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Some Effects of Cruise Speed and Engine Matching on Supersonic Inlet Design

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An analytical study was conducted to determine the impact of flight Mach number on inlet type selection for a supersonic cruise aircraft. External and mixed-compression axisymmetric and two-dimensional inlets were considered. The internal contraction of the mixed-compression inlets was limited to achieve self-starting. At Mach 2.0, the axisymmetric mixed-compression inlet provided the best aircraft range. At Mach 2.3, the two-dimensional mixed-compression inlet was the most attractive if enough variable geometry were incorporated to minimize spillage during subsonic cruise. Increases in transonic-to-cruise air flow ratio gave lower aircraft range.

Nomenclature

A/A^*	= ratio of flow area to critical flow area
A/B	= afterburning
A_C	= inlet capture area
A_{TH}	= inlet throat flow area
A_W	= wetted area of supersonic diffuser
C_D	= drag coefficient
$C_{D_{BLD}}$	= bleed drag coefficient
$C_{D_{SPILL}}$	= spillage drag coefficient
L/D	= lift-drag ratio
m_{BLD}/m_L	= inlet bleed-to-local mass flow ratio
M_L	= inlet local Mach number
M_0	= freestream (flight) Mach number
P_0	= ambient static pressure
P_{T_0}	= freestream total pressure
P_{T_L}	= inlet local total pressure
P_{T_2}	= fan-face total pressure

Subscripts

OW	= overwing
UW	= underwing

Introduction

RECENT supersonic cruise research (SCR) studies at the Lockheed-California Company were directed toward aircraft designed for cruise at Mach numbers of 2.0, 2.3, and 2.55. The general purpose of this effort was to assess at what point a change in cruise speed imposed a change in technology level for certain components of the aircraft.

At Mach 2.0, external-compression inlets were expected to be competitive with mixed-compression types. By contrast, cruise at Mach 2.55 clearly required mixed-compression inlets. Studies at Mach 2.3 were also undertaken to define more clearly a crossover Mach number at which the advantage would swing to a higher technology, mixed-compression inlet.

Another issue that arose in these and earlier studies was the desirability of engines with relatively large takeoff and transonic flow capacity. Variable cycle engines, such as those being developed by General Electric (GE) and by Pratt & Whitney Aircraft (P & WA), offer a wide range of takeoff and transonic air flow capacities relative to supersonic cruise. On account of the dominant influence of transonic-to-cruise corrected air flow ratio (WCR) on inlet design, it was important to evaluate the influence of this parameter on aircraft range.

The effects of subsonic cruise distance on total aircraft range were also explored. It is desirable for a supersonic cruise aircraft to have efficient subsonic cruise capability, to enhance its usefulness for both overwater and overland operations. Any effects of inlet design on aircraft range for mixed supersonic and subsonic cruise are thus potentially important.

In general, inlet performance cannot be optimized in isolation from engine and airframe performance. Thus aircraft range was used as the figure of merit in evaluating inlet-engine combinations.

The main objectives of the present study were to 1) obtain quantitative performance comparisons on the effect of inlet internal contraction for aircraft with supersonic cruise Mach numbers of 2.0 and 2.3; 2) evaluate the effect of transonic-to-cruise corrected air flow ratio on aircraft range; and 3) identify inlet design requirements for efficient subsonic cruise performance of the aircraft.

Study Configurations

Both axisymmetric and two-dimensional inlets were studied at Mach 2.0, 2.3, and 2.55. The mixed-compression inlets studied at Mach 2.0 and 2.3 were limited to self-starting types. Such inlets can be restarted without any change in inlet geometry, and so have potentially fewer unstart problems than inlets requiring variable geometry for restart. They also have potentially higher total pressure recovery and lower cowl drag than external-compression inlets.

The Mach 2.55 two-dimensional and axisymmetric inlet designs are described in Refs. 1 and 2.

The Mach 2.0 aircraft used in this study is shown in Fig. 1. It and the Mach 2.3 aircraft are derivatives of the Lockheed baseline Mach 2.55 aircraft, described in Ref. 3. All aircraft in this study have a takeoff gross weight of 592,000 lb and 290 passengers. Other characteristics are listed in Table 1.

The optimum wing loading and takeoff thrust-to-weight ratio for each aircraft were determined from the Lockheed advanced systems synthesis and evaluation technique (ASSET).

Each of the study engines had a maximum corrected air flow which was constant from takeoff to transonic speeds. The engine takeoff air flows were matched by use of auxiliary inlet doors. All of the inlet configurations could match the maximum transonic airflow capability of the various engines except for the axisymmetric inlets with translating centerbodies.

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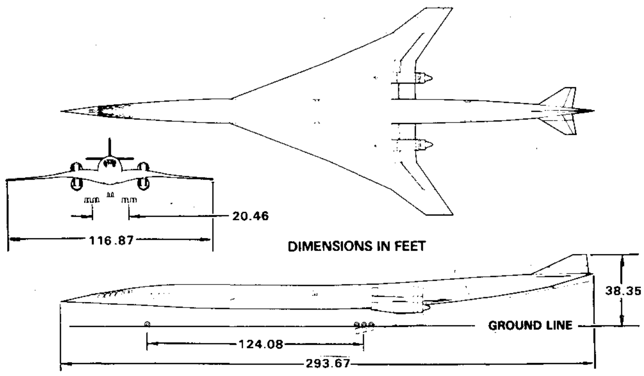

Fig. 1 General arrangement Mach 2.0 SCR vehicle.

Table 1 Some characteristics of aircraft included in this study

Mach no.	Wing loading, psf	Leading-edge sweep, deg	Aspect ratio
2.0	91	68/66/53	2.10
2.3	85	71/67/55	1.95
2.55	88	73/70/58	1.72

Table 2 Differences in inlet local Mach number

M_0	$M_{L,\mathrm{OW}}$	$M_{L,\mathrm{UW}}$
2.0	2.16	1.97
2.3	2.48	2.26
2.55	2.75	2.51

Each of the Mach 2.0 two-dimensional inlet types, and also the Mach 2.55 axisymmetric collapsing spike inlet (Ref. 2), were matched with two or more engines. The purpose was to assess the influence of WCR on aircraft range. Increased WCR was accompanied by increased engine fan diameter. The larger engine diameter generally forced greater inlet length, because of limitations on subsonic diffuser divergence angle.

There were significant differences in inlet local Mach number M_L between the OW and UW engine positions (see Table 2).

The supersonic diffuser shape was designed for $M_{L,\mathrm{OW}}$ at supersonic cruise. The underwing inlet was then operated off-design at cruise, but with only a small critical spillage drag penalty. The inlets were sized to provide the same corrected air flow rate at cruise. Thus the underwing capture area was smaller than the overwing value.

A family of Mach 2.0, two-dimensional, external-compression (2.0/2-D/EX) inlets was designed to match several variable-cycle engines. Figure 2 shows the inlet design matched to the GE21/J11B21 engine. This inlet had a variable-geometry vertical wedge centerbody with a fixed 7-deg half-angle initial wedge. This was followed by a movable isentropic compression surface that merged into a straight ramp which terminated at the inlet throat. At supersonic cruise, this ramp angle was 20.9 deg. The throat was at the forward edge of the centerbody bleed slot. The cowl lip internal angle was 10.2 deg. The cowl shock was a strong-solution oblique shock extending to the forward edge of the centerbody bleed slot. A Mach 2.2 inlet with a similar shock system was described in Ref. 4. The overwing and underwing inlets had identical planforms, but differed in height because of the different capture areas.

For all of the inlets, when the cowl lip shock was attached, the geometries of the overwing and underwing inlets were varied with M_L in the same way. For M_L less than the value for cowl lip shock attachment, the geometries of the overwing and underwing inlets were varied with M_L and engine corrected air flow in different ways. This was done to minimize spillage drag.

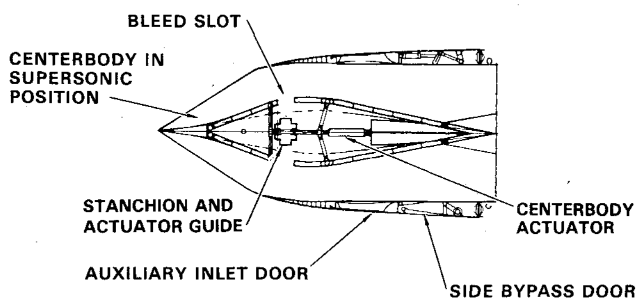

Fig. 2 2.0/2-D/EX inlet for GE21/J11B21 engine.

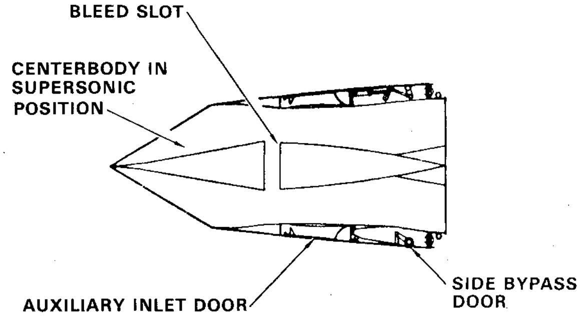

Fig. 3 2.0/2-D/SS inlet for GE21/J11B21 engine.

Mach 2.0, two-dimensional, self-starting (2.0/2-D/SS) inlet designs were developed for the GE21/J11B21 and GE21/J11B13 engines. A ground rule was that the inlet transonic air flow capacity match or exceed the maximum engine demand at the underwing inlet installation. External compression was achieved by a vertical wedge, followed by an isentropic compression region, followed by a shock corner. Internal compression was achieved by compressive turning through the cowl lip shock, followed by isentropic cowl compression between the cowl lip and the throat. The cowl lip shock was cancelled at the centerbody by a corner expansion. Depending on the desired throat angle, a centerbody isentropic compression or expansion was required just upstream of the expansion corner. This was selected to achieve a uniform Mach number at the throat.

The procedure for generating self-starting limits used experimental starting area ratio data for inlets with no boundary-layer bleed (Ref. 5). These data were adjusted to reflect the presence of boundary-layer bleed by decreasing the required starting throat area by the amount of throat flow area associated with the boundary-layer bleed. Further details are given in Ref. 3.

The 2.0/2-D/SS inlet design with the GE21/J11B21 engine is shown in Fig. 3. The initial wedge half-angle was 4 deg, followed by isentropic compression to 6 deg. At the shock corner the flow was turned to 10 deg. The internal cowl lip angle was 0 deg, and the throat angle was −4.4 deg.

A similar design was executed for the 2.0/2-D/SS inlet with the GE21/J11B13 engine. It is significant that this inlet had a 4-deg internal cowl lip angle because of the need to provide higher transonic air flow for the GE21/J11B13 engine. The amount of centerbody collapse was limited by mechanical constraints, so the additional transonic flow area was provided by moving the cowl outward. For nearly the same capture area as with the GE21/J11B21 engine, this required a greater cowl angle. Thus, the increased WCR of the GE21/J11B13 engine led to a nacelle drag penalty. The limits on centerbody collapse also led to some internal contraction

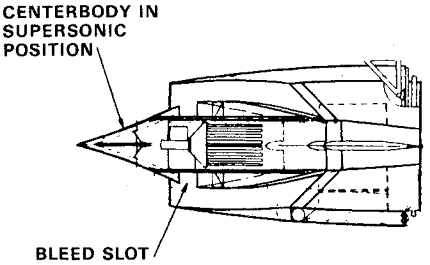

Fig. 4 2.0/AX/EX inlet for GE21/J11B21 engine.

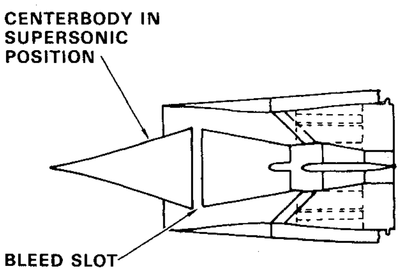

Fig. 5 2.0/AX/SS inlet for GE21/J11B21 engine.

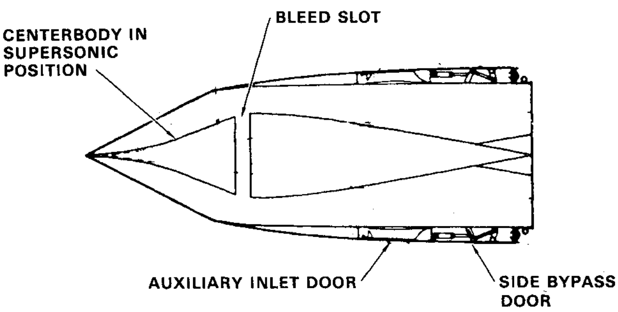

Fig. 6 2.3/2-D/EX inlet for GE21/J11B19 engine.

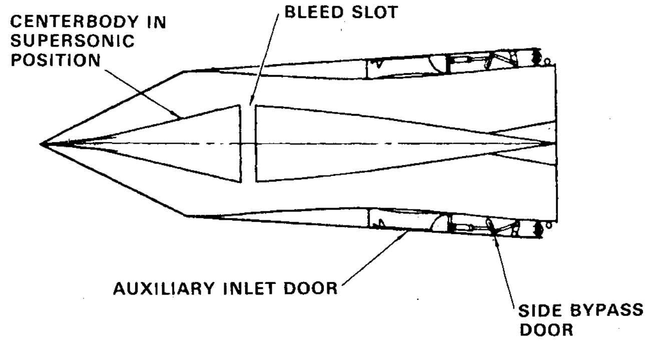

Fig. 7 2.3/2-D/SS inlet for GE21/J11B19 engine.

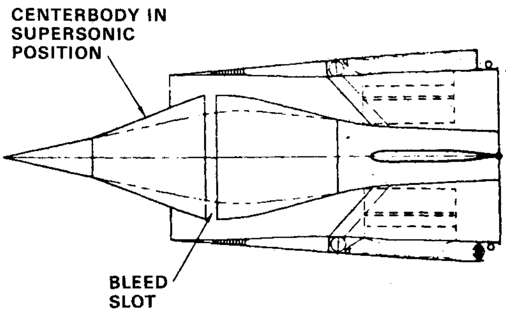

Fig. 8 2.3/AX/SS inlet for GE21/J11B19 engine.

at the fully-collapsed position, resulting in subcritical spillage at Mach numbers below the started value.

A Mach 2.0, axisymmetric, external-compression (2.0/AX/EX) inlet was designed for the GE21/J11B21 engine. The spike consisted of an initial cone with an 18-deg half-angle, followed by an isentropic compression surface which terminated with a conical section of 23.9 deg half-angle. A strong-oblique cowl lip shock extended to the forward edge of the bleed slot. The internal cowl lip angle was 3 deg, in order to minimize nacelle wave drag. As a result, the cowl lip shock detached for M_L less than 1.9. The 2.0/AX/EX inlet design is shown in Fig. 4.

Flow area variation for the 2.0/AX/EX inlet was achieved by translating the spike both fore and aft from the supersonic cruise design position. Throat area was increased for takeoff by forward spike translation, and was decreased for subsonic engine-throttled operation by aftward spike translation. The limited throat area variation of this inlet prevented it from using the maximum transonic air flow of the engine during climb. Further details of the inlet design are given in Ref. 3.

The last of the Mach 2.0 inlet designs was an axisymmetric, self-starting (2.0/AX/SS) inlet for the GE21/J11B21 engine, shown in Fig. 5. The inlet achieved external compression by use of a 12-deg half-angle cone, followed by isentropic compression to a final angle of 16.9 deg. Internal compression was achieved by a cowl lip shock, followed by isentropic compression turning to a throat Mach number of 1.3. The cowl lip shock was cancelled at the forward edge of the bleed slot. The optimum internal cowl lip angle was 0 deg. This inlet also could not satisfy the maximum transonic air flow capability of the engine during climb. A detailed description of the design and operation of the 2.0/AX/SS inlet is given in Ref. 3.

A Mach 2.3, two-dimensional, external-compression (2.3/2-D/EX) inlet design was matched to the GE21/J11B19 engine. The 2.3/2-D/EX inlet design is shown in Fig. 6. It was generally similar to the 2.0/2-D/EX inlet designs. The initial wedge half-angle was 5 deg, and the maximum centerbody ramp angle was 22 deg. The internal cowl lip angle was 7 deg.

The Mach 2.3, two-dimensional, self-starting (2.3/2-D/SS) inlet design for the GE21/J11B19 engine was also similar to its Mach 2.0 counterparts. It is shown in Fig. 7. The initial wedge half-angle was 4 deg, followed by isentropic compression to 8 deg, followed by turning at the shock corner to 13.5 deg. The internal cowl lip angle was 0 deg. This inlet also had some internal contraction with the centerbody fully collapsed.

The axisymmetric inlet selected for the Mach 2.3 aircraft with the GE21/J11B19 engine was similar to the bicone inlet (Ref. 2) developed for the Mach 2.55 aircraft. An attempt was first made to use a translating spike. The resulting transonic air flow capacity was less than the minimum required by the engine, however. The final 2.3/AX/SS inlet design is shown in Fig. 8. It had a collapsing spike for off-design throat area control. To minimize weight, the translation capability of the Ref. 2 design was not included. As a result, the inlet had some internal contraction with the spike in the fully collapsed position. The inlet throat area control was sufficient to satisfy the maximum air flow demand of the GE21/J11B19 engine throughout the aircraft flight regime.

For the spike, the initial cone half-angle was 12.5 deg. The second cone half-angle was 21.5 deg at the supersonic cruise design point. The inner cowl lip angle was 0 deg. At the design point, the cowl lip shock intersected the forward edge of the spike bleed slot.

Inlet Performance

Because the performance of a number of inlet designs was being compared, it was necessary to estimate bleed flow requirements in a consistent manner. Figure 9 shows the bleed flow correlation presented in Ref. 6. Some data points have been added for Mach 2.2 two-dimensional inlets from Ref. 4. The NASA Lewis bicone inlets (Ref. 7), indicated by the circles on the lower line, do not correlate well with the other data. These bicone inlets would probably have to be operated with a stability bleed system, however. To be conservative, the upper line in Fig. 9 was used to estimate bleed flow requirements.

The allowable internal contraction of the self-starting inlets also depended on the amount of steady-state bleed. As stated in the previous section, the required throat area for self-starting with bleed was made less than the throat area for self-starting without bleed. The difference was the equivalent throat flow area associated with the boundary-layer bleed. As a consequence, the allowable internal contraction for self-starting inlets increased as the amount of their steady-state bleed increased. The correlation of Fig. 9 shows that the amount of steady-state bleed increased as wetted area of the supersonic diffuser increased and as Mach number increased.

Bleed drag coefficient for the Mach 2.0 inlets with GE21/J11B21 engines is shown in Fig. 10. The drag coefficients shown are for four inlets based on aircraft wing area, and illustrate penalties from bleed drag. The total pressure recovery for these inlets is shown in Fig. 11. As expected, the self-starting inlets have higher pressure recovery at supersonic cruise because they have some internal contraction. Note that the low recovery of the 2.0/AX/EX inlet resulted from the optimization of turning angles in the design process. Here increased pressure recovery was traded against increased cowl drag in order to maximize range.

Inlet spillage drag (additive drag less lip suction force) can be a dominant factor in aircraft performance at off-design conditions. Figure 12 shows spillage drag along the aircraft climb profile for the Mach 2.0 inlets with the GE21/J11B21 engines. At climb conditions only the 2.0/2-D/SS inlet had significant amounts of subcritical spillage, because it had some internal contraction with the centerbody fully collapsed. The consequent drag penalty is illustrated in Fig. 12. For the

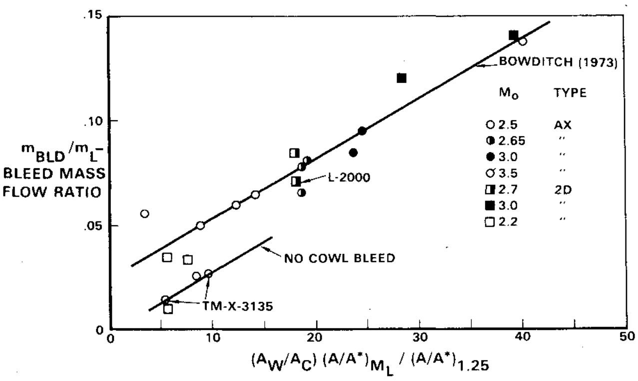

Fig. 9 Inlet bleed flow correlation.

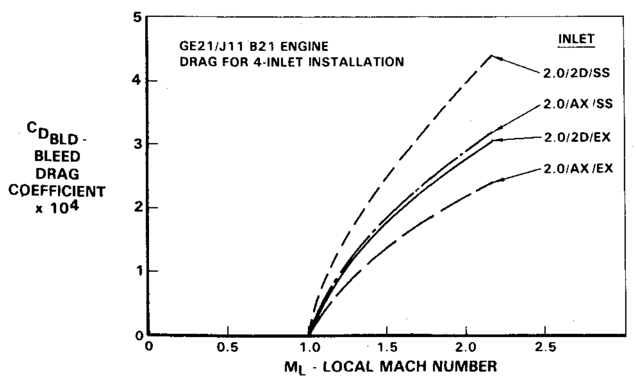

Fig. 10 Bleed drag for Mach 2.0 inlets with GE21/J11B21 engines.

reduced power condition of subsonic cruise at Mach 0.9 the 2.0/AX/EX inlet had no subcritical spillage, and the 2.0/2-D/EX inlet had only small amounts.

The installed specific fuel consumption (SFC) for the Mach 2.0 inlets with the GE21/J11B21 engines is shown in Fig. 13. Installed SFC gives the propulsion system performance including the effects of inlet total pressure recovery, bleed drag, spillage drag, and bypass drag. The lines in Fig. 13 show performance at maximum thrust with and without afterburning. The symbols show the SFC at Mach 2.0 supersonic cruise and Mach 0.9 subsonic cruise. Mission analysis showed that total mission fuel was minimized by use of maximum afterburning during climb. At supersonic cruise the 2.0/AX/EX had the highest SFC mainly because of its lower total pressure recovery. At subsonic cruise, the 2.0/2-D/SS inlet had the highest SFC because of its subcritical spillage.

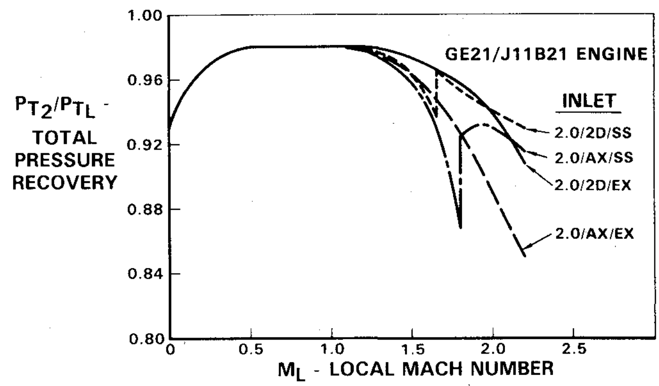

Fig. 11 Total pressure recovery for Mach 2.0 inlets with GE21/J11B21 engines.

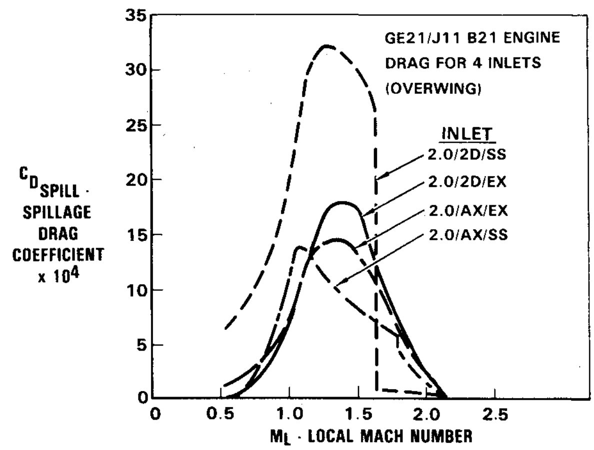

Fig. 12 Spilage drag for Mach 2.0 inlets with GE21/J11B21 engines.

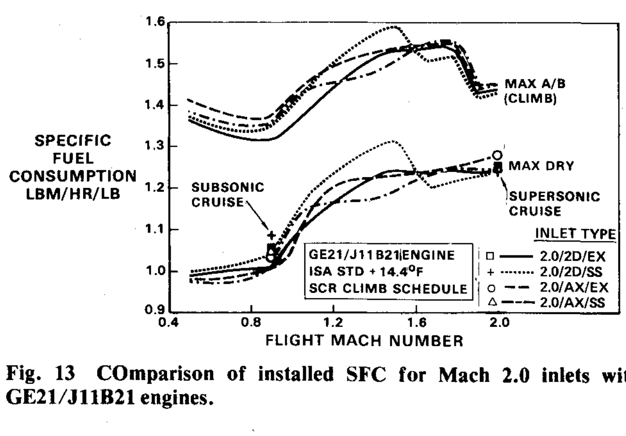

Fig. 13 COmparison of installed SFC for Mach 2.0 inlets with GE21/J11B21 engines.

Table 3 Performance summary, four-engine average

Engine inlet	(A)GE21/J11B21 2.0/2-D/EX	(A) 2.0/AX/EX	(A) 2.0/2-D/SS	(A) 2.0/AX/SS	(B)GE21/J11B13 2.0/2-D/EX	(B) 2.0/2-D/SS	(C)GE21/J11B19 2.3/2-D/EX	(C) 2.3/2-D/SS	(C) 2.3/AX/SS
Airflow ratio, WCR	1.23	1.07	1.23	1.13	1.32	1.32	1.45	1.45	1.45
Supersonic cruise									
Internal contraction, %	0	0	42.3	39.5	0	42.2	0	35.3	31.7
P_{T_2}/P_{T_0}	0.928	0.876	0.938	0.925	0.928	0.950	0.881	0.923	0.879
m_{BLD}/m_L	0.0349	0.0284	0.0483	0.0349	0.0349	0.0497	0.0408	0.0567	0.0408
Avg. SFC, lbm/h/lb	1.248	1.278	1.241	1.244	1.251	1.239	1.402	1.340	1.392
Avg. L/D	7.92	7.68	7.97	8.09	7.59	7.87	7.85	7.90	7.75
Subsonic cruise									
Avg. SFC, lbm/h/lb	1.053	1.033	1.086	1.046	1.070	1.065	1.083	1.126	1.098
Avg. L/D	14.31	14.33	14.31	14.33	14.33	14.31	14.20	14.20	14.28

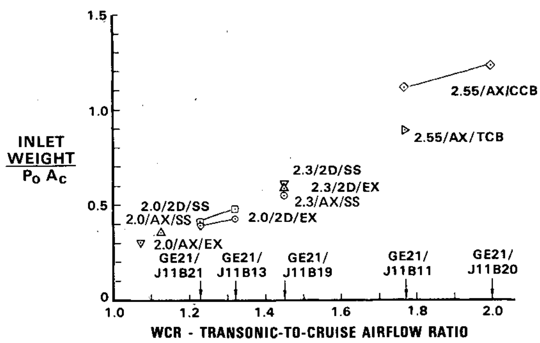

Fig. 14 Inlet weight.

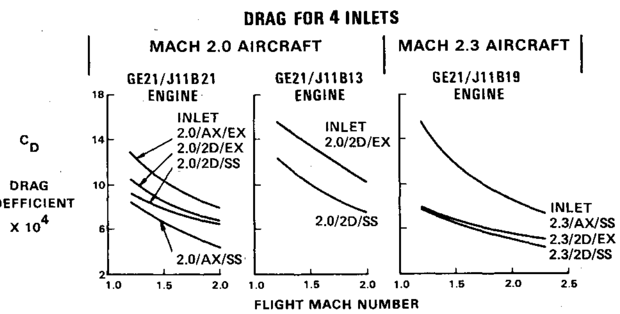

Fig. 15 Isolated nacelle wave drag for Mach 2.0 and 2.3 aircraft.

The 2.0/AX/EX inlet had the lowest SFC because it had only critical spillage. This was a result of its small throat area which limited its transonic air flow capacity.

Tabulated four-engine average performance characteristics for all study configurations are presented in Table 3 for the Mach 2.0 and Mach 2.3 aircraft.

Inlet weight was affected by inlet type and by WCR. Figure 14 shows results from the present study and from Ref. 2. The average weight of the four inlets (two overwing and two underwing) was made nondimensional by the ambient pressure at supersonic cruise altitude and by the average capture area. There was a consistent trend toward higher inlet weight with increases in WCR, both as M_0 increased and as the engine changed at constant M_0. Complete inlet weights and dimensions are given in Ref. 3.

Nacelle wave drag comparisons for the Mach 2.0 and 2.3 designs are shown in Fig. 15. The figure shows wave drag coefficient based on aircraft wing area for four nacelles. The results are for the isolated nacelles plus diverters, and were computed by the far-field wave drag (FFWD) method of Ref. 8. This method is an application of the supersonic area rule based on linearized theory. The FFWD method was also used to compute the complete Mach 2.0 aircraft wave drag for the 2.0/AX/SS inlet GE21/J11B21 engine installation. The increments in the isolated nacelle wave drag values of Fig. 15 were used to arrive at complete aircraft wave drag for the remaining Mach 2.0 cases. For the Mach 2.3 aircraft, the reference case had the 2.3/AX/SS inlet GE21/J11B19 engine installation.

This approach for calculating the aircraft drag assumed that there was no change in nacelle interference drag relative to the reference aircraft configuration. The near-field wave drag (NFWD) method of Ref. 8 can be used to obtain interference drag for axisymmetric nacelle shapes. Similar analytical methods for the three-dimensional nacelle shapes of the two-dimensional inlets are not available, however. An attempt was made to evaluate the three-dimensional nacelles by use of the NFWD method for bodies of revolution with the same area distribution as the three-dimensional nacelles. This was unsuccessful because the equivalent body of revolution had lower surface slopes near the inlet cowl lip than did the actual design, resulting in significantly lower isolated nacelle drag. Accurate prediction of drag increments between the various configurations awaits development of an analytical method for three-dimensional nacelles.

For a given engine, the Mach 2.0 external-compression inlets had higher wave drag than the self-starting inlets, as expected, because of their larger external flow turning. For a given inlet type, the wave drag increased as WCR increased. This is illustrated by the 2.0/2-D/EX and 2.0/2-D/SS inlets for the GE21/J11B21 and GE21/J11B13 engines. The need for a higher cowl angle to match the larger engine diameter, for almost the same supersonic cruise air flow, was responsible for this result.

The remaining wave drag comparisons from Fig. 15 can be explained from considerations of inlet length and cowl lip angle. It was at first surprising that the 2.3/AX/SS inlet had higher wave drag than the other two Mach 2.3 inlets. Inlet dimensions show that the 2.3/AX/SS inlet was 17% shorter than the 2.3/2-D/SS inlet. These dimensions were the result of the bleed flow and self-starting criteria used in this study, and of the desire to minimize inlet weight by minimizing inlet length. Because the 2.3/AX/SS inlet had less wetted area than the 2.3/2-D/SS inlet, it had less bleed flow and less allowable internal contraction for self-starting. (See Table 3.) It also had a lower total pressure recovery. It now seems possible that an increase in subsonic diffuser length could have a favorable overall effect, with the reduction in wave drag more than offsetting the increased weight.

Uncertainties exist concerning the magnitude of nacelle wave and interference drag for the various installations. These uncertainties are magnified when off-design considerations such as spillage and overboard bleed and bypass effects are taken into account.

Aircraft Performance

Aircraft performance was evaluated for each case. The mission profile had a block segment and a reserves segment. The block segment included takeoff, acceleration and climb, deceleration and descent, subsonic cruise and supersonic

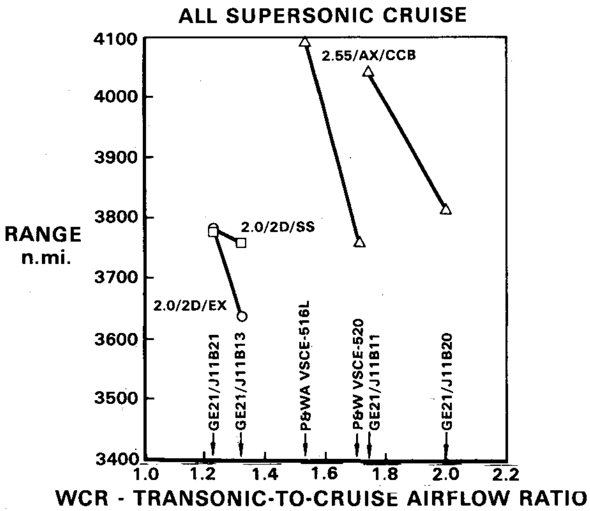

Fig. 16 Effect of corrected air flow ration on range.

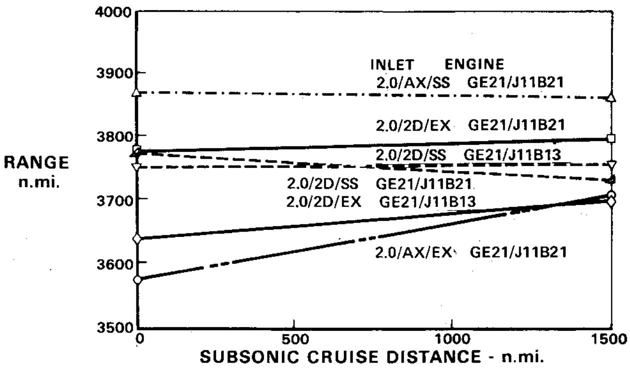

Fig. 17 Effect of subsonic cruise distance on aircraft range, Mach 2.0 aircraft.

cruise. (See Ref. 3.) The subsonic cruise segments considered were 0 and 1500 n.mi.

In Fig. 16, results of the mission performance studies show the effect of WCR on aircraft range for all-supersonic cruise. The 2.0/2-D/EX inlets with the GE engines had nearly the same installed SFC at supersonic cruise, as shown in Table 3. The aircraft with the GE21/J11B21 engine had lower nacelle wave drag and hence higher L/D (Table 3). It also had lower inlet weight (Fig. 14). Thus it had greater supersonic range. Similar circumstances applied for the 2.0/2-D/SS inlets and for the Mach 2.55, mixed-compression, bicone inlets with collapsing centerbodies (CCB). These results suggest that for engines of the same family, increased WCR yields reduced supersonic range. The responsible factors are primarily higher nacelle wave drag and also higher inlet weight. (Note that a large part of the range advantage for the Mach 2.55 aircraft was the result of assuming lower inlet bleed corresponding to the lower line in Fig. 9.) This conclusion applies to podded nacelle installations.

Further reductions in WCR should be explored to determine whether range goes through a maximum, and to assess the controlling factors. A possible controlling factor is the need to keep takeoff jet noise below prescribed levels.

Figures 17 and 18 show total aircraft range as a function of subsonic cruise distance for the Mach 2.0 and Mach 2.3 study cases, respectively. (The variation was assumed to be linear because of earlier results from Ref. 3.) Table 3 presents corresponding average SFC and L/D results. For the Mach 2.0 aircraft, subsonic cruise distance had little impact on total range except for the 2.0/AX/EX installation. This was in contrast to earlier studies at Mach 2.55 (Ref. 2) which showed

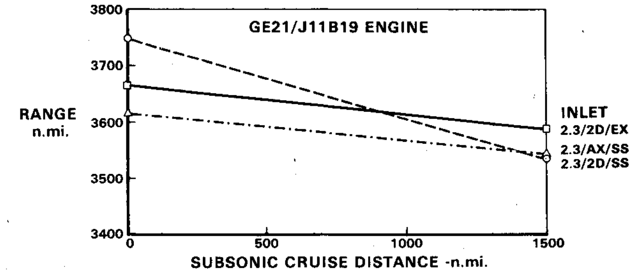

Fig. 18 Effect of subsonic cruise distance on aircraft range, Mach 2.3 aircraft.

Table 4 Effect of subsonic cruise distance on total range

Inlet	Engine	Range difference, all-supersonic to 1500 n.mi. subsonic, %
2.0/2-D/EX	GE21/J11B21	0.4
2.0/AX/EX	GE21/J11B21	3.8
2.0/2-D/SS	GE21/J11B21	−1.2
2.0/AX/SS	GE21/J11B21	−0.2
2.0/2-D/EX	GE21/J11B13	1.7
2.0/2-D/SS	GE21/J11B13	0
2.3/2-D/EX	GE21/J11B19	−2.0
2.3/2-D/SS	GE21/J11B19	−5.7
2.3/AX/SS	GE21/J11B19	−2.0
2.55/AX/TCB	P&WA VSCE-516L	−4.9
2.55/AX/TCB	GE21/J11B11	−5.9
2.55/AX/CCB	GE21/J11B11	−8.2
2.55/AX/CCB	GE21/J11B20	−7.4

significant range reduction as subsonic cruise distance increased. The 2.0/AX/EX installation had the lowest range factor $(M_0/\text{SFC})(L/D)$ at subsonic cruise because of its low spillage drag. The relative values of $(M_0/\text{SFC})(L/D)$ for each installation at supersonic and subsonic cruise account for the variation in range with subsonic cruise distance.

The inlet installations for the Mach 2.3 aircraft showed substantial range reductions as subsonic cruise distance increased. This was again consistent with the relative values of $(M_0/\text{SFC})(L/D)$. The range reduction for the 2.3/2-D/SS inlet was particularly large, because of its large subcritical spillage at Mach 0.9. This illustrates the importance of designing supersonic inlets to have no internal contraction at subsonic cruise conditions.

These mission results, and the earlier results for Mach 2.55 aircraft (Ref. 2), show that increased subsonic cruise distance had a generally more adverse effect on total range as supersonic cruise Mach number increased. (See Table 4.) This was directly related to the difference between supersonic and subsonic cruise values of $(M_0/\text{SFC})(L/D)$. This difference increased as supersonic cruise Mach number increased. From a general viewpoint, this behavior may be a result of the widening separation between supersonic and subsonic cruise design points.

These results are based on aircraft configurations such as that of Fig. 1. Another configuration might show a smaller effect of supersonic cruise Mach number on total range for mixed supersonic/subsonic missions.

For the Mach 2.0 aircraft cases, there were only minor differences in supersonic cruise SFC, except for the 2.0/AX/EX inlet installation with its lower total pressure recovery (Table 3). There was little increase in inlet weight because of mixed compression, but the two-dimensional inlets were noticeably heavier than the axisymmetric (Fig. 14). The main differences were in L/D, as a result of differences in nacelle wave drag. Thus the range advantage of the

2.0/AX/SS inlet was mainly due to its low wave drag.

Although the 2.0/2-D/EX inlet provided less range than the 2.0/AX/SS inlet, its generally greater flow stability (no unstart) and high off-design performance make it an attractive alternative.

For the Mach 2.3 aircraft cases, the 2.3/2-D/SS inlet provided the greatest range at all-supersonic cruise because of its higher total pressure recovery, and lower wave drag. As previously discussed, the 2.3/AX/SS inlet gave higher SFC and lower L/D at supersonic cruise because of the limitations on internal contraction imposed by self-starting, and because of its shorter length. It now seems possible that the aircraft range might be improved by lengthening the subsonic diffuser of the 2.3/AX/SS inlet. At Mach 0.9 cruise, the 2.3/2-D/SS inlet had high spillage drag and high SFC because it had some internal contraction even with the ramp fully collapsed. The Mach 0.9 performance of the 2.3/2-D/SS inlet could be significantly improved, however, if additional variable geometry were added to eliminate internal contraction. The 2.3/2-D/EX inlet was best at subsonic cruise because it operated with minimum spillage.

As with the 2.0/2-D/EX inlet, the generally greater flow stability and high off-design performance of the 2.3/2-D/EX inlet make it an attractive alternative to the 2.3/2-D/SS inlet.

Conclusions

1) Aircraft range was sensitive to changes in transonic-to-cruise corrected air flow ratio, with larger values giving lower range. This was mainly attributable to increased nacelle wave drag, and also to increased inlet weight.

2) For higher supersonic cruise Mach number designs, increases in subsonic cruise distance had a more adverse effect on total range. The total range of the Mach 2.0 aircraft cases was nearly independent of subsonic cruise distance. This may depend on the type of aircraft configuration.

3) The 2.0/AX/SS inlet gave the greatest range for the Mach 2.0 aircraft, mainly because it had the lowest nacelle drag.

4) For the Mach 2.3 aircraft, the 2.3/2-D/SS inlet gave the greatest range at all-supersonic cruise, but had large spillage drag at subsonic cruise because of some remaining internal contraction. This could be removed by additional variable geometry, however.

5) Uncertainties exist concerning the magnitude of nacelle wave and interference drag for the various installations. These uncertainties are magnified when off-design considerations such as spillage and overboard bleed and bypass effects are taken into account.

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