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Inlet Design Studies for a Mach 2.2 Advanced Supersonic Cruise Vehicle

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Various inlet-engine combinations have been studied to find a preferred inlet concept for integration with an advanced technology Mach 2.2 cruise vehicle having a cruise lift-to-drag ratio of 9.6. Inlet concept selection studies are described which indicated that an axisymmetric, mixed compression inlet was preferred. This study considered four inlet and three engine cycle combinations where the engine airflow was tailored to the inlet airflow delivery capability. Detailed design studies of two mixed compression inlet types are discussed. These were a translating centerbody inlet and a collapsing centerbody bicone inlet. The aerodynamic design of each inlet is described. These inlets were also matched to different engine cycles tailored to the inlet airflow capability. The range increments for a fixed takeoff-gross weight favored the bicone inlet concept primarily because of lighter weight, reduced bleed air, and greater transonic airflow/thrust capability.

Introduction

INLETS designed for an advanced supersonic cruise aircraft must provide high internal performance for the engine and a minimum of drag for the airplane. Douglas Aircraft Company, using internal and NASA funds,§ has been conducting a comprehensive design and aircraft integration study of inlets designed for a Mach 2.2 cruise vehicle, in support of the NASA Supersonic Cruise Aircraft Research program. Results of an inlet screening study, which considered single, dual, and quadruple engine arrangements in a given engine pod and a range of inlets including two-dimensional and axisymmetric with either mixed or external compression were presented previously.[1] The results of the previous investigation indicated the axisymmetric inlet type installed on a single-engine pod was preferred for the aircraft configuration being studied. This type of inlet provides high-pressure recovery, low distortion, and low wave drag and is lightweight.

Based on the inlet screening study results, it was not certain whether it was best to have external compression or mixed compression inlets. This uncertainty was due to the inability to assess the installed drag of the high angle cowls inherent in the external compression inlet designs with the analytical procedures available.

It was hoped that the high pressures calculated for the isolated external compression nacelle could be used on the lower surface of the wing to recover some of the isolated high cowl drag. However, subsequent wind-tunnel testing showed that this cannot be done because the high pressures on the lip do not get transmitted to the wing lower surface due to viscous effects on the wing lower surface and radial attenuation from the nacelle. With the results of the wind-tunnel test it was now possible to assess a drag penalty to the cowl lip and properly assess the installed drag for a study inlet.

This paper covers the investigations that have occurred since the initial screening process and wind-tunnel investigations discussed above. A more detailed investigation of an external compression axisymmetric inlet and mixed compression axisymmetric and two-dimensional inlets was conducted which combined the results of the wind-tunnel investigation and further refinements in inlet characteristics. This study included inlet-engine tailoring, which involved variations in engine airflow characteristics to better match the candidate inlets.

Inlet Concept Selection

Studies were conducted to select a preferred inlet type for single-engine pod installations before proceeding with detailed inlet design efforts for a Mach 2.2 cruise vehicle. In these studies, engine cycles, each with different airflow schedules, were matched to different inlet concepts and the aircraft range increments were calculated for each of the inlet-engine combinations.

Four inlets were chosen and were integrated with three engine cycles. The first was an axisymmetric external compression inlet (Fig. 1) with a collapsing centerbody. Because all of the compression including the normal shock occurs externally, the external cowl angle for this inlet was high, 24 deg. The second was an axisymmetric mixed compression inlet (Fig. 2) with a centerbody that translates fore and aft. Because part of the compression occurs internally, the external cowl angle for this inlet was only 6 deg. The same inlet was selected for the third configuration except that the forward section of the centerbody was translated aft to open up an annular passage, thus increasing the flow area by 12% [identified as a centerbody (CB) auxiliary inlet, as shown in the lower half of Fig. 2]. The fourth configuration was a bifurcated two-dimensional mixed compression inlet with variable geometry vertical ramps (Fig. 3). The external cowl angle for this inlet was the same as for the two preceding configurations. Inlets 1 and 2 were identified in earlier studies as the best candidates. Inlet 3 was selected to alleviate the low transonic airflow delivery capability of the second inlet. The last configuration, the two-dimensional inlet, was added to the study because it offered the high transonic airflow delivery capability of the first external compression inlet but had a less complex variable geometry system since only flat surfaces were being moved as opposed to sliding curved surfaces in the first inlet.

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The three engines used in the inlet integration study were: 1) a dry turbojet cycle developed for internal use by Douglas, 2) an advanced technology low-bypass engine made by General Electric Company (GE21/J10-B3), and 3) a GE advanced technology variable cycle engine which featured a double-bypass system (GE21/J11-B10). The inlets were integrated with each engine, whose airflow schedule was adjusted as much as possible to match the inlet delivery capability.

Each propulsion system was installed on a Mach 2.2 supersonic cruise aircraft having a cruise lift-to-drag (L/D) ratio near 9.6, with small variations in L/D and weight occurring owing to the installed propulsion system package.

The resulting range increments for a fixed takeoff gross weight are shown in Fig. 4. For the Douglas turbojet, where the centerbody auxiliary was not considered, the basic mixed compression axisymmetric inlet was best. For the GE engines, the mixed compression inlet with the centerbody auxiliary, inlet 3, was superior to the others. This conclusion has been substantiated in another study where the second and third inlets were matched to a Pratt & Whitney Aircraft (P&WA) low-bypass engine.[2]

Based on these studies, the mixed compression axisymmetric-type inlet was the clear choice. The high drag due to the high angle cowl required by the external compression inlet and the greater weight of the two-dimensional inlet were principal factors that degraded their range performance. As a result of these studies, a more in-depth investigation of the mixed compression axisymmetric inlet type was conducted. In this follow-on study, the high transonic airflow delivery feature of the collapsing centerbody used for the external compression inlet was incorporated in a mixed compression design. This inlet was studied in equal depth with a translating centerbody mixed compression inlet incorporating a centerbody auxiliary inlet system.

Inlet Design of the Preferred-Inlet-Type
Aerodynamic Design

The translating centerbody inlet achieves part of the compression externally by using a 12.5-deg half-angle cone; the remainder is provided internally aft of the cowl lip using both the internal cowl and centerbody surfaces (Fig. 5). The cowl lip is placed immediately aft of the shock generated by the cone and has an external angle of 6 deg and an internal angle of 0.5 deg, both outward relative to the centerline. The external cowl angle was set by the flow conditions behind the shock generated by the cone, while the internal angle was set by internal compression and structural requirements. The 12.5-deg half-angle cone was selected from results of studies conducted by NASA and from requirements for off-design operation and mechanical design. A normal shock occurs downstream in the minimum area region to reduce the flow to subsonic speeds, and a short diffuser with vortex generators is employed to reduce the Mach number as required by the engine. A translating centerbody is used to maintain supersonic flow within the supersonic diffuser portion of the inlet down to a Mach number where an expelled normal shock does not produce an unreasonable drag penalty.

The supersonic diffuser was designed by using a Douglas-developed rotational method-of-characteristics (MOC) computer program.[3] This procedure was used to define the inviscid supersonic diffuser contours for the design cruise conditions, as shown in Fig. 6. With this method, a normalized surface Mach number distribution is specified and the MOC solution generates the surface. Results of a NASA Q-type inlet were used as a starting point for these prescribed pressure distributions. Once the on-design geometry was defined, the off-design lower Mach number analysis was conducted by inputting the geometry and solving for the flow conditions. This is an iterative procedure where the centerbody is translated forward from the on-design position as the Mach number is reduced. Figure 7 shows the resulting centerbody translation schedule and the shock patterns obtained from MOC solutions indicating started inlet operation. Maintaining inlet operation below Mach 1.6 was not considered since the geometry would have to be changed and this would complicate the design of the inlet from a mechanical viewpoint, and since the normal shock losses are relatively small below this Mach number.

This inlet has been designed to keep the throat (minimum duct area) at the same centerbody position as it is translated for the off-design operation, as shown in Fig. 7. This characteristic allows for a simplified bleed system in the centerbody which will be discussed later. These features, however, produce a duct area that does not increase significantly as the centerbody is translated during the off-design condition. A centerbody auxiliary inlet concept for this type of inlet designed and tested by NASA,[4] and the results show that there is an increase in duct flow area of approximately 12% of the capture area. This auxiliary system is shown in Fig. 2. The inlet airflow delivery capability with and without the auxiliary inlet is shown in Fig. 8. The auxiliary inlet system is used below Mach 1.6, where the normal shock is expelled from the inlet.

The boundary-layer bleed system of the translating centerbody inlet is shown in Fig. 9. The bleed regions are placed

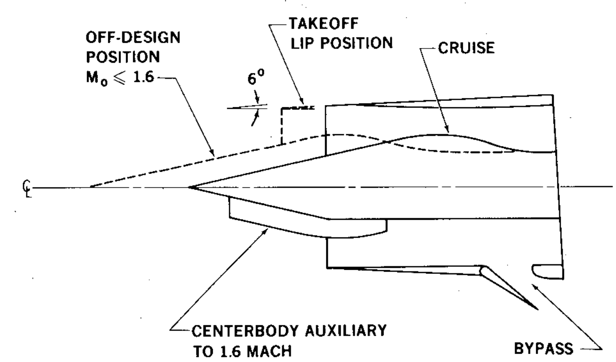

Fig. 2 Mixed compression inlet with translating centerbody and auxiliary inlet.

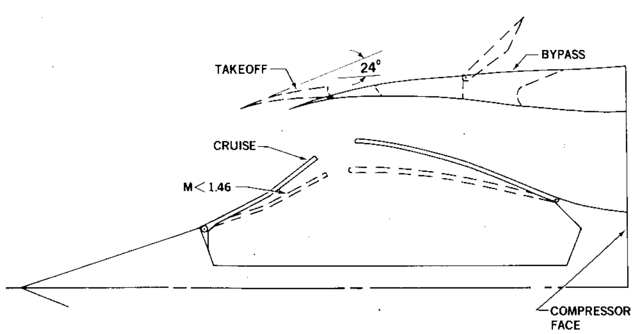

Fig. 1 External compression inlet.

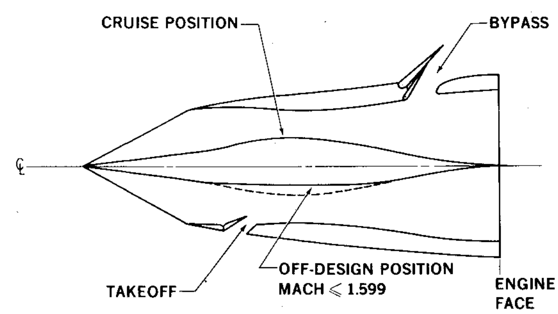

Fig. 3 Two-dimensional mixed compression inlet.

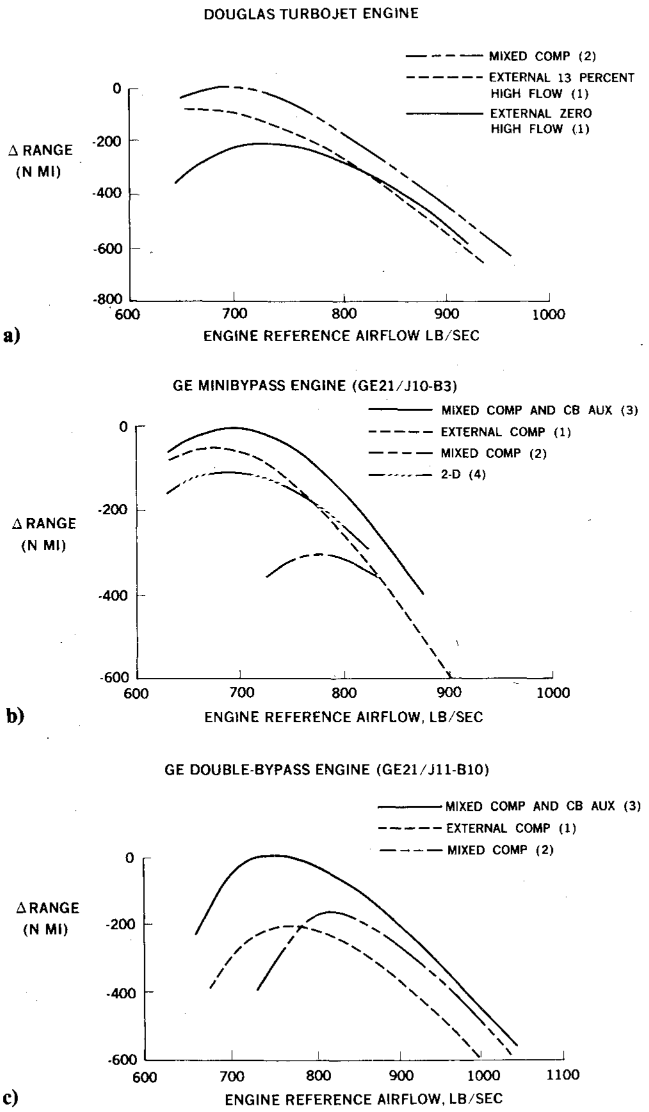

Fig. 4 Effect of inlet-engine combination on aircraft mission range.

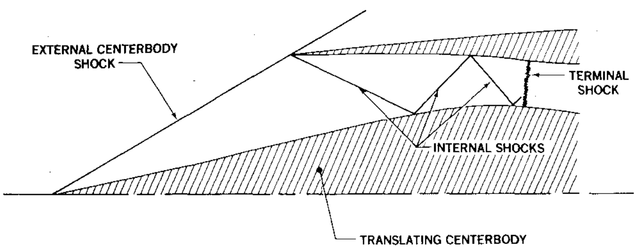

Fig. 5 Mixed compression translating centerbody inlet concept.

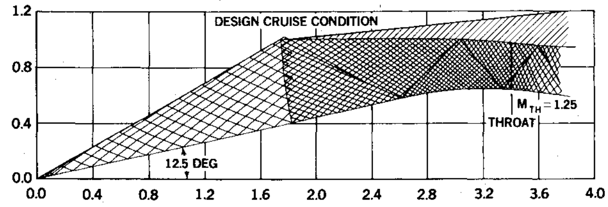

Fig. 6 Translating centerbody inlet, $M_L = 2.16$ MOC solution.

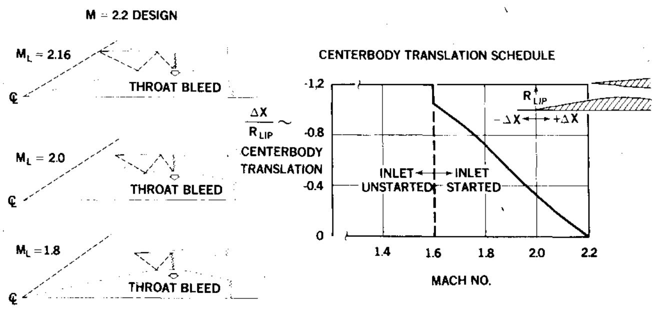

Fig. 7 Translating centerbody inlet off-design inlet operation.

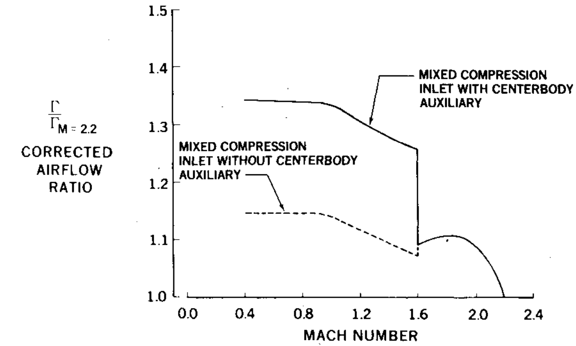

Fig. 8 Centerbody auxiliary inlet airflow delivery capability.

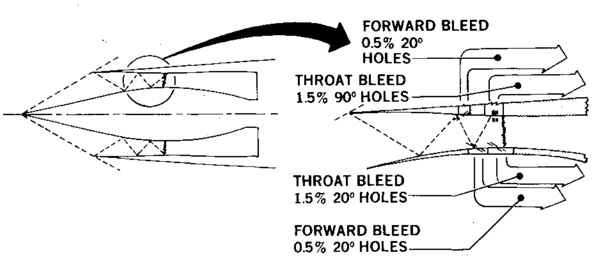

Fig. 9 Translating centerbody inlet bleed.

downstream of the first shock intersection and upstream of the terminal shock on the cowl. On the centerbody, the bleed regions are placed aft of the second shock intersection and forward of the terminal shock.

The cowl and centerbody holes are slanted 20 deg, relative to the inlet centerline, in the forward regions to maximize pressure recovery at the bleed exit in order to keep the momentum loss of the bleed mass flow to a minimum. In the aft region near the throat, the 20-deg holes are retained on the centerbody to keep the pressure high and minimize the duct area required to pass the bleed flow out the support tube and overboard. On the cowl, 90-deg holes are used to increase inlet unstart margins. The ratio of the airflow passed for subsonic external flow to that passed for supersonic external flow is larger for the 90-deg holes than for the 20-deg holes. As the normal shock moves forward in the throat in an inlet unstart, the subsonic flow region moves over the 90-deg cowl bleed holes and increases the bleed flow, thus stabilizing the inlet flowfield. The cowl bleed flows are vented overboard through slots on the outer cowl. The centerbody bleed flows are kept separate and are ducted across the auxiliary inlet, aft through the support tube, and across the subsonic diffuser through struts to the outer cowl. Since the inlet is designed so that the terminal shock stays fixed on the centerbody as the centerbody is translated for off-design conditions, there is no need for many throat bleed regions on the centerbody with its attendant complexity. The total bleed flow is 4% of the captured flow at the design cruise condition.

The subsonic diffuser has been designed using the throat and engine face Mach numbers at the design cruise condition and a minimum diffuser length based on a linear Mach number distribution that does not exceed a specified limit ($\Delta M/R_{LIP} = 0.210$). The subsonic diffuser design criteria used includes the use of vortex generators downstream of the throat.

Bicone Inlet

The bicone inlet is characterized by having two cones for external compression and a shaped internal cowl that isentropically compresses the flow. The cowl compression is focused on the centerbody in the throat region, as shown in Fig. 10. Results of a similar inlet designed and tested by NASA Lewis were used to guide the compression surface design.[5] Off-design started operation between Mach 2.16 and 1.6 is accomplished by progressively collapsing the second cone. For unstarted operation (terminal shock outside the cowl lip) below Mach 1.6, the second cone is fully collapsed to the initial cone angle.

Several combinations of initial and second cone angles were investigated by using the MOC procedure to determine the best cone angles that would yield high inlet performance and minimize mechanical complexity. Figure 11 shows one of the cone angle combinations investigated and the MOC solutions at the on-design cruise condition. The inviscid pressure recovery at the throat for each configuration is shown in the lower part of Fig. 11. The external and internal cowl angles were kept the same as the translating centerbody inlet angles of 6 and 0.5 deg, respectively. The second cone segment length was determined by the on-design (Mach 2.16) cowl shock intersection point on the centerbody. Once the location was determined, the second cone length was fixed and a bleed slot located over the region where the cowl compression was distributed (Fig. 10). Having the on-design geometry, an off-design MOC analysis was conducted by varying the Mach number and second cone angle while maintaining supersonic flow within the diffuser. The cowl shock was not allowed to intersect the surface of the second cone because the cowl shock wave would be reflected toward the cowl compression region where the surface Mach numbers are already low. This condition would result in subsonic flow and cause the inlet to unstart. Figure 12 shows the cowl shock wave intersection points for the 9- and 12-deg initial cone angle configurations. When the second cone is fully collapsed to the initial cone angle for the 9-deg cone angle configurations, the cowl shock intersects the throat slot region of the 17.5-deg second cone segment, whereas it intersects the 15-deg second cone segment ahead of the throat slot. Similar results were found for the 12-deg initial cone angle configurations. Therefore the 9/15- and 12/16.5-deg combinations were eliminated from further considerations. The 9/17.5-deg configuration was selected over the 12/18.5-deg configuration because it had a slightly higher pressure recovery level (Fig. 11). The intersection of the cowl shock on the second cone could be solved by translating the centerbody forward, but the added complexity and weight were not justified for the small recovery advantage of these configurations.

For the selected inlet, the off-design shock wave and second cone angle schedule are shown in Fig. 13.

The bicone inlet uses a single bleed slot in the centerbody at the throat to control separation caused by the interaction of the terminal shock wave and the boundary layer (Fig. 10). No cowl bleed is anticipated, as shown by NASA test data obtained for an inlet of this type designed for Mach 2.5.[6] This is primarily due to the relatively short cowl length and, hence, smaller boundary layer growth in the supersonic diffuser and to the absence of any reflected shocks that could cause boundary layer separation. The centerbody boundary layer is bled through the slot formed by the gap between the supersonic and subsonic diffusers, as shown in Fig. 10. The slot width for the on-design condition is determined from the cowl shock position and the region over which the focused cowl compression is distributed. The bleed slot width for the selected configuration is $0.25R_{LIP}$. The centerbody bleed flow is ducted through the centerbody support struts that are located in the subsonic diffuser, and the flow exits through louvers on the external cowl. The total bleed flow is 2% of the captured flow at the design cruise condition.

The subsonic diffuser has been designed to the same aerodynamic criteria as the translating centerbody inlet except for mechanical constraints imposed by the collapsing centerbody concept.

Bypass System and Takeoff Operation for Both Inlets

The identical bypass system is used on both inlets. It is sized to bypass 90% of the capture airflow at the design cruise condition for a seized rotor. A door system is located forward of the engine face and the bypass flow exits through the doors and then through fixed louvers on the external cowl surface of the nacelles. The doors are used to bypass excess inlet air as well as for any shock control that is required.

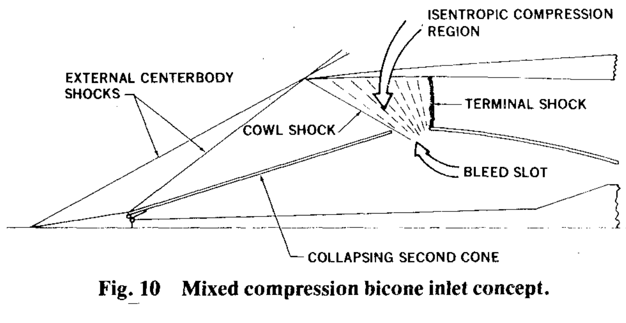

Fig. 10 Mixed compression bicone inlet concept.

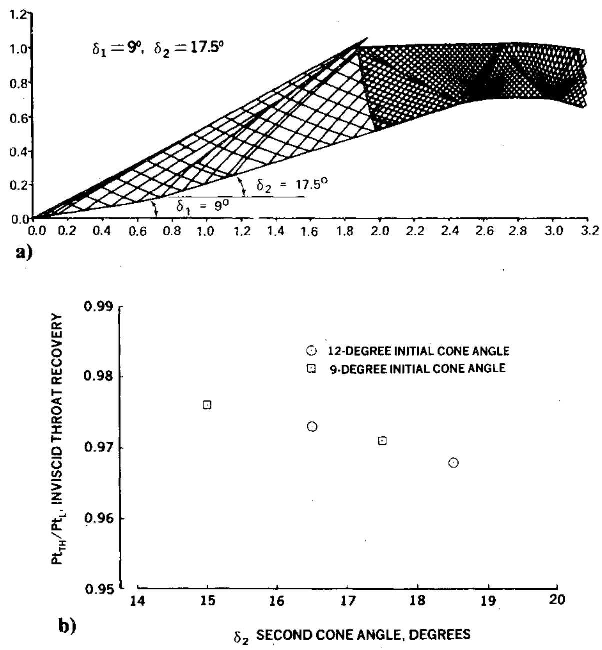

Fig. 11 Bicone MOC solution and throat recoveries, $M_L = 2.16$.

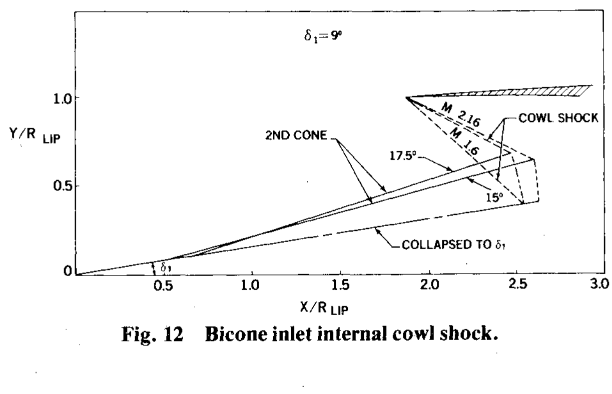

Fig. 12 Bicone inlet internal cowl shock.

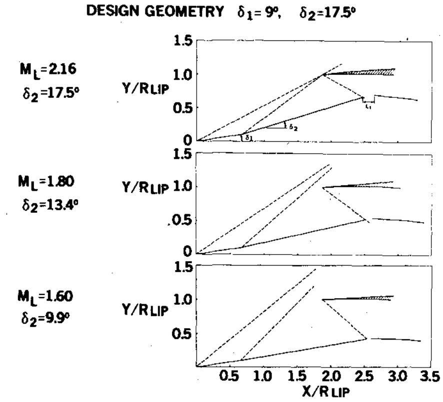

Fig. 13 Bicone inlet off-design operation.

GE 21/J11 — B18 ENGINE
W2R = 340 KG/SEC (750 LB/SEC)

INLET ITEM	BICONE INLET WEIGHT (POUNDS)	TRANSLATING INLET WEIGHT (POUNDS)	DELTA WEIGHT (POUNDS)
INLET COWLING	1125	1289	164
CENTERBODY AND SUPPORT	685	1227	542
ADDITIONAL ITEMS (PLUMBING, FLUID, ETC.)	52	52	0
TOTAL FUNCTIONAL INLET WEIGHT	1862	2568	706

Fig. 14 Inlet weight comparison.

Both inlets utilize a translating cowl lip to reduce the inlet losses and engine face distortion at takeoff and low-speed conditions. The cowl lip is translated forward to open a slot with a moderately thick lip, which exposes a forward facing surface on which to generate suction to turn the flow into the inlet. This concept has proven to be effective in previous tests.[7,8]

Weight

Based on preliminary design drawings, the weight comparison shown in Fig. 14 indicates that the bicone mixed compression inlet is lighter than the translating centerbody mixed compression inlet owing to the shorter length and the smaller overhung moment. The translating centerbody structure has a greater weight than the bicone inlet owing to the centerbody auxiliary air duct passage, the centerbody bleed struts across the duct, the centerbory auxiliary air exit doors, and the mechanism required for the door actuation.

Inlet-Engine Integration

The inlet performance characteristics required for inlet-engine integration, primarily inlet total pressure recovery and airflow delivery capability, are shown in Fig. 15 for the translating centerbody and bicone inlets. The recovery levels of both inlets are nearly equal throughout the operating range, with the bicone inlet having a slight advantage in the transonic region. The airflow delivery capability of the bicone inlet is significantly higher in the transonic region owing to the large variation in throat area achieved by the collapsing centerbody.

The inlet-engine cycles were tailored by GE and P&WA. Each was supplied with the inlet performance characteristics of the translating centerbody inlet and the bicone inlet. Each company developed advanced engine cycles that were tailored to match the inlet airflow delivery capability within operating constraints imposed on the engine. These engine cycles were different than those discussed in the inlet concept selection. GE developed a variable-cycle engine, designated the

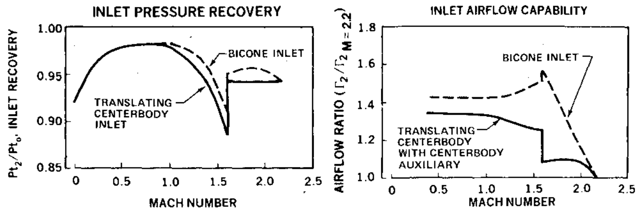

Fig. 15 Mixed compression inlet performance comparison.

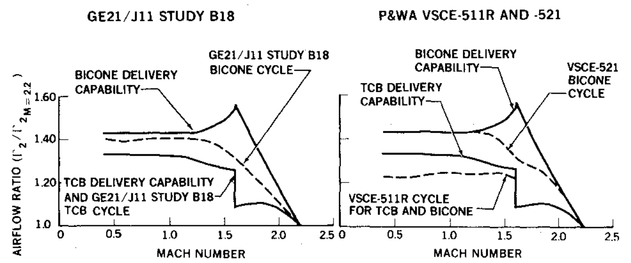

Fig. 16 Inlet engine match for translating centerbody and bicone inlets.

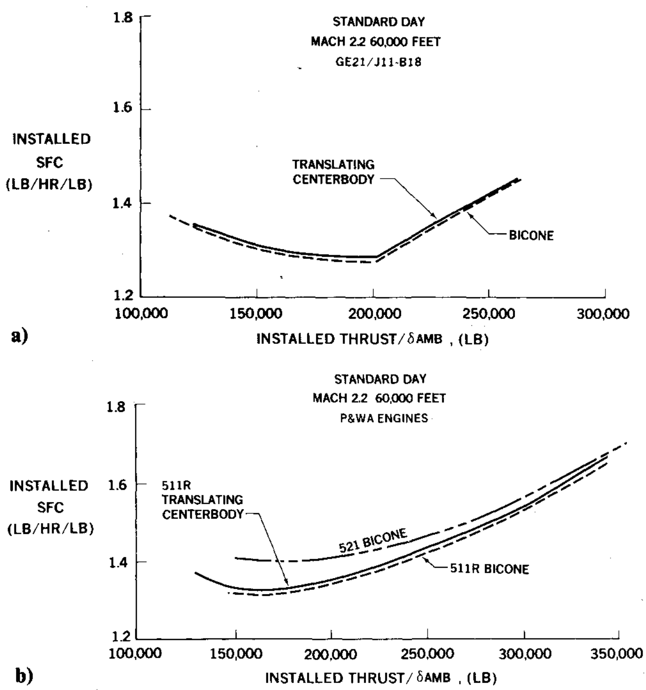

Fig. 17 Installed supersonic cruise propulsion system performance.

GE21/J11 Study B18, which featured a variable bypass concept. P&WA developed two duct-burning turbofan engines: the VSCE-511R to be used with both inlets and the VSCE-521 to be used only with the bicone inlet with a cycle tailored to the bicone inlet delivery schedule. The engine airflow schedules are compared with the inlet delivery schedules of both inlets in Fig. 16.

The performance of the installed propulsion system was obtained by combining the inlet performance and nacelle drag characteristics with the performance of the uninstalled engine. The nacelle drag evaluation covered the drag due to boundary layer bleed, cooling and environmental system air, external nacelle skin friction, afterbody drag in excess of the cruise condition, and integrated nacelle/airframe wave drag. The inlet was sized for cruise where the required capture area was largest and matched to the engine airflow characteristics throughout the Mach number range. The inlet sizing

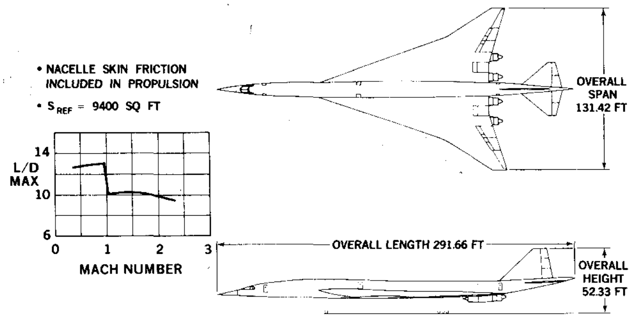

Fig. 18 Baseline aircraft for mission performance studies.

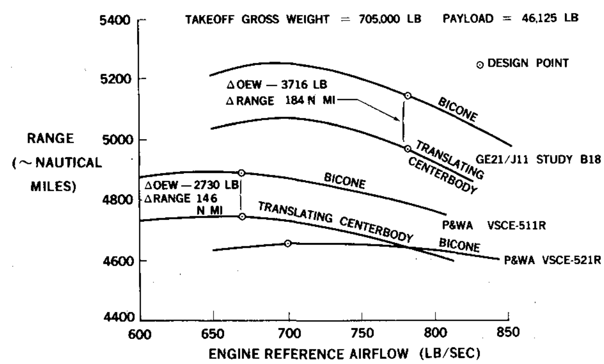

Fig. 19 Effect of inlet design on aircraft range.

ENGINE	GE21/J11 STUDY B18		P&WA VSCE-511R		P&WA VSCE-521R
INLET	TCB	BICONE	TCB	BICONE	BICONE
Γ_2 MISSION SIZE (LB/SEC)	782[1]	782[1]	670[2]	670[2]	700[3]
EMPTY WEIGHT (LB)	292,590	288,874	285,690	282,960	280,375
RANGE (N MI)	4961	5145	4740	4886	4652
L/D MIDPOINT CRUISE	9.62	9.63	9.52	9.48	9.47
SFC MIDPOINT CRUISE (LB/HR/LB)	1.286	1.280	1.374	1.361	1.466
TAKEOFF FIELD LENGTH (FT)	10,900	10,900	11,000	11,000	10,530
HEIGHT AT 3.5 N MI (FT)	1173	1173	1175	1175	1609

NOTES
1. ENGINE SIZED BY TAKEOFF NOISE
2. ENGINE SIZED BY TAKEOFF FIELD LENGTH OF 11,000 FEET
3. ENGINE SIZED BY MAXIMUM RANGE

Fig. 20 Mission performance summary.

procedure accounted for engine airflow, boundary layer bleed, and engine compartment cooling and environmental system airflow. Once the inlet was sized, any excess airflow was either bypassed or spilled, and the resulting drag included depending on which resulted in minimum loss.

Specific fuel consumption (SFC) during cruise flight with the engine installed is shown in Fig. 17. The bleed drag resulting from the 2% difference in bleed flow is the primary factor in the differences shown between the translating centerbody and bicone inlets for a given engine. The bicone/engine combinations also had more climb thrust because of increased airflow capability.

Integrated Aircraft Mission Performance

The installed propulsion system performance was combined with the aerodynamic characteristics of the Douglas Model D3231 Mach 2.2 cruise aircraft, an updated configuration from that used in the previous range study. Figure 18 shows the general arrangement of the aircraft configuration and the maximum L/D characteristics as a function of Mach number. The vehicle is configured to carry 225 passengers in a mixed-class configuration, has a fixed takeoff gross weight of 705,000 lb, and has a modified arrow wing with an area of 9400 ft^2. The wing, body and nacelles were optimized to obtain a minimum-wave drag configuration. The mission analysis was conducted by maintaining a constant takeoff gross weight and adhering to takeoff field length and noise constraints. Adequate thrust margins were maintained during the climb portion of the mission.

The resulting mission performance of each of the inlet-engine configurations is shown in Figs. 19 and 20. The range differences between the bicone and translating centerbody inlet installation for either engine are primarily due to differences in the inlet weight and cruise boundary layer bleed drag. The GE21/J11-B18 bicone inlet installation also benefits during the climb portion by having a significantly higher thrust in the transonic region. The VSCE-521 bicone inlet installation suffers a range penalty relative to the VSCE-511R bicone inlet installation because of a higher cruise SFC and a slightly higher engine weight required to obtain the higher engine airflow.

Conclusion

The results of the inlet concept selection study considering four inlets (axisymmetric external compression, axisymmetric mixed compression, axisymmetric mixed compression with centerbody auxiliary, and two-dimensional mixed compression) and three engine cycles have shown the axisymmetric mixed compression inlet concept installed in a single-engine nacelle to be the preferred concept for installation on a Mach 2.2 cruise vehicle. The principal factors that result in this conclusion are the high drag of the external compression inlet cowl lip and the greater weight of the two-dimensional inlet. Subsequent detailed design studies conducted for a translating centerbody inlet with a centerbody airflow auxiliary device and a bicone collapsing centerbody inlet indicate that the bicone inlet concept has superior performance. The bicone performance advantages are due to lighter weight, reduced bleed drag, and greater climb airflow/thrust capability.

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