Fig. 8b. This is not unexpected, since the pressure recovery more strongly dictates the momentum recovered for the fully expanded condition. For the reference inlet pressure recovery schedule, the influence of the bleed pressure recovery becomes more pronounced for bleed recoveries less than 50% of the inlet recovery, especially for the fully expanded condition.

The transonic airflow capability of the inlet system can have a considerable effect on the performance of the vehicle, since the size and weight of the propulsion system are dictated by the thrust requirements in the transonic regime. The airflow capability of the inlet in this regime is dictated by the maximum throat area attainable within the limits of the variable geometry. The effect on range of varying the transonic mass-flow capability is shown in Fig. 9 as a function of changes

Fig. 7 Bleed-pressure recovery trade.



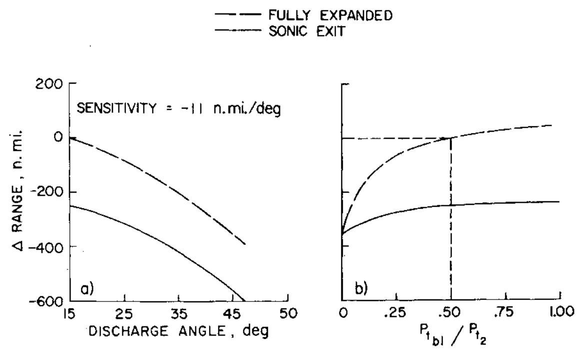


Fig. 8 Influence of bleed discharge angle and pressure recovery.

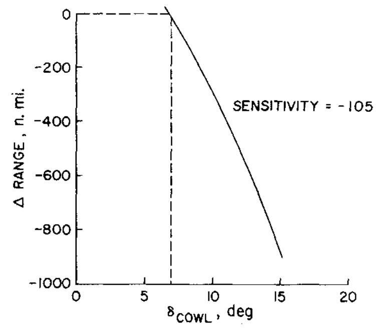


Fig. 10 Influence of cowl angle.

in the ratio of the maximum throat area to capture area. For each maximum throat area, the propulsion system was resized to obtain the maximum range. The resulting range sensitivity at the reference condition (Δ range = 0) was a 35-naut mile increase per percentage increase in transonic airflow. Typically, an increase in transonic airflow allowed a reduction in inlet size with the subsequent reduction in propulsion system weight. This reduction in weight resulted in an increase in transonic acceleration, reducing the fuel required for the climb phase of the mission and increasing the fuel available for cruise.

The cowl pressure drag had the most significant effect compared to the other inlet performance parameters. This was indicated previously in the comparisons of the fuel consumed to overcome the various inlet drag components. The effect of varying the external cowl angle is presented in Fig. 10. Here again, the propulsion system was resized for each cowl angle to obtain the maximum range. The average range sensitivity for external cowl angles between 7° and 15° was a 105-naut miles increase per degree decrease in external cowl angle. This significant effect of cowl pressure drag is attributable to the fact that the cowl drag is present throughout the entire mission, especially during cruise when it directly affects the maximum L/D of the vehicle and, subsequently, the range finally achieved.

Summary

The study of three axisymmetric inlet systems designed for a Mach 6.0 cruise vehicle illustrates the superior over-all range performance of the translating centerbody configuration over the two translating cowl configurations. For the mission and vehicle used in the study, the translating centerbody inlet provided a 13.6% increase in range over the two translating cowl systems. This range increment was a direct consequence of the lower levels of spillage and cowl pressure drag relative to those of the translating cowl systems. The inherent capability of the translating cowl systems to achieve high inlet mass-flow ratios, particularly at the high off-design Mach numbers, did not adequately compensate for the accompanying increase in transonic spillage drag and over-all cowl pressure drag.

With the translating centerbody configuration as a basis, the sensitivity of the vehicle's range to variations in the pressure recovery, the performance of the boundary-layer bleed system, the transonic airflow capability of the inlet, and the cowl pressure drag were examined. These results illustrate the relative importance of these inlet performance parameters and indicate areas in which the greatest performance gains can be realized. The resulting sensitivity factors are summarized in Fig. 11. The cowl pressure drag, the boundary-layer-bleed mass flow, and the transonic airflow capability of the inlet had the most substantial effect of the parameters studied. The cowl pressure drag had the most significant influence due primarily to its effect on the maximum L/D of the vehicle during cruise.

Although these results illustrate that no single inlet performance item had a dominant influence on the vehicle's range capability, taken collectively, the effects of improving the various aspects of inlet performance can be substantial. This is witnessed by the 13.6% greater range of the translating centerbody system over the two translating cowl system.

Appendix: Inlet Performance Characteristics

The aerodynamic performance of the inlets presented in Fig. 1 consisted of the inlet pressure recovery, airflow characteristics, spillage drag, and cowl pressure drag. A discussion of the preliminary design criteria and a description of the various performance parameters for each inlet is presented in this section.

Internal Performance

The pressure recovery schedule for each of the three inlets is shown in Fig. 12. For Mach numbers less than the starting Mach numbers for the inlet, the pressure recovery was based on an external shock system consisting of the conical shock followed by a normal shock, whose strength was evaluated using the cone surface Mach number. For Mach numbers greater than the starting Mach number, the recovery was taken to be the standard military schedule,[6] Mil-E-5008B. The particular starting Mach number for each inlet depended

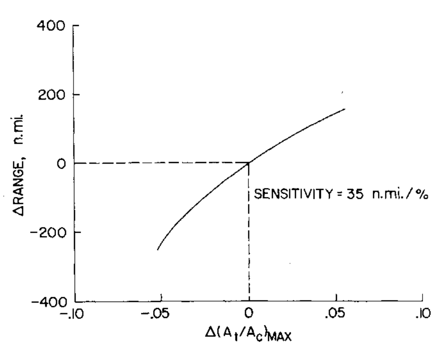


Fig. 9 Influence of inlet transonic airflow capability.

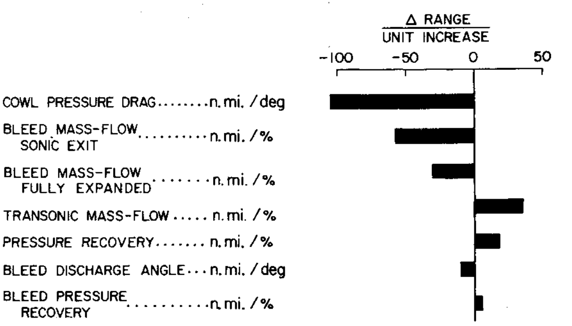


Fig. 11 Summary.

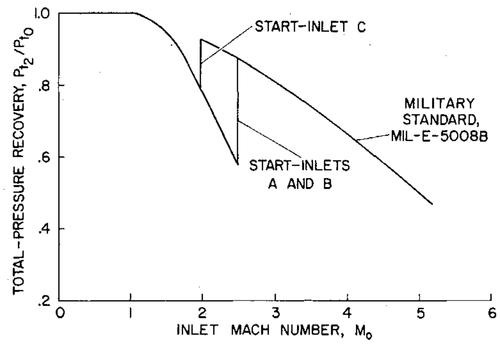


Fig. 12 Pressure recovery schedules.

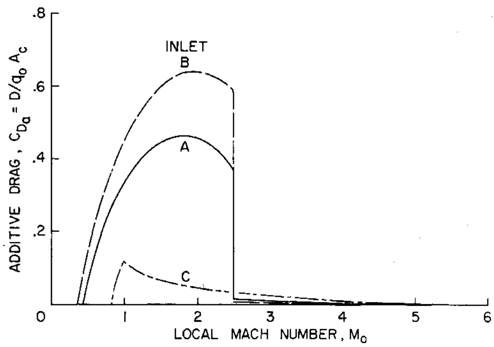


Fig. 14 Additive drag.

primarily on the minimum internal contraction ratio attainable between the cowl lip and throat stations. For the translating cowl systems, this contraction ratio is inherently quite large, resulting in the high starting Mach number of 2.5 for inlets A and B. On the other hand, inlet C (translating centerbody system) has a minimum contraction ratio of unity with the possibility of starting the inlet at any Mach number above 1.0. However, the control problems associated with operating a mixed compression system at low supersonic Mach numbers would likely dictate a starting Mach number somewhat greater than 1.0. Accordingly, a starting Mach number of 2.0 was assumed to be representative.

To achieve the levels of pressure recovery shown, boundary-layer bleed was assumed necessary. Without bleed it is believed that the required internal compression field could not be achieved. The bleed mass-flow ratio was assumed to vary linearly with local inlet Mach number from 0 to Mach number 1.0 to 10% of the capture mass flow at Mach number 5.2. The bleed airflow was assumed to have an average total-pressure recovery of one-half that of the engine airflow, and to be discharged at the local static pressure. The average discharge angle of the bleed flow was assumed to be 15° relative to the local inlet flowfield.

The primary design difference among the three inlets was centered in their design airflow characteristics as a function of Mach number. The preliminary design of the internal geometry was based on the desired airflow characteristics of each inlet subject to the constraints of achieving the required contraction ratio at the design Mach number and maintaining a slowly divergent subsonic diffuser. In addition, to insure reasonable performance, the throat Mach number was assumed to be 1.25 for the started condition, whereas for the unstarted and subsonic conditions, the maximum throat Mach number was assumed to be 0.8.

The airflow schedule for each inlet as a function of local Mach number is shown in Fig. 13. Inlet A was designed to have as high a transonic airflow capability as practical. To achieve this, the inlet was designed to have the minimum possible contraction ratio or maximum possible throat area at the most forward cowl position that was consistent with the preliminary design constraints. The resulting minimum contraction ratio was 2.0, yielding a mass flow ratio of 0.48 at Mach number 1.0, as shown in Fig. 13. The remaining portion of the airflow schedule for Mach numbers less than the starting Mach number was based on this minimum contraction ratio 2.0, the throat Mach number of 0.8, and the pressure recovery schedule given in Fig. 12. The airflow schedule for Mach numbers greater than the starting Mach number was based on the resulting variation in contraction ratio with translation combined with the prescribed pressure recovery schedule and throat Mach number.

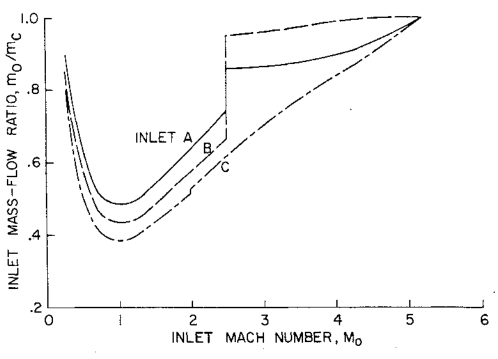


Fig. 13 Mass-flow ratio schedules.

Inlet B was designed to maintain an inlet mass-flow ratio of unity from the design Mach number of 5.2 to Mach number 4.5. For this condition, the required cowl position was uniquely determined by the local inlet Mach number and the criteria of maintaining the intersection of the initial shock with the cowl lip. The schedule of contraction ratio vs cowl position, dictated by the prescribed pressure recovery schedule and throat Mach number, required that the internal throat contours have a very low positive slope in order to match the required contraction ratio at the predetermined cowl position. The internal geometry downstream of the throat region for this range of Mach numbers (M_0 = 4.5–5.2) was then contoured to achieve the maximum possible transonic airflow while maintaining a slowly divergent subsonic diffuser at the design condition. The minimum contraction ratio achieved was 2.22, which yield a transonic mass-flow ratio of 0.43 as shown in Fig. 13. With the geometry defined, the remainder of airflow schedule was determined in the same manner as for inlet A.

Inlet C, the translating centerbody system, was designed to achieve the maximum transonic airflow and therefore required the minimum possible contraction ratio at the most forward centerbody position. The minimum contraction ratio achieved was 2.5, which resulted in a mass-flow ratio of 0.39 at Mach number 1.0. The remaining portion of the airflow schedule was determined in the same manner as for the previous two inlets.

An important fact to be noted in the study of the translating cowl systems (inlet A and B) is that there exists a definite trade between the maximum transonic airflow and the airflow at the high off-design Mach numbers. In essence, as the Mach number range for which a mass-flow ratio of unity is maintained is increased, the maximum throat area that can be achieved is decreased, reducing the transonic airflow capabil-

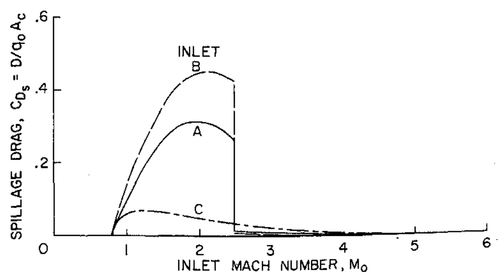


Fig. 15 Spillage drag.

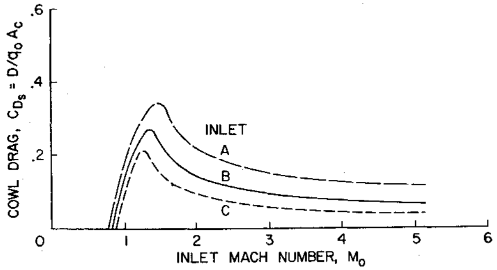


Fig. 16 Cowl pressure drag.

ity of the inlet. The airflow schedules for inlets A and B illustrated this trend.

External Performance

The external performance of the inlets includes the spillage and cowl pressure drags. The spillage drag of each inlet was calculated from its additive drag characteristics, which are shown in Fig. 14 as a function of local inlet Mach number. The additive drag characteristics were obtained from a combination of theoretical[7,8] and experimental[9] results. For Mach numbers less than the starting Mach number, there is a significantly higher level of additive drag for the translating cowl inlets than for the conventional translating centerbody inlet. This is inherent in the translating cowl systems. For this Mach number range, the translating cowl inlets, in order to achieve the maximum transonic airflow, operate at their minimum contraction ratio, which corresponds to the most forward cowl position. With the cowl so positioned, there is a significant degree of internal contraction between the cowl lip and throat stations. Since the throat Mach number is 0.8, the Mach nunber at the cowl lip is considerably less, necessitating a large degree of compression of the airflow from the freestream to the cowl lip. This resulted in the high levels of additive drag presented in Fig. 14. In contrast, the translating centerbody inlet, because of its minimum contraction ratio of unity, does not entail a large degree of external compression and consequently can produce considerably less additive drag in this Mach number range.

To account for the effects of cowl lip suction, the spillage drag for each inlet (Fig. 15), was calculated from the corresponding additive drag utilizing a technique presented in Ref. 10. The technique is based on the external cowl geometry and inlet airflow characteristics and consisted of determining the ratio of spillage drag to additive drag as a function of local inlet Mach number.

The cowl pressure drag for the three inlets (Fig. 16) reflects the reduction in drag associated with the reduction in exterior cowl angle from 14° for inlet A to 7° for inlet C. Since the calculation of the spillage drag includes the effects of the subsonic spillage prior to starting, the results presented here assume supersonic spillage down to the local Mach number corresponding to shock-wave detachment from the cowl lip. The average pressure coefficient over the cowl surface was taken to be one-half the pressure coefficient at the cowl lip based on the local lip Mach number and flow angle. The skin friction of the inlet was included in the skin friction of the entire nacelle, which was based on the local flow conditions and the turbulent boundary-layer data given in Ref. 11.

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