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HIGH-TRANSONIC-SPEED TRANSPORT AIRCRAFT STUDY

Summary Report

by Robert M. Kulfan

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16. Abstract

An initial design study of high-transonic-speed transport aircraft has been completed. Five different design concepts were developed. These included fixed swept wing, variable-sweep wing, delta wing, double-fuselage yawed-wing, and single-fuselage yawed-wing aircraft. The "boomless" supersonic design objectives of range = 5560 km (3000 nmi), payload = 18,143 kg (40,000 lb), Mach = 1.2, and FAR Part 36 aircraft noise levels were achieved by the single-fuselage yawed-wing configuration with a gross weight of 211,828 kg (467,000 lb). A noise level of 15 EPNdB below FAR Part 36 requirements was obtained with a gross weight increase to 226,796 kg (500,000 lb). The off-design subsonic range capability for this configuration exceeded the Mach 1.2 design range by more than 20%. Although wing aeroelastic divergence was a primary design consideration for the yawed-wing concepts, the graphite-epoxy wings of this study were designed by critical gust and maneuver loads rather than by divergence requirements. The transonic nacelle drag is shown to be very sensitive to the nacelle installation. A six-degree-of-freedom dynamic stability analysis indicated that the control coordination and stability augmentation system would require more development than for a symmetrical airplane but is entirely feasible. A three-plane development plan is recommended to establish the full potential of the yawed-wing concept.

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HIGH-TRANSONIC-SPEED TRANSPORT AIRCRAFT STUDY

SUMMARY REPORT

By Robert M. Kulfan
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SUMMARY

During the period June 1972 through May 1973, the contractor conducted a two-phase study, the objective of which was to evaluate the potential gains that would be derived from the application of advanced technology to transport aircraft designed to cruise at high transonic speeds. The goal was to achieve a 30% to 40% speed improvement over current aircraft and to avoid or minimize sonic boom by proper choice of cruise altitude and Mach number. A payload of 18 143 kg (40 000 lb) and range of 5560 km (3000 nmi) were selected. During phase I, five wing planform concepts were configured and compared: (1) fixed swept, (2) variable swept, (3) delta, (4) twin-fuselage yawed, and (5) single-fuselage yawed. Phase I results showed high promise for the single-fuselage yawed-wing concept; however, more extensive development study was required. The contractor was, therefore, directed to pursue trade studies needed to provide a better understanding of the concept during phase II. The phase II work also emphasized improved configuration arrangement and conduct of range, payload, noise, and speed sensitivity studies. Because of the unique characteristics of the yawed-wing concept, much attention was directed toward the development of analytical methods of analyzing aerodynamics, wing structural flexibility, and control.

It was determined that the single-fuselage yawed-wing concept is feasible and that study range, payload, FAR Part 36 noise, and sonic boom objectives can be achieved with a 211 828-kg (467 000-lb) gross weight aircraft. A 226 796-kg (500 000-lb) gross weight is required to achieve 15-EPNdB below the FAR Part 36 noise level. Design cruise Mach number was 1.2. The other configuration concepts were heavier and, with the exception of the double-fuselage yawed-wing arrangement, could not meet the low noise objectives. Aeroelastic divergence was found to be a primary design consideration for the yawed-wing, although the critical design conditions were gust and maneuver loads rather than wing divergence for the graphite-epoxy wings. Further work is required to optimize the design, and the contractor recommends a three-phase follow-on effort consisting of studies, wind tunnel tests, and full-scale hardware demonstration.

INTRODUCTION

This summary report describes briefly the work accomplished by the contractor under contract NAS2-7031, "High Transonic Speed Transport Aircraft Study," for the NASA Ames Research Center. The work began on June 20, 1972 and was completed on May 20, 1973. All aspects of this study are described in detail in the final report, NASA CR-114658.

As a result of sonic boom from supersonic aircraft flying over populated land masses, there is interest in aircraft designed for transonic cruise speeds. This interest has been enhanced by advances in supercritical flow aerodynamics technology and in design concepts such as yawed-wing aircraft.

The objectives of this study were to develop five specific configuration types suitable for cruise in the high transonic speed regime, make cross comparisons of each, conduct design tradeoff sensitivity studies, and identify critical research areas pertinent to development of high-transonic-speed transport aircraft.

In the initial phase of the study, size parameters and technology levels were identified as applicable to all the configurations, and a first-cycle design definition was accomplished for all five configurations. These initial definitions were developed and analyzed in detail to provide the parametric data necessary to determine the optimum wing area and engine match to meet the design objectives. Following this, second-cycle designs were completed and reviewed with representatives of the Ames Research Center at the end of approximately 4-1/2 months.

The results at that time identified promising potential for the single-fuselage yawed-wing concept; however, it would require more extensive development because of its unique characteristics. The following recommendations were made:

- Concentrate the remainder of the study effort on trade studies to optimize this concept.
- Suspend further developmental work on the other concepts.
- Forego the comparative performance and economics studies.

The study plan was revised to incorporate these recommendations and thereby allow for developing an improved configuration arrangement for this yawed-wing concept followed by range, payload, noise, and speed sensitivity studies.

This document presents a summary of the descriptions and performance characteristics of the configurations that have been synthesized for each of the five concepts. The design synthesis process is traced. The design and analysis methods are reviewed, along with results of the more significant trade studies that have provided design guidance. Conclusions and recommendations for needed additional work are included.

DESIGN SYNTHESIS

The configurations evolution during the study is summarized in figure 1, and the procedure used to synthesize the airplane configurations is illustrated in figure 2.

A parametric performance analysis computer program, described in references 1 and 2, was used to determine the combination of aircraft characteristics that resulted in airplanes that met the range/payload objectives and constraints with a minimum gross weight.

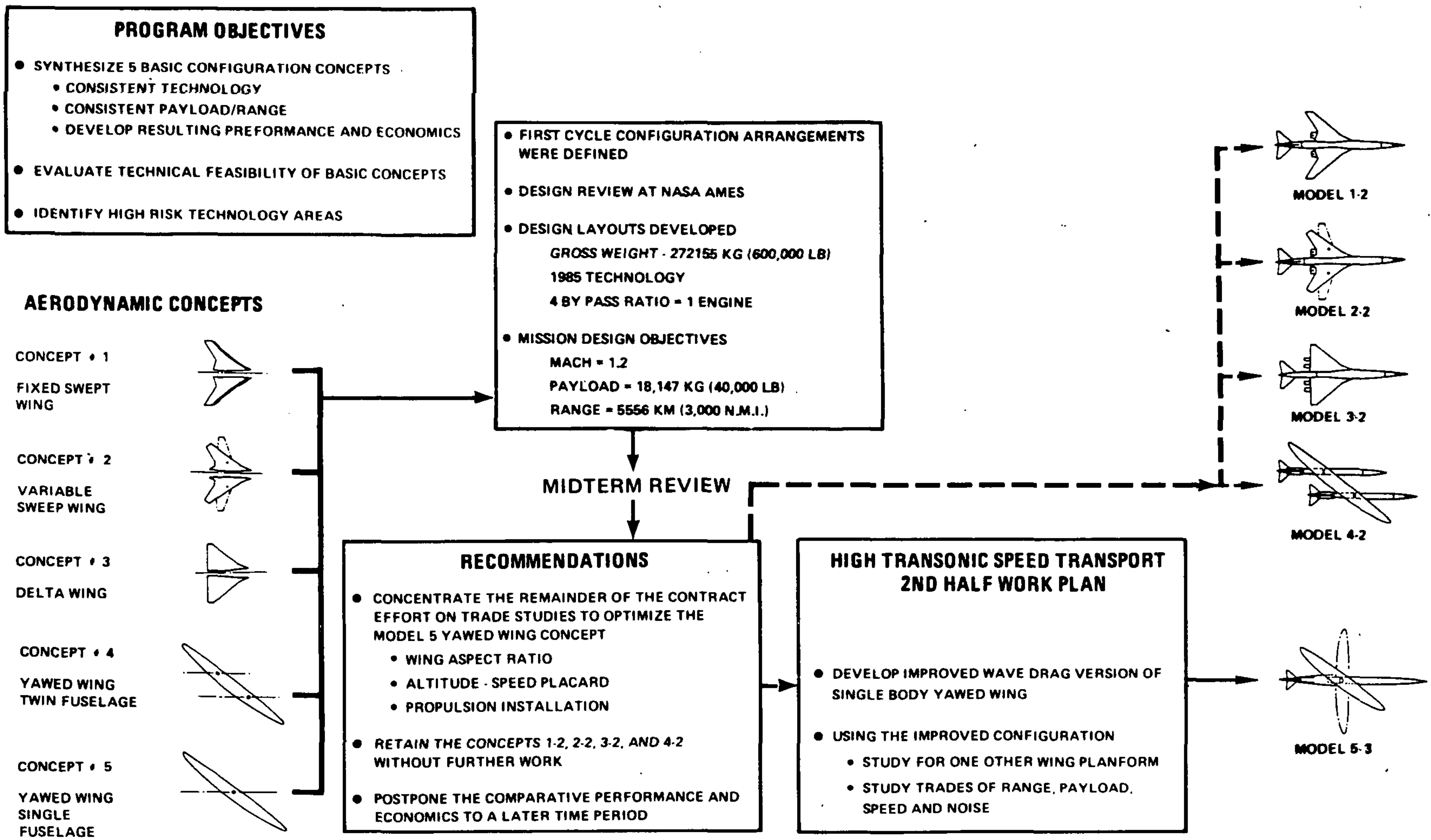


FIGURE 1.—HIGH-TRANSONIC-SPEED TRANSPORT AIRCRAFT STUDY CONTRACT NAS2-7031

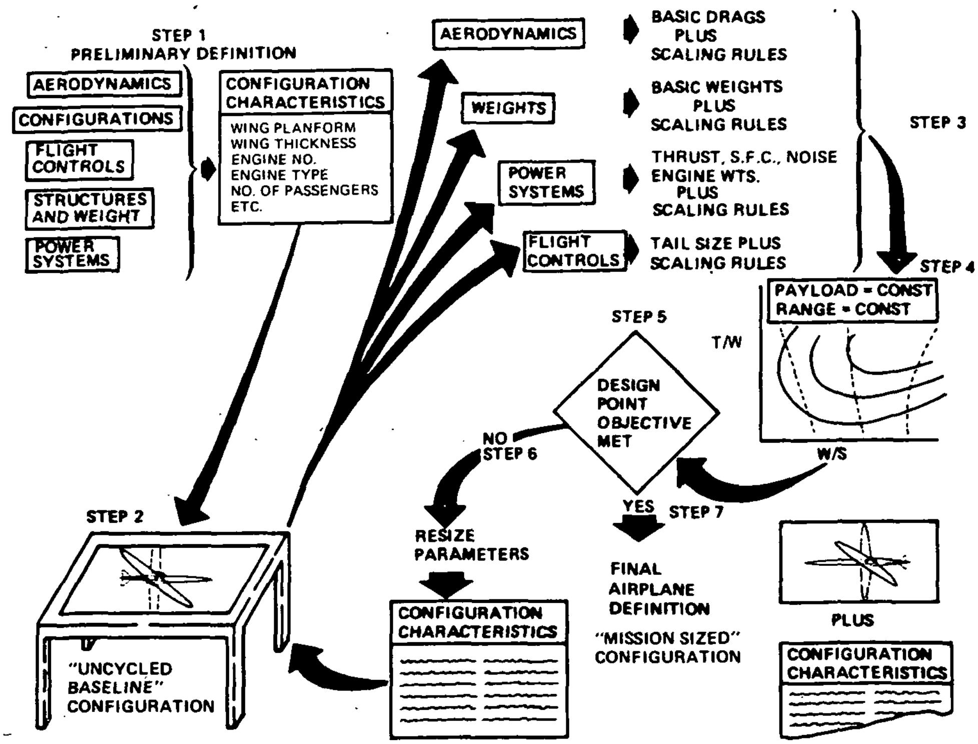


FIGURE 2.–DESIGN SYNTHESIS PROCESS

MISSION RULES AND PERFORMANCE OBJECTIVES

The flight profile and mission rules used in the sizing process were consistent with those used in the NASA Advanced-Transport Technology study. Allowances were used for the climb, descent, and reserves in lieu of detailed evaluations. Key items were:

Range	5560 km (3000 nmi)
Payload	18 143 kg (40 000 lb)
Cruise Mach	1.2 (to avoid sonic boom)
Cruise altitude	11 887 m (39 000 ft) at a maximum structural limit of 180 m/sec (350 kt)
Operating field length	3505 m (11 500 ft) maximum
Approach speed	333.4 km/hr (180 kt)
Noise goal	15 EPNdB below FAR Part 36

CONFIGURATION DESCRIPTIONS

The payload was equivalent to 195 passengers and their baggage for domestic operations. The passenger cabin for each configuration was designed for a 15% first class and 85% tourist class distribution. Volume was provided below the passenger cabin floor for containerized and bulk cargo. The airplanes were designed to be compatible with current and projected airport ramp areas, taxiways, and runway facilities. Landing gear design provides flotation for projected 1980-90 time period airport facilities.

The characteristics of the final mission-sized configurations that were developed for each concept are summarized in table 1. A design layout typical of the type developed for each concept is shown in figure 3 for the single-fuselage yawed-wing configuration (model 5-3).

Design considerations that were incorporated in the single-fuselage yawed-wing configuration (model 5-3) are summarized in table 2.

The aft-end design details, and the small gear tread relative to the large turnover moments of this high-wing aircraft during ground maneuvers are areas of concern that warrant more detailed investigations.

CONFIGURATION PERFORMANCE

The performance characteristics of the five configurations are summarized in table 3. Figure 4 contains a gross weight comparison of the configurations sized to meet the mission objectives.

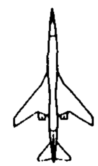
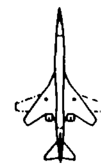
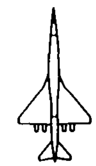
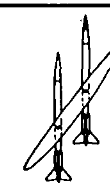
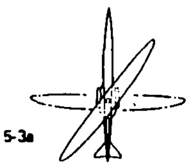
The single-fuselage yawed-wing configuration had the lowest takeoff gross weight because of the low fuel requirements. This directly reflected the high cruise lift/drag ratios achieved by this arrangement. The excellent landing and takeoff characteristics were the result of the high aspect ratio (10.2) with the wing unswept.

Fixed-swept-wing configuration 1-2a and variable-sweep-wing configuration 2-2a were appreciably heavier. The primary cause was the high installed nacelle drag associated with the double-pod arrangements. The pivoting wing structural weight of configuration 2-2a provided an additional detrimental effect.

Delta wing configuration 3-2a has the lightest structural weight. The landing and takeoff speed and field lengths exceed those of the other configurations because of the low aspect ratio of the delta wing.

Double-fuselage yawed-wing configuration 4-2a has excellent low-speed performance but is quite heavy. This configuration could conceivably be improved with a lower aspect ratio wing. An improved nacelle arrangement would also be necessary.

TABLE 1.—MACH 1.2 SIZED TRANSPORT CONFIGURATION DESIGN BASELINE CHARACTERISTICS

ITEM		CONFIGURATION CONCEPT				
		MODEL NUMBER 1-2a 	2-2a 	3-2a 	4-2a 	5-3a 
PASSENGERS (15%/85% MIX) RANGE Km (NM) CONFIGURATION FINENESS RATIO, l/d_e DESIGN MACH NUMBER		197 5560 (3000) 14.6 1.2	193 5560 (3000) 15.0 1.2	193 5560 (3000) 14.0 1.2	188 5560 (3000) 14.7 1.2	190 5560 (3000) 18.5 1.2
WEIGHT	TOGW, KT (LB)	275 300 (607 000)	388 300 (857 000)	226 796 (500 000)	280 700 (619 000)	211 828 (467 000)
FUSELAGE	BODY LENGTH, m (FT) CABIN LENGTH, m (FT) MIN/MAX DIAMETER (TC) (M/M) (IN./IN.) MIN/MAX ABREAST SEATING (TC) MIN/MAX NO. OF AISLES (TC)	78.49 (257.5) 47.83 (156.9) 3.12/4.95 (123/195) 4/6 1/2	 46.91 (153.9) 3.12/4.88 (123/192) 4/6 1/2	 40.94 (134.3) 3.12/5.38 (123/212 4/7 1/2	65.79 (215.8) 22.76 (74.7) 3.56/3.56 (140/140) 5/5 1/1	87.63 (287.5) 43.97 (144.3) 3.56/4.06 (140/160) 4/6 1/1
WING	AREA, m^2 (FT^2) ASPECT RATIO LE SWEEP, RAD (DEG) THICKNESS RATIO, ROOT/TIP, %/% TAPER RATIO WING C/4 LOCATION ON BODY % BODY LENGTH	434 (4670) 3.98 0.87 (50) 4.5/2.5 0.30 56.5	612 (6590) 3.06 (SWEPT) 0.94 (54) 4.1/2.5 0.285 56.5	437 (4700) 2.61 0.90 (51) 3.6/3.0 0.127 59	442 (4760) 12.8 (UNYAWED) 0.92 (53) 10.0/0 10:1 ELLIPSE 56	319.6 (3440) 10.2 (UNYAWED) 0.96 (55) 12.0/0 8:1 ELLIPSE 58
EMPENNAGE	HORIZONTAL TAIL AREA, m^2 (FT^2) ASPECT RATIO LE SWEEP, RAD (DEG) THICKNESS RATIO, ROOT/TIP, %/% TAPER RATIO	50.8 (547) 2.6 0.87 (50) 4.0/4.0 0.2	110.8 (1193) 2.6 0.87 (50) 4.0/4.0 0.2	34.7 (373) 2.6 0.87 (50) 4.0/4.0 0.2	67.7 (729) x 2 2.6 0.87 (50) 4.0/4.0 0.2	27.4 (295) 2.6 0.87 (50) 4.0/4.0 0.2
	VERTICAL TAIL AREA, m^2 (FT^2) ASPECT RATIO LE SWEEP, RAD (DEG) THICKNESS RATIO, ROOT/TIP, %/% TAPER RATIO	36.2 (390) 1.11 0.87 (50) 3.5/3.5 0.254	73.2 (788) 1.11 0.87 (50) 3.5/3.5 0.254	37. (398) 1.11 0.87 (50) 3.5/3.5 0.254	86.7 (933) x 2 1.11 0.87 (50) 3.5/3.5 0.254	25.5 (275) 1.11 0.87 (50) 3.5/3.5 0.254
PROPULSION	TYPE/BPR NUMBER OF ENGINES/LOCATION STATIC THRUST/ENGINE, SL/90 F, N(LBF)	ATSA 1.20 1-3000-16/1 4/UNDERWING 284 241 (63,900)	ATSA 1.20 1-3000-16/1 4/UNDERWING 406 122 (91 300)	ATSA 1.20 1-3000-16/1 4/UNDERWING 216 183 (48 600)	ATSA 1.20 1-3000-16/1 4/TAIL 226 859 (51 000)	ATSA 1.20 1-3000-16/1 4/AFT BODY 156 133 (35 100)

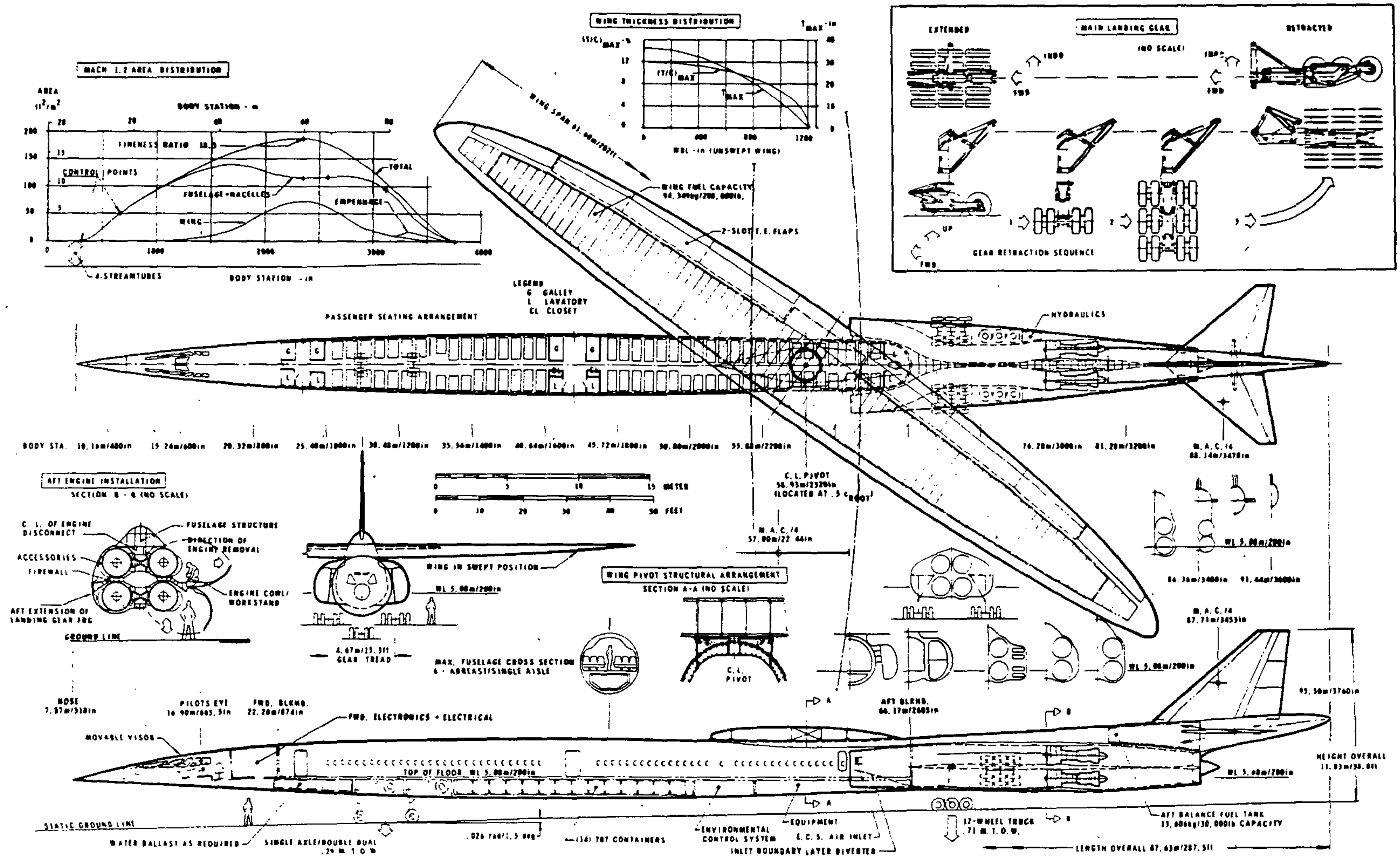


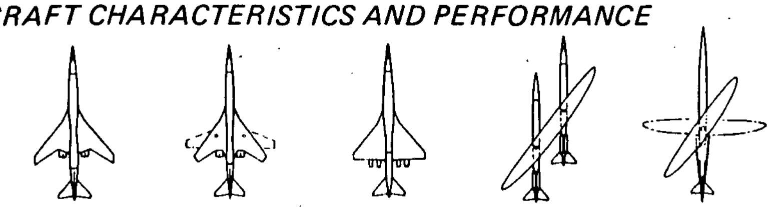
FIGURE 3.–CONCEPT 5–SINGLE FUSELAGE, YAWED WING (8:1 ELLIPSE), MODEL 5-3

TABLE 2.—DESIGN REQUIREMENTS VERSUS CONFIGURATION FEATURES— SINGLE FUSELAGE, YAWED WING—MODEL 5-3

DESIGN REQUIREMENT OR CHARACTERISTIC	RESULTING CONFIGURATION FEATURE
• PIVOTING WING	— BODY-MOUNTED ENGINES — BODY-MOUNTED LANDING GEAR WITH NARROW TREAD — HIGH WING ARRANGEMENT — USEABLE FUSELAGE CROSS SECTION REDUCED BELOW PIVOT
• POWER PLANT INSTALLATION WITH LOW DRAG	— 4-ENGINES INTEGRATED IN AFT FUSELAGE
• LANDING GEAR ARRANGEMENT THAT DOES NOT COMPROMISE CONFIGURATION FINENESS RATIO	— BICYCLE-TYPE LANDING GEAR AFT OF PASSENGER CABIN — LONG S-DUCT ENGINE INLETS — NEAR-LEVEL ATTITUDE OF AIRCRAFT DURING TAKEOFF AND LANDING — TWIN STRUT NOSE GEAR, LARGE NUMBER OF GEARS
• WING-BODY ARRANGEMENT WITH LOW DRAG AND EASE OF CONFIGURATION	— HIGH WING ARRANGEMENT
• WING-BODY INTEGRATION STRUCTURALLY EFFICIENT	— HIGH WING ARRANGEMENT — WING SUPPORT BEARINGS LOCATED OUTSIDE OF — PRESSURIZED FUSELAGE
• WING PLANFORM WITH OPTIMUM WEIGHT/DRAG TRADE	— 8:1 ELLIPSE
• FUSELAGE LENGTH WITH OPTIMUM WAVE DRAG/WEIGHT TRADE	— LARGE FUSELAGE FINENESS RATIO (22:1) — MINIMUM 5-ABREAST, SINGLE AISLE PASSENGER SEATING — ARRANGEMENT, WITH 4 ABREAST BELOW PIVOT — AFT FUSELAGE EXTENSION FOR EMPENNAGE SUPPORT
• AIRCRAFT BALANCE	— AFT-MOUNTED ENGINES BALANCED BY FORWARD PAYLOAD AND/OR FORWARD BALLAST
• PASSENGER SAFETY, LOW CABIN NOISE	— AFT-MOUNTED ENGINES
• LOW DRAG COCKPIT	— MOVEABLE VISOR NOSE

TABLE 3.—AIRCRAFT CHARACTERISTICS AND PERFORMANCE

MACH 1.2
PAYLOAD = 18 143 KG (40 000 LB)
RANGE = 5560 Km (3000 NMI)
INITIAL CRUISE ALTITUDE = 11 887 m (39 000 FT)
TAKEOFF FIELD LENGTH 3505 m (11 500 FT)
PERIPHERAL NOISE TREATMENT



AIRPLANE CONFIGURATION	1-2a	2-2a	3-2a	4-2a	5-3a
TAKEOFF GROSS WEIGHT KG (LBS)	275283 (607000)	388283 (857000)	226796 (500000)	280726 (619000)	211828 (467000)
OPERATING EMPTY WEIGHT KG (LBS)	122626 (270500)	180726 (398500)	103855 (229000)	146804 (322600)	113832 (251000)
WING AREA m^2 (FT^2)	433.8 (4670)	612.2 (6590)	436.6 (4700)	442.2 (4760)	319.6 (3440)
ENGINE THRUST RATING SEA LEVEL STATIC N (LBS)	284241 (63900)	406123 (91300)	216184 (48600)	226859 (51000)	156113 (35100)
NUMBER OF ENGINES /BYPASS RATIO	4/1	4/1	4/1	4/1	4/1
THRUST LOADING (T/W)	0.42	0.43	0.39	0.33	0.30
WING LOADING (W/S) N/m^2 (LB/FT^2)	6224 (130)	6224 (130)	5075 (106)	6224 (130)	6512 (136)
L/D CRUISE	8.1	8.1	8.9	10.6	12.3
TAKEOFF FIELD LENGTH: MAX FLAPS m(FT)	2438 (8000)	1554 (5100)	3505 (11500)	2225 (7300)	2179 (7150)
REDUCED FLAPS m(FT)	3353 (11000)	2286 (7500)	3505 (11500)	3078 (10100)	2947 (9670)
L/D COMMUNITY: REDUCED FLAPS	8.8	9.2	6.3	22	6.9
APPROACH SPEED: REDUCED FLAPS Km/HR(KT)	333 (180)	296 (160)	317 (171)	261 (141)	254.5 (137.4)
COMMUNITY NOISE: Δ EPNdB FROM FAR PART 36					
• TAKEOFF WITH THRUST CUTBACK AT NOISE STATION	-6.0	-10.2	+1.8	-15.0	-0.4
• SIDELINE	+3.0	+ 3.5	+3.4	+ 3.1	+2.0
• APPROACH	-0.7	- 1.9	-0.5	- 2.8	-2.0
• TRADED	+1.0	+ 1.5	+1.4	+ 1.1	0.

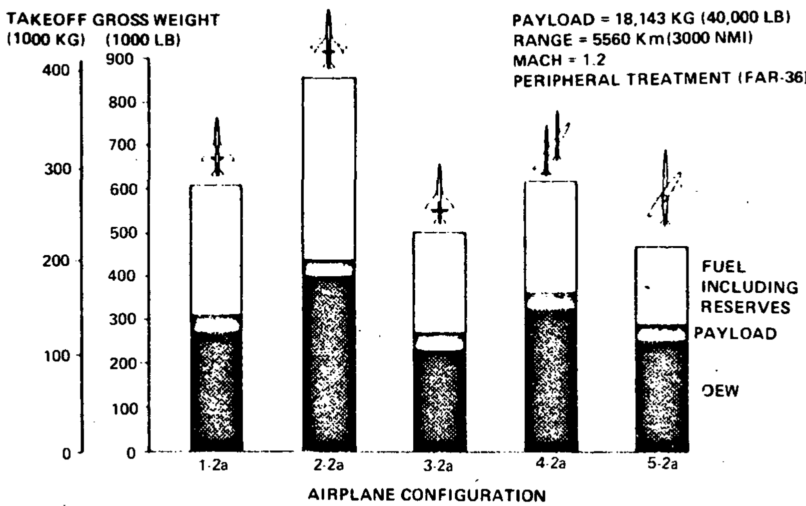


FIGURE 4.—GROSS WEIGHT SUMMARY

COMMUNITY NOISE IMPACT

Three levels of engine nacelle noise treatment were assessed to determine the takeoff gross weight (TOGW) penalty versus noise reduction. The traded noise level calculated from FAR Part 36 rules was used as a single noise level comparison criteria. No evaluation was made of airframe noise, which may be limiting. The impact on TOGW of achieving lower noise levels with engine nacelle noise treatment is shown in figure 5. The TOGW increased because of the added propulsion weight and engine performance losses due to the acoustic treatment.

RANGE, SPEED, AND PAYLOAD SENSITIVITY

Range, speed, and payload sensitivities were calculated for the single-fuselage yawed-wing configuration (model 5-3a). The fuel-volume-limited range, at the design Mach of 1.2, was 6945 km (3750 nmi). This would require an increase in takeoff gross weight of approximately 36 300 kg (80 000 lb). The cruise altitude would have to be lower than that constrained by the speed/altitude placard. Lowering the design cruise altitude would result in an additional structural weight penalty.

The off-design range capability of model 5-3a was evaluated for cruise Mach numbers from 0.9 to 1.35. The results indicated that this configuration could achieve the design range of 5560 km (3000 nmi) for the complete "boomless" speed regime up to Mach 1.2. At Mach numbers above 1.2, the cruise thrust cannot balance the aerodynamic drag at altitudes that satisfy the structural speed placard. The subsonic range capability is more than 20% greater than the Mach 1.2 design range.

Additional payloads were evaluated and compared to the baseline configuration payload. The weight, drag, and tail size changes due to the body length variations were accounted for. The results are shown in figure 6

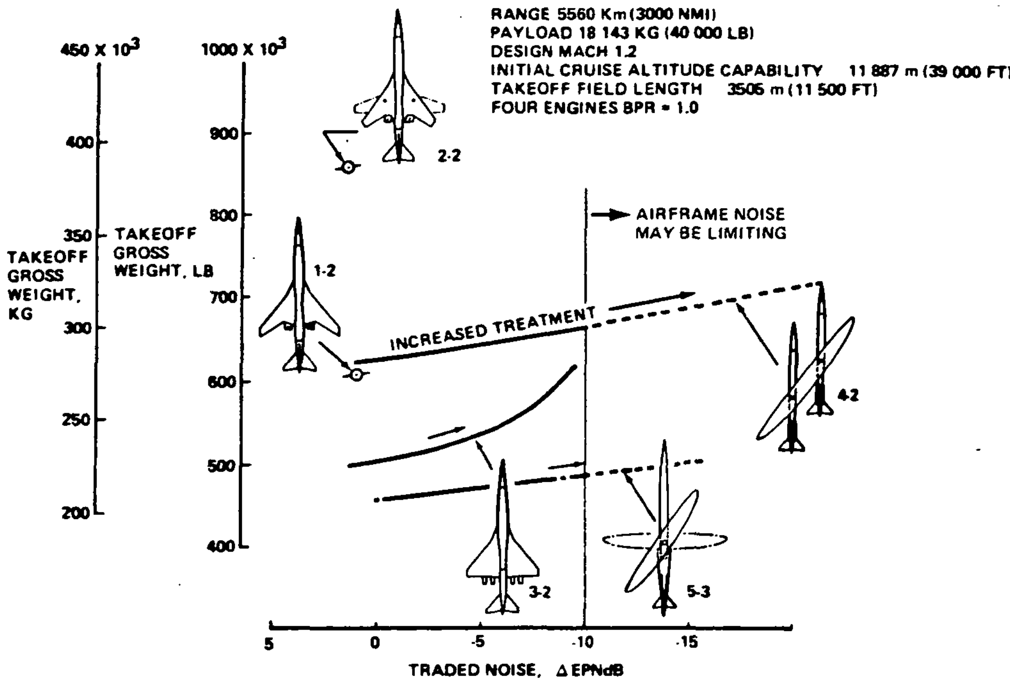


FIGURE 5.—IMPACT OF NOISE TREATMENT ON SIZED AIRPLANE TAKEOFF GROSS WEIGHT

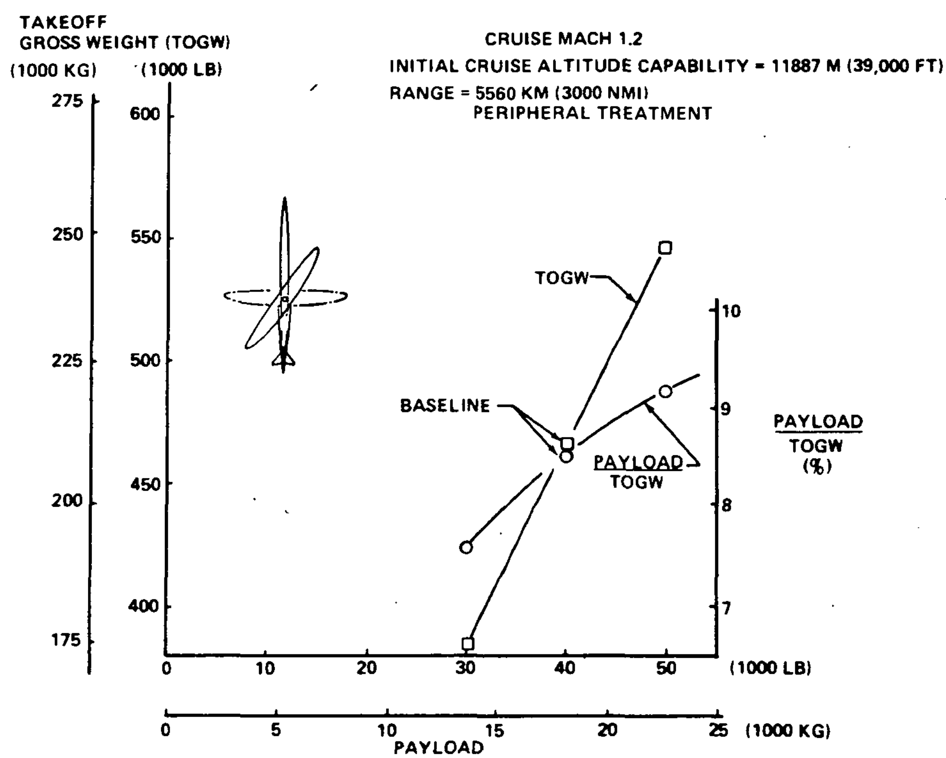


FIGURE 6.—MODEL 5-3A PAYLOAD STUDY

SINGLE-FUSELAGE YAWED-WING CONFIGURATION DEVELOPMENT

Extensive conceptual design and analysis efforts were necessary to evolve single-fuselage yawed-wing configuration 5-3. The major difficulty proved to be the integration of the landing gear and engines with the pivoting wing mounted on the slender fuselage.

The initial single-fuselage yawed-wing configuration developed for comparative evaluation with the other concepts (5-2-4) was a three-engine arrangement having two body-mounted engines and a single center engine with an S-duct inlet. The planform for this configuration had an elliptic axis ratio of 10:1 (unswept aspect ratio 12.7).

The results of efforts to improve this configuration are summarized in figure 7. A significant reduction in the size of the airplane required to achieve the design mission objectives was achieved.

BYPASS RATIO STUDY

The sensitivity of the single-fuselage yawed-wing configuration to engine bypass ratio was investigated on the three-engine arrangement. The bypass-ratio-1 engines were replaced with bypass-ratio-4 engines. The configuration was resized to achieve the design mission.

The results of the study indicated that, even at equal noise levels, the bypass-ratio-1 configuration is a much lighter arrangement. The higher bypass ratio configuration suffers from the weight penalty associated with the rapid growth in engine size required to produce the same thrust at the cruise altitude as for a lower bypass ratio engine.

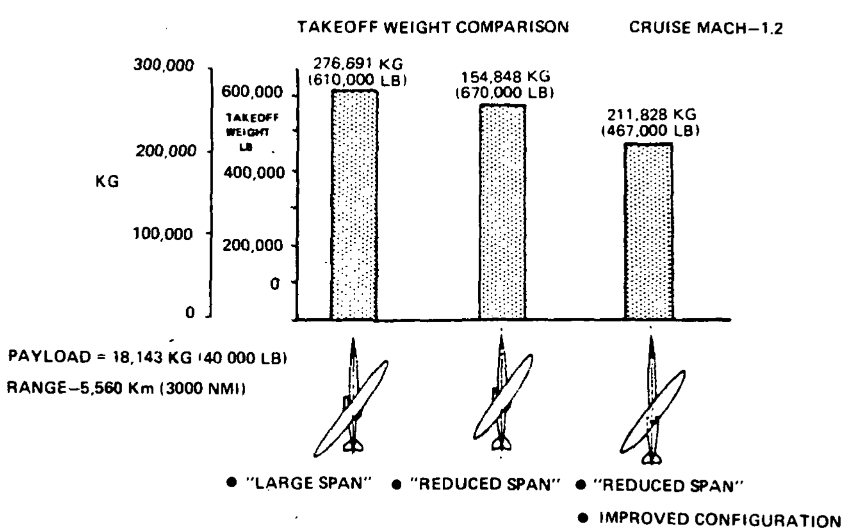


FIGURE 7.–IMPROVED CONFIGURATION RESULTS

WING DEVELOPMENT STUDIES

A weight versus drag trade study was made to determine the optimum wing thickness/chord ratio for 8:1 and 6:1 elliptic axis ratio wing planforms. The variations of wing weight and drag with thickness ratio are shown in figure 8. These variations in weight and drag were combined and equated to equivalent takeoff weight changes by sensitivities derived for the single-fuselage yawed-wing configuration.

The thickness/chord ratio of 12% is close to the optimum thickness/chord ratio for the 6:1 wing. The unconstrained optimum thickness/chord ratio for the 8:1 wing exceeds 12%. Because of possible buffet and flow separation, the wing maximum thickness was limited to 12% in this study. The optimum thickness provided enough depth so that wing divergence was not a critical design factor for the graphite-epoxy structure of the wing.

The effect of reducing the wing elliptic axis ratio from 10:1 to 8:1 was investigated on three-engine configuration 5-2-4. This effect was further investigated on aft integrated engine configuration 5-3 by further reducing the elliptic axis ratio from 8:1 to 6:1. The combined results of these studies, as shown in figure 9, indicate that the 8:1 wing (unswept aspect ratio = 10.2) is very nearly optimum.

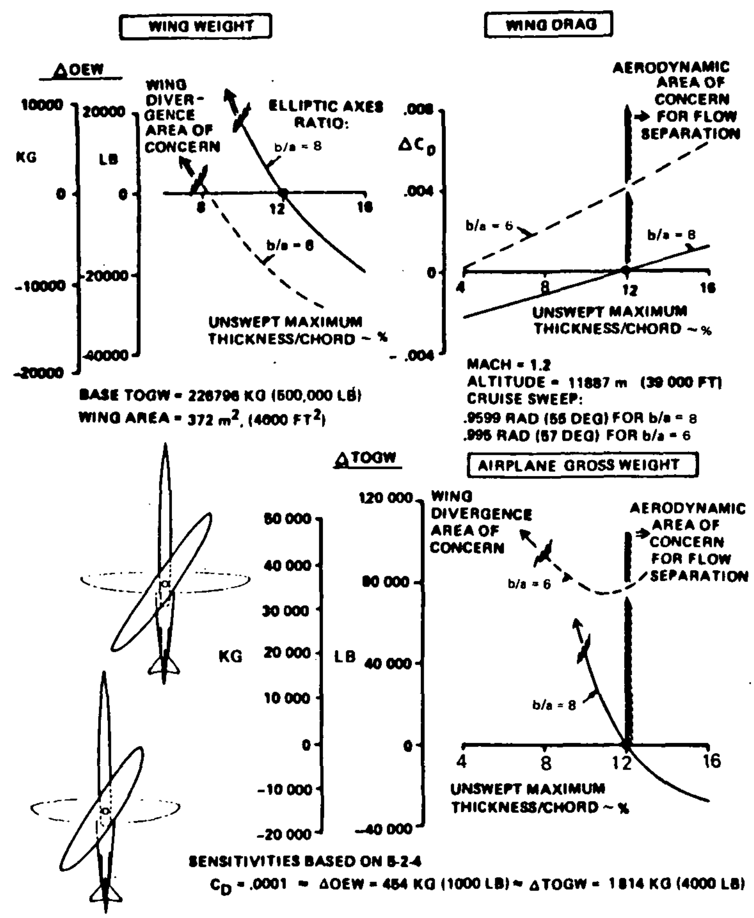


FIGURE 8.—YAWED-WING THICKNESS STUDY RESULTS

PAYLOAD = 18143 KG (40 000 LB)
RANGE = 5560 Km (3000 NMI)

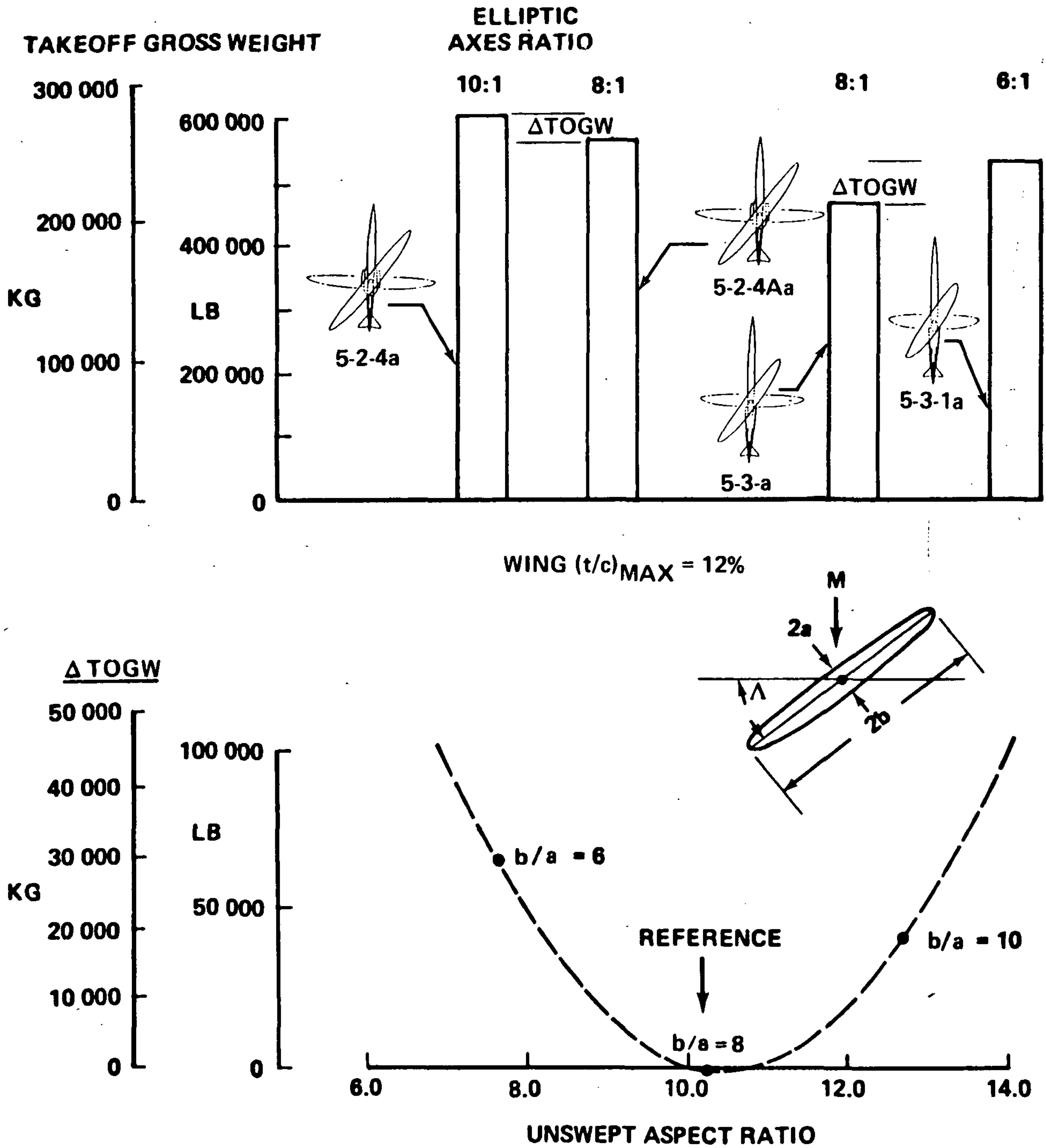


FIGURE 9.—ASPECT RATIO STUDY RESULTS

CONFIGURATION ANALYSIS AND METHODS

This section contains a brief description of the design and analysis methods that have been used in the study. The technology levels assumed in the development of the configurations are identified. The results of specialized studies that influenced the development of the configurations are described.

AERODYNAMICS

The aerodynamic design approach was to design for minimum cruise drag within practical design constraints. These practical constraints, which affect such things as wing thickness distribution, wing aspect ratio, airfoil shapes, and nacelle location, are necessary to provide a balance between aerodynamic, structural, and configuration arrangement requirements. The aerodynamic characteristics of all of the concepts were developed by similar procedures.

The yawed-wing planform studied and tested at NASA-Ames (ref. 3) was initially selected for the yawed-wing configurations. The elliptic axis ratio of the planform was subsequently reduced from 10:1 to 8:1 as a result of detailed weight versus drag trade studies. An optimization program that combines analytic wave drag and drag-due-to-lift expressions for a yawed elliptic wing (refs. 4 and 5) and the wing skin friction drag (ref. 6) was used to select the design cruise sweep angle as the angle for maximum isolated-wing lift/drag ratio.

The camber and twist distributions for all configurations were developed using linear aerodynamic theory.

The bodies for all of the configurations were area ruled to minimize the volume wave drag by the use of the transfer rule described in references 7 and 8. Figure 10 illustrates the aerodynamic definition of the single-fuselage yawed-wing configuration. This is typical of the aerodynamic development that led to each configuration.

The drag calculation methods that have been used for all of the configurations are:

•	Friction drag	Sommer and Short T* method (ref. 6)
•	Wave drag	Supersonic area rule (ref. 7)
•	Drag due to lift and trim drag	Middleton-Carlson Mach box (ref.s 9, 10, and 11)
•	Miscellaneous drag	Boeing SST data and procedures

It was necessary to modify these methods for the yawed-wing analyses.

A major difference in drag for the configurations was found to be the wave drag due to volume. The double-pod installed drag on the fixed wing and on the variable-sweep wing was significantly higher than the single-pod installation on the delta-wing concept.

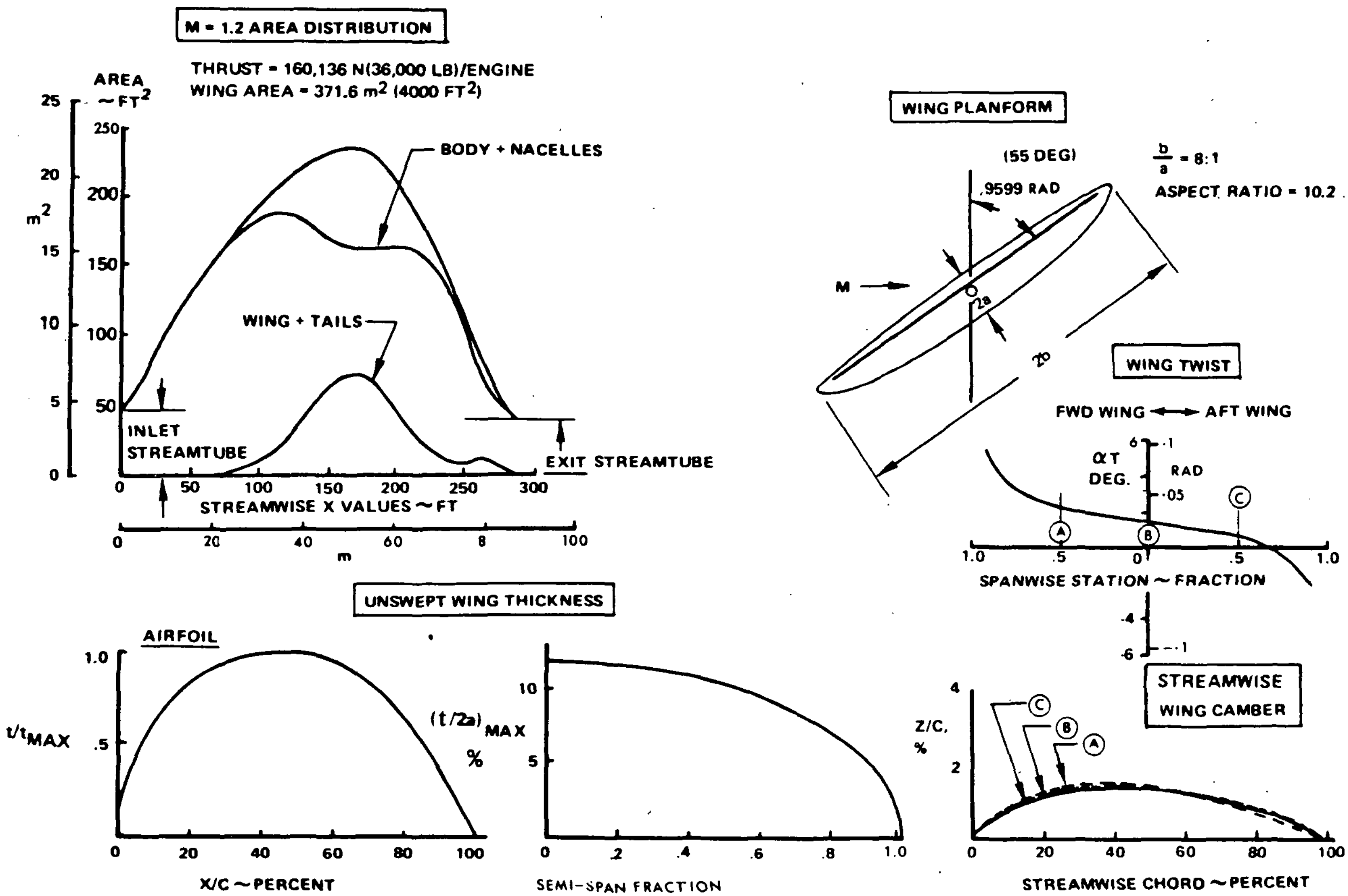


FIGURE 10.—MODEL 5-3 AERODYNAMIC DEFINITION

The integrated drag of the double-fuselage yawed-wing configuration was significantly higher than the sum of the isolated drags. This was primarily due to the unfavorable interference on the tail-mounted nacelle installation. It should be possible to integrate the nacelles for no more than isolated nacelle wave drag. This drag level with zero nacelle interference has been used to identify the "drag potential" for the double-fuselage yawed-wing configuration. To achieve this reduced drag level, the nacelles would have to be separated, this could be achieved by moving the nacelles forward on the fuselage.

LOW-SPEED AERODYNAMICS

The low-speed aerodynamic characteristics were estimated using methods developed by the contractor for preliminary designs on which no wind tunnel data exist. In general, the procedures are based on theoretical considerations but are tempered by flight test and wind tunnel data wherever applicable.

Single-fuselage yawed-wing configuration 5-3a takes off and lands without rotation. This is unorthodox for transport-category airplanes but should present no operational problems since the concept has long since been proven on such airplanes as the B-47 and B-52. Discussions with B-47 and B-52 pilots verify the operational simplicity of a nonrotating configuration.

Although a nonrotating configuration could be certified under current Federal Air Regulations, a reexamination of FAR Part 25 would be recommended, particularly with regard to the section relating rotation speed, liftoff speed, and minimum unstick speed.

NACELLE INSTALLED DRAG

A number of studies were undertaken to provide a better understanding of the nacelle interference drag at transonic speeds. These studies investigated:

- Nacelle separation and stagger effects
- Engine arrangement effects on nacelle installed drag
- Engine size and bypass ratio effects on wing-mounted, body-mounted, and buried engine arrangements.

The results of the stagger and separation study, which include the data in figure 11, indicated that the lowest wave drag installation occurs when the nacelles are mounted close to the body without stagger.

The results of the engine size studies indicated that:

- The unfavorable effect of engine size on transonic nacelle drag is most severe for wing-mounted installations.
- The integrated engine arrangement has very low installed drag for low-bypass-ratio engines.
- The body-mounted nacelle installation was the lowest drag arrangement for high-bypass-ratio engines.

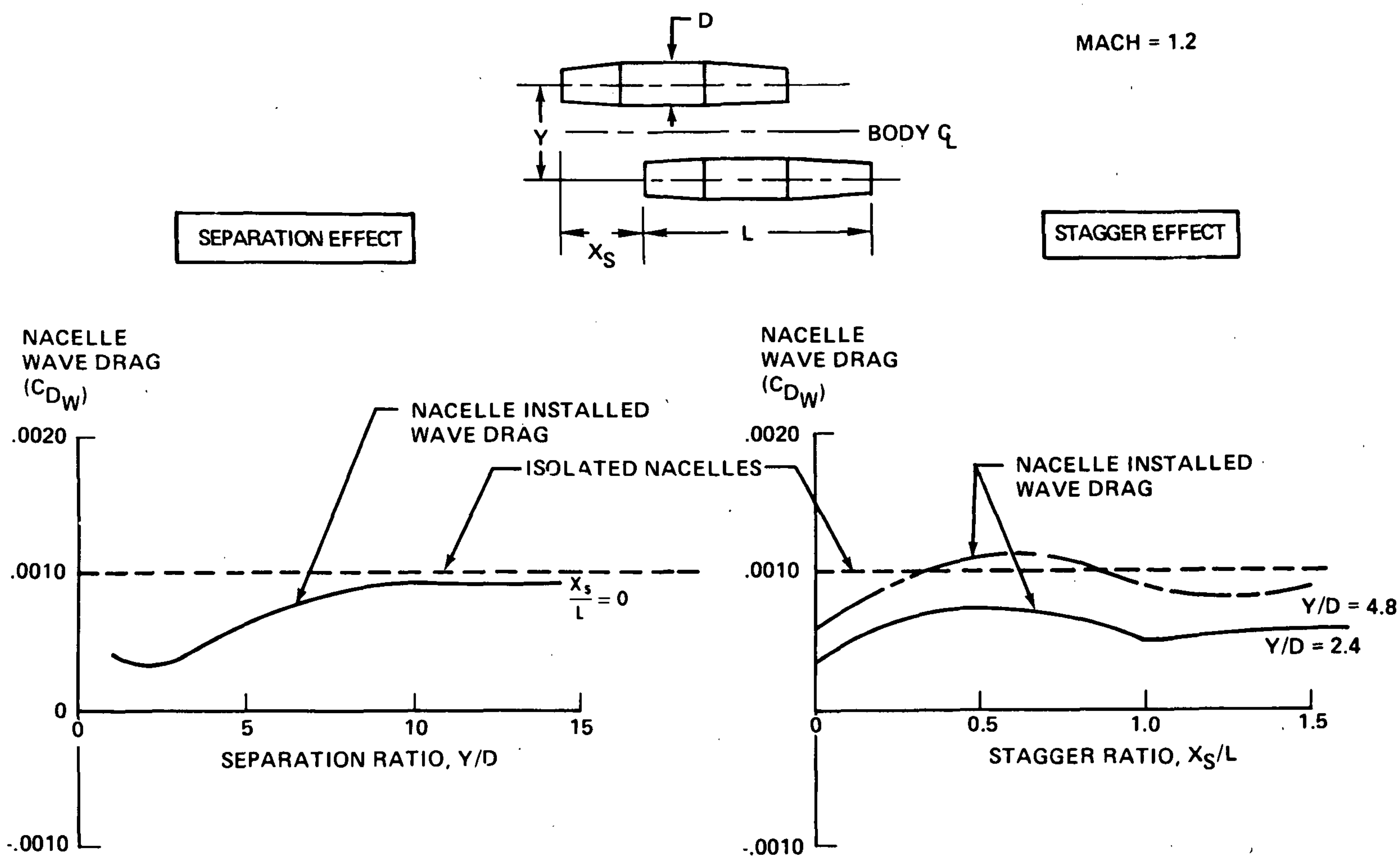


FIGURE 11.—EFFECT OF SEPARATION AND STAGGER ON BODY-MOUNTED NACELLE WAVE DRAG

The range variation with cruise speed was calculated for single-fuselage yawed-wing configuration 5-3a. This required that:

- Variation of the optimum sweep angle with Mach number be determined
- Off-design cruise drag be calculated at the optimum sweep angles.

The results of the sweep selection study indicated that the normal Mach number corresponding to the optimum sweep angle was approximately constant and equal to 0.73. The variation of the cruise drag of model 5-3 with Mach number is shown in figure 12. The maximum lift/drag ratio for the mission-sized configuration varies from 20.4 at Mach 0.7 to 11.3 at Mach 1.35. These maximum lift/drag ratios, $(L/D)_{max}$, significantly exceed the L/D ratios for the other configuration concepts in this study. To achieve these theoretical low levels of drag, the elliptic wings develop lift near the trailing edges. The possibility of trailing edge separation induced by the pressure gradients near the trailing edge is an area of concern that requires wind tunnel guidance.

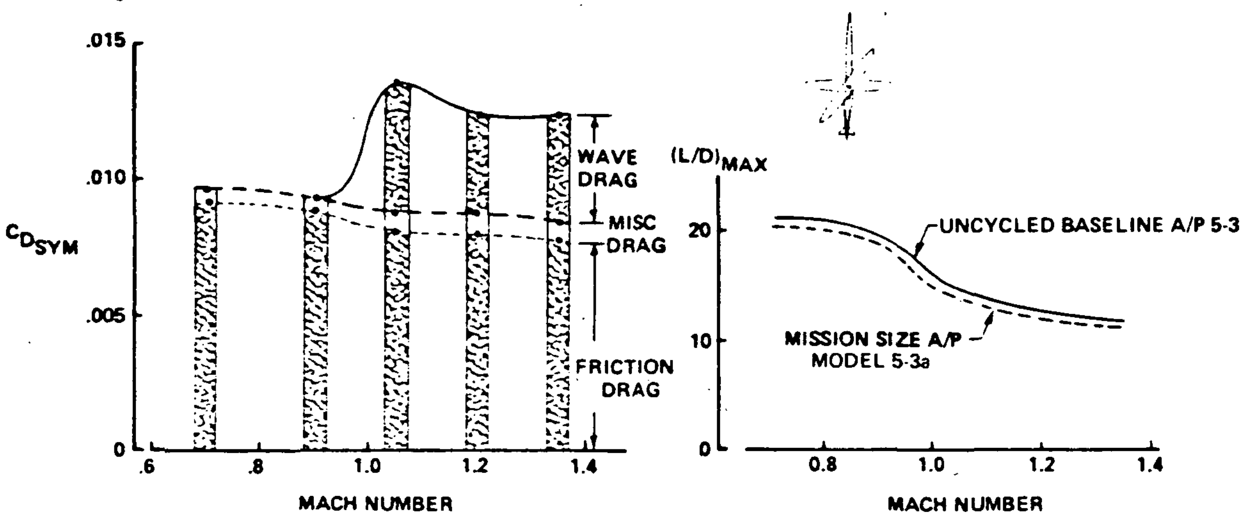


FIGURE 12.—CRUISE DRAG VERSUS MACH NUMBER, MODEL 5-3A

FLIGHT CONTROLS

Horizontal and vertical stabilizing and control surfaces were chosen to provide adequate trim and maneuvering capability throughout the flight envelope. The horizontal and vertical tails were sized to provide adequate augmented dynamic stability, takeoff rotation (except for model 5-3 which does not rotate), engine-out control, landing trim, and flare capability, in addition to sufficient nose-down control power to avoid high-alpha locked-in stall. A flight-critical SAS, comparable to the U.S. SST design, was assumed to ensure that the resulting augmented longitudinal and lateral-directional static and dynamic stability characteristics would be acceptable.

The yawed-wing airplane introduced unique stability and control characteristics. A complete six-degrees-of-freedom large-disturbance solution of the equations of motion was required to predict the dynamic stability characteristics in order to understand the impact of the cross-coupling inertial and aerodynamic forces and moments uniquely associated with a yawed wing. Examples of the aerodynamic cross-coupling stability derivatives are shown in figure 13.

The longitudinal response to an elevator control pulse was comparable to present transport aircraft. However, because of the induced aerodynamic cross coupling, the yawed wing developed a rolling motion and heading change in phase with the pitching motion.

The lateral-directional response of the yawed-wing airplane to a rudder control pulse was also very comparable to present transport aircraft. However, in addition to the yawing and rolling accelerations felt by the passengers, a vertical acceleration would also be apparent.

A conceptual stability augmentation and control coordination system was formulated for the single-fuselage yawed-wing configuration. Stability augmentation is required because the empennage and cg range were selected with the ground rule that the basic airframe would be unstable in order to minimize tail size. Also, because of the cross coupling, it may be desirable to interconnect the longitudinal and lateral-directional axis (control coordination) to maintain acceptable flying qualities. This system would require more development than that required for a symmetrical airplane, but it is believed to be entirely feasible.

The aeroelastics effects of the airplane were not included in the analyses. Wind tunnel testing and detailed aeroelastic stability and control analyses are quite necessary to obtain a more complete understanding of the yawed-wing airplane control requirements.

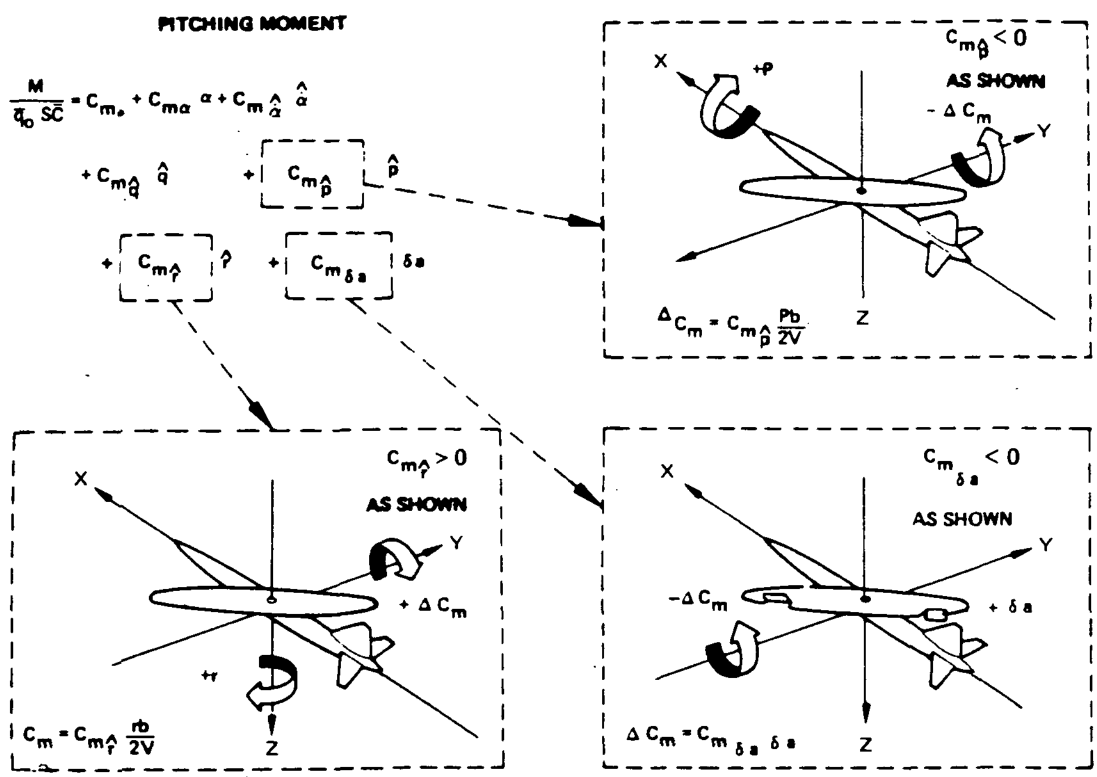


FIGURE 13.—YAWED-WING AERODYNAMIC PITCHING MOMENT CROSS-COUPLING STABILITY DERIVATIVES

POWER SYSTEMS AND ENVIRONMENTAL CONSIDERATIONS

Engine performance, size, and weight characteristics were obtained from a computerized advanced transonic/subsonic parametric engine family tailored to be representative of advanced-technology engines designed for a specified time period. The engines used were shown to be consistent with those projected by the engine manufacturers under the Advanced Technology Transport (ATT) contract.

A study was made initially using "nominal" airplane characteristics to determine the effect of bypass ratio. The objectives were to determine the penalty of reducing the jet noise by increasing engine bypass ratio, as compared with that for the introduction of jet suppression for lower bypass ratio installations.

The noise characteristics were computed at levels of takeoff and approach thrust equal for all engines. Figure 14 shows the results of the initial "nominal" aircraft/engine bypass ratio study. On the basis of these results, the bypass-ratio-1 engine cycle, with jet suppression, was selected for all of the configurations.

EMISSIONS

The emission requirements specified as ground rules for this study were compared with levels representative of current engines. Levels thought to be achievable by the engine manufacturers during the previous ATT studies for an advanced combustor design were also considered.

The study ground rules emission goals for unburned hydrocarbons and carbon monoxide appear to be achievable with advanced combustor design. However, the goal for nitrogen oxides appears to be too stringent to be obtained simply by advanced combustor design and can only be met with the use of water injection. This approach, however, entails a great many operational disadvantages. The combustor design modifications were estimated to be achievable at negligible performance penalty.

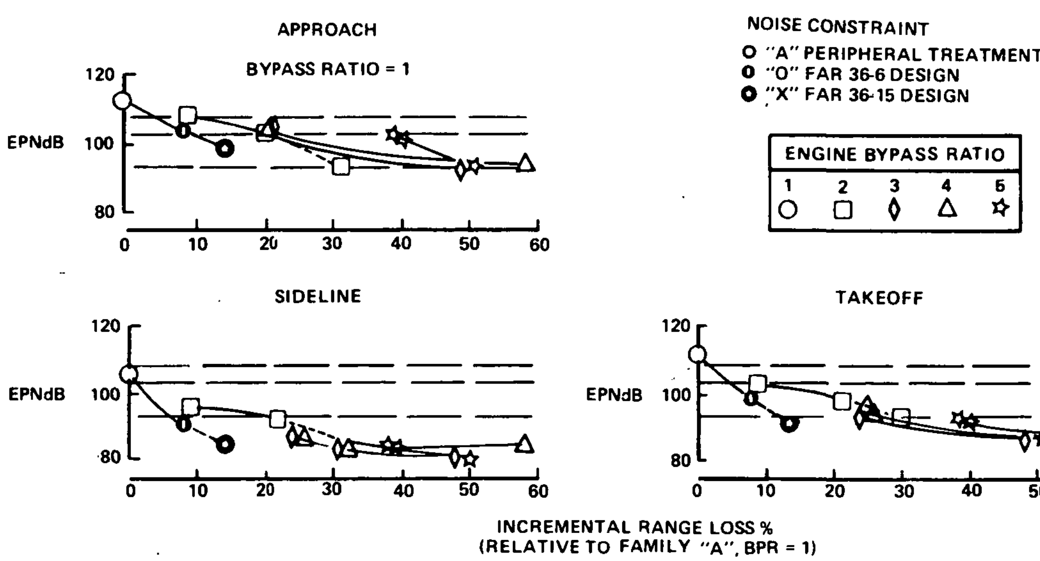


FIGURE 14.—NOISE/PERFORMANCE TRENDS OF "ATT TECHNOLOGY" ENGINES

STRUCTURES AND MATERIALS

Structural feasibility was evaluated for each of the concepts studied. Constraints such as the requirement for area ruling, ground clearance, landing gear arrangement, and engine location were considered. Estimates of load transfer were made to ensure sufficient space for structure, pivots, and mechanisms and to check for reasonable load paths.

The flight speed placard was selected to provide a low cruise dynamic pressure while allowing cruise at an altitude near that for best performance.

MATERIALS SELECTION

Advanced structural materials for all configurations were derived from ATT study results (ref. 12). The level of advanced technology assumed is that corresponding to an airplane availability date of 1985. This availability date is contingent on the completion of the research programs recommended as part of the ATT program (ref. 13).

Structural materials selection analyses were directed at defining:

- Areas for each of the airplane concepts best suited for application of advanced-composite materials
- Types of structural materials to be considered
- Percent weight savings of advanced structural materials over conventional aluminum skin-stringer construction.

A typical result of these analyses is shown in figure 15 for the single-fuselage yawed-wing configuration. Similar material selection charts were developed for each configuration concept.

Structural analyses were conducted to determine the nature of aeroelastic divergence of a yawed-wing airplane. Results of the dynamic stability analysis are presented in figure 16 in terms of airplane speed versus damping ratio.

The results of these analyses and some preliminary strength analyses indicated that a reasonable approximation to the structural weight of the wing would result from sizing the structure to the more stringent of:

- Gust and maneuver loads at zero yaw angle
- Cantilever divergence of the forward-swept wing.

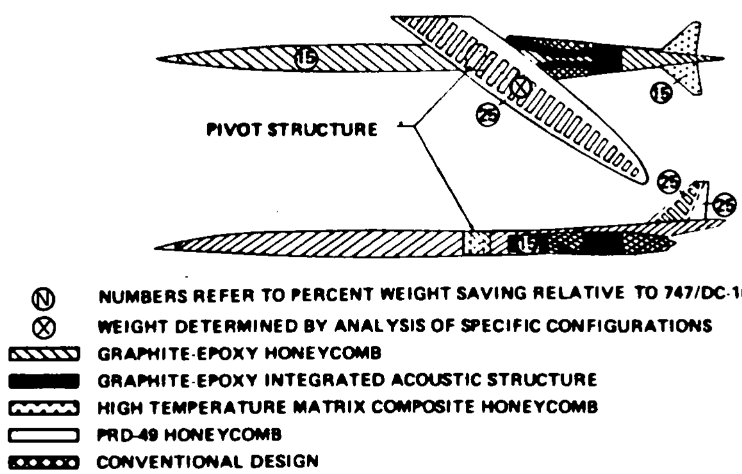


FIGURE 15.—MATERIALS SELECTION, MODEL 5-3

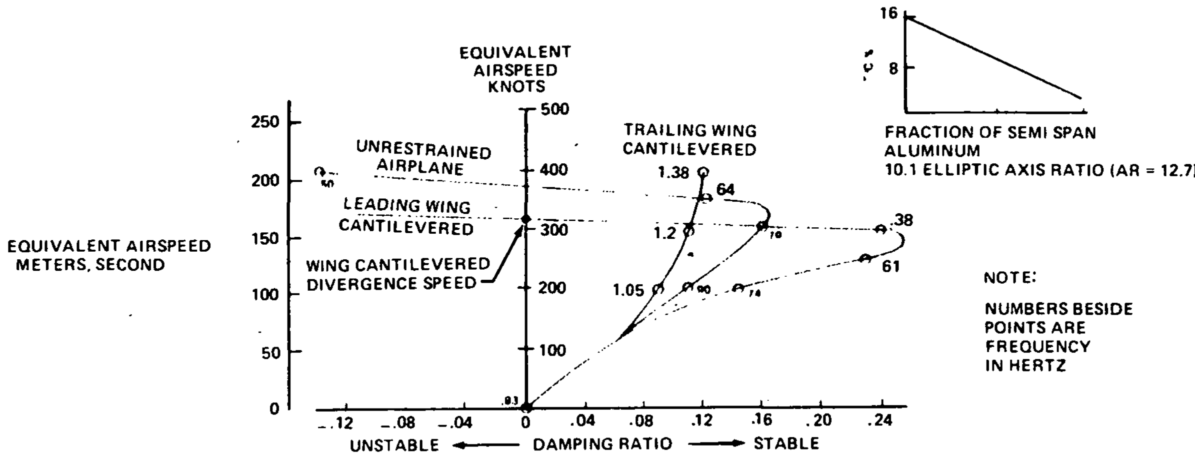


FIGURE 16.—UNRESTRAINED YAWED-WING AIRPLANE STABILITY

YAWED-WING ANALYSES

Graphite-epoxy advanced filamentary composite structure was applied to the yawed wing. High-modulus graphite was used. Fiber orientations were selected to enhance wing bending direction strength and stiffness while retaining reasonable strength in other directions. The graphite-epoxy was evaluated by comparison with a conventional aluminum structure. Sizing criteria used were strength at zero yaw and divergence avoidance at 45° yaw. For aluminum structure, the divergence avoidance criterion required considerably more material than the strength criterion. For the case using graphite-epoxy, both divergence and strength required nearly equal amounts of material.

The material requirements based on strength considerations were determined using a computerized wing structural synthesis program that combines an aeroelastic loads analysis based on (1) beam theory and lifting line aerodynamics, as described in NACA TN 3030 (ref. 14), (2) a simplified box beam stress analysis, and (3) a weight analysis of the wing box.

WEIGHT AND BALANCE

The U.S. SST prototype program model 2707-300 was selected as a base point to develop the weight for the structure and equipment systems. Weight adjustments were determined for changes in geometry, structural loading, and temperature effects on material selection for Mach 1.2. The weight analyses for the yawed-wing configurations were based on wing structural analyses. Advanced-technology weight adjustments were applied to the structure, propulsion, equipment, and payload systems.

Each configuration was subjected to a weight and balance evaluation to develop a meaningful arrangement. The results of the balance and loading analysis for the single-fuselage yawed-wing configuration (5-3) indicated that ballast would be required for payloads differing from the design payload.

The single-fuselage yawed-wing configuration warrants further detailed design and analysis investigations to validate fully the weight estimates. The details of the structural arrangement and methods of construction of the wing require more detailed definition to determine the transmittal of loads from the wing through the pivot and body structure and to define the static and dynamic forebody loads in the area of the pivot.

CONCLUSIONS

The most significant conclusions of this study are:

- The "boomless" supersonic mission requirements were met at FAR Part 36 noise levels by a delta configuration at 226 796 kg (500 000 lb) gross weight and by a single-fuselage yawed-wing configuration at 211 828 kg (467 000 lb). The higher lift/drag ratio of the yawed-wing concept led to its lower gross weight. Configurations based on the other concepts resulted in heavier airplanes.

- The noise goal of 15 EPNdB below FAR Part 36 can be met with the single-fuselage yawed-wing configuration at approximately 226 796 kg (500 000 lb) gross weight. This noise goal cannot be met reasonably by the other configurations. The yawed-wing configuration has a large advantage in takeoff and landing performance.

- A yawed-wing configuration designed for Mach 1.2 can achieve the design range for all supersonic Mach numbers up to 1.2 and will have a 20% excess range capability at subsonic speeds.

- The selected structural design speed placard restricted the minimum Mach 1.2 cruise altitude to 11 887 m (39 000 ft). This restriction constrained the size of all of the configurations and has probably resulted in performance losses.

- Although wing aeroelastic divergence is a primary design consideration for yawed-wing configurations, the graphite-epoxy wings of the study were designed by critical gust and maneuver loads rather than by divergence requirements.

- Advanced filamentary composite materials offer about a 20% structural weight saving over aluminum for a strength-designed yawed wing.

- A variation in the yawed-wing aspect ratio results in a trade between lift/drag ratio and wing weight due to divergence. The best planform was obtained with an elliptic axis ratio of 8:1 (unyawed aspect ratio 10.2) and an unyawed maximum t/c of 12%.

- The rigid dynamic stability and control characteristics of all five concepts are acceptable. However, aeroelastics may have a significant effect on the flying characteristics of the yawed-wing configurations.

- For high transonic speed applications, low-bypass-ratio engines with suppression result in lower gross weight airplanes than configurations with high-bypass-ratio engines, even at equal community noise levels.

- The total drag for any transonic configuration is very sensitive to the way in which the the nacelles are installed. Double-pod installations result in high wave drag. Engines integrated into the body result in low drag.

RECOMMENDATIONS

The conclusion of this study relative to the promising potential of the single-fuselage yawed-wing concept led to the recommendation that a program be undertaken to verify and further develop the potential of the yawed-wing concept. A three-phase program is recommended as follows:

PHASE I

- Determine the best structural design speed placard by studying the trade between airframe weight and aerodynamic performance.
- Develop a Mach 1.2 configuration alternate to configuration 5-3. The objective of this development should be to simplify the engine and landing gear installation while retaining the aerodynamic efficiency.
- Develop a low-transonic-speed yawed-wing configuration to compare directly with the ATT configurations.
- Match the engine cycle, the amount of noise suppression required, the flap system, and the takeoff and landing procedures to minimize the community noise for the synthesized basic and alternate yawed-wing configurations.
- Conduct an analysis of the stability and control characteristics of a flexible yawed-wing airplane to identify control system requirements.
- Conduct a theoretical and experimental wing development study to fully identify the maximum practical wing thickness/chord ratio and the minimum achievable drag due to lift.
- Analyze operational characteristics of a yawed-wing commercial transport in airline operation and estimate total operating costs. Compare these costs with wide-body and ATT operating costs for similar payload/range categories.

PHASE II

- Verify the performance of the best Mach 1.2 configuration developed in phase I by a coordinated theoretical-experimental program covering both the low- and high-speed flight regimes.
- Conduct a market analysis to determine potential total airline fleet requirements.
- Based on the results of the phase I stability and control study and available test data, develop a moving-base simulation of the airplane in order to evaluate flight control systems.
- Perform an aeroelastic model wind tunnel test to confirm the wing divergence and flutter characteristics.
- Develop detailed plans, including the design criteria, for a yawed-wing flight test vehicle.

PHASE III

Design and fabricate a yawed-wing flight test airplane.

SUPPORTING TECHNOLOGY DEVELOPMENT

In addition to the development work described above for the yawed-wing configuration, the basic advanced-technology programs recommended as part of the Advanced Transport Technology study (ref. 10) should be pursued since they apply nearly universally to this concept. This is particularly true in the structures, flight control, and power systems areas, which require the projected technology advances to achieve the potential identified in this study.

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