HSCT DESIGN FOR REDUCED SONIC BOOM

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LOW-SONIC-BOOM DESIGN PERSPECTIVE

CURRENT GOAL: No perceptible boom over populated areas

ASSUMPTION IN HSCT VIABILITY STUDIES:
No supersonic flight over land
Optimized over water routing

HSCT ENVIRONMENTAL IMPACT STUDIES WITH "ACCEPTABLE" BOOM

OBJECTIVES:

Evaluate the impact of applying innovative sonic boom technology to practical HSCT configurations, for possible overland supersonic cruise.

Identify design issues, performance and noise characteristics, and economic benefits relative to a baseline configuration.

RESULTS:

Three low-boom configurations developed, one in each HSCT Phase III, IIIA, and IIIB.

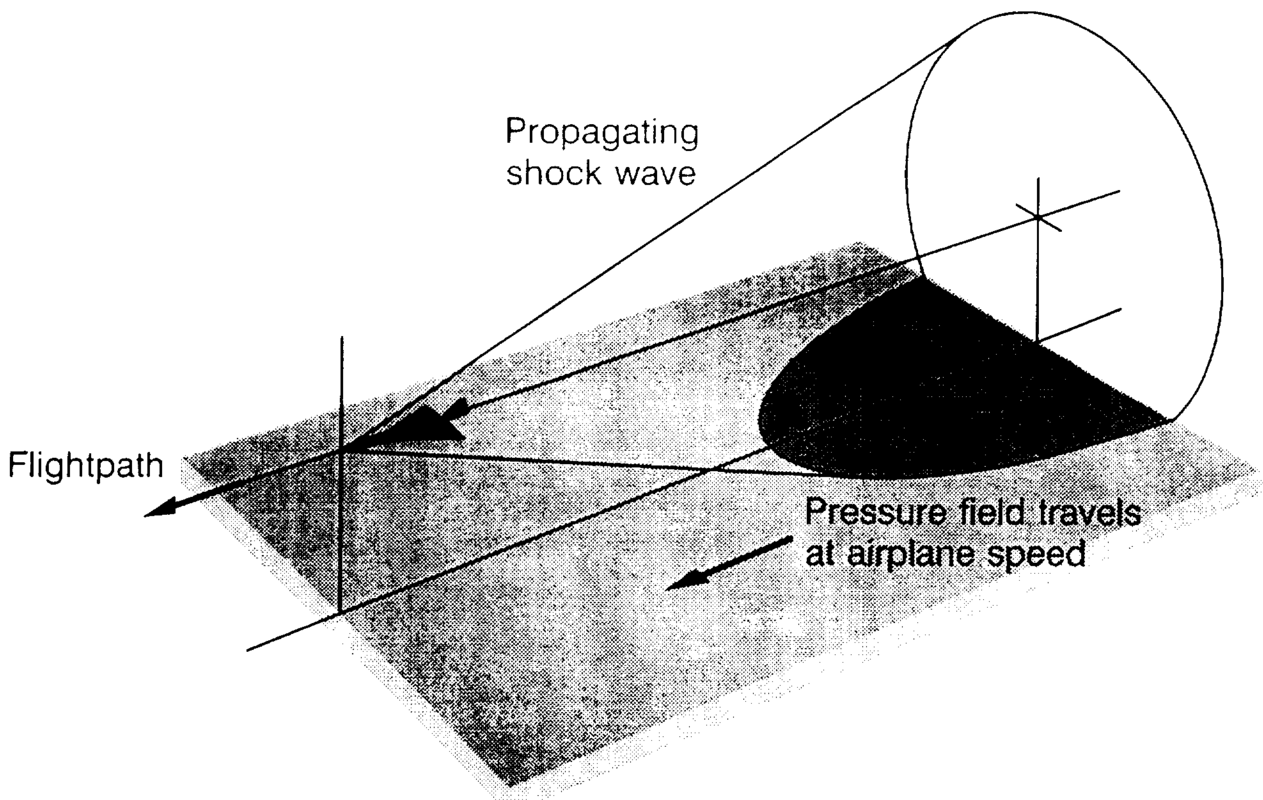

Figure 1. Sonic boom pressure field.

DESIGN APPROACH FOR REDUCED SONIC BOOM

Unfortunately, the sonic boom design goal is not yet firmly established, because we do not know enough to precisely define sonic boom waveforms that are psycho-acoustically acceptable to humans. However, for this study, the sonic boom design goal was to obtain a sonic boom waveform at the ground with loudness of 72 dBA or less. The 72 dBA loudness criterion was developed from an analysis of available human response test data acquired during the 1970s (ref. 2). This reduced loudness is obtained by reducing the magnitude of the pressure jump across each shock wave in the sonic boom waveform to a value of about 0.75 lb/ft^2.

The sonic boom constraint defined above has a profound effect on the airplane design. In particular, the airplane lifting surfaces must be highly swept, lightly loaded, and spread along the horizontal length of the airplane. In addition, the distribution of volume must be closely dove-tailed to the lift distribution. An appropriate flight condition (Mach, altitude, and gross weight) must also be selected to achieve a realistic configuration.

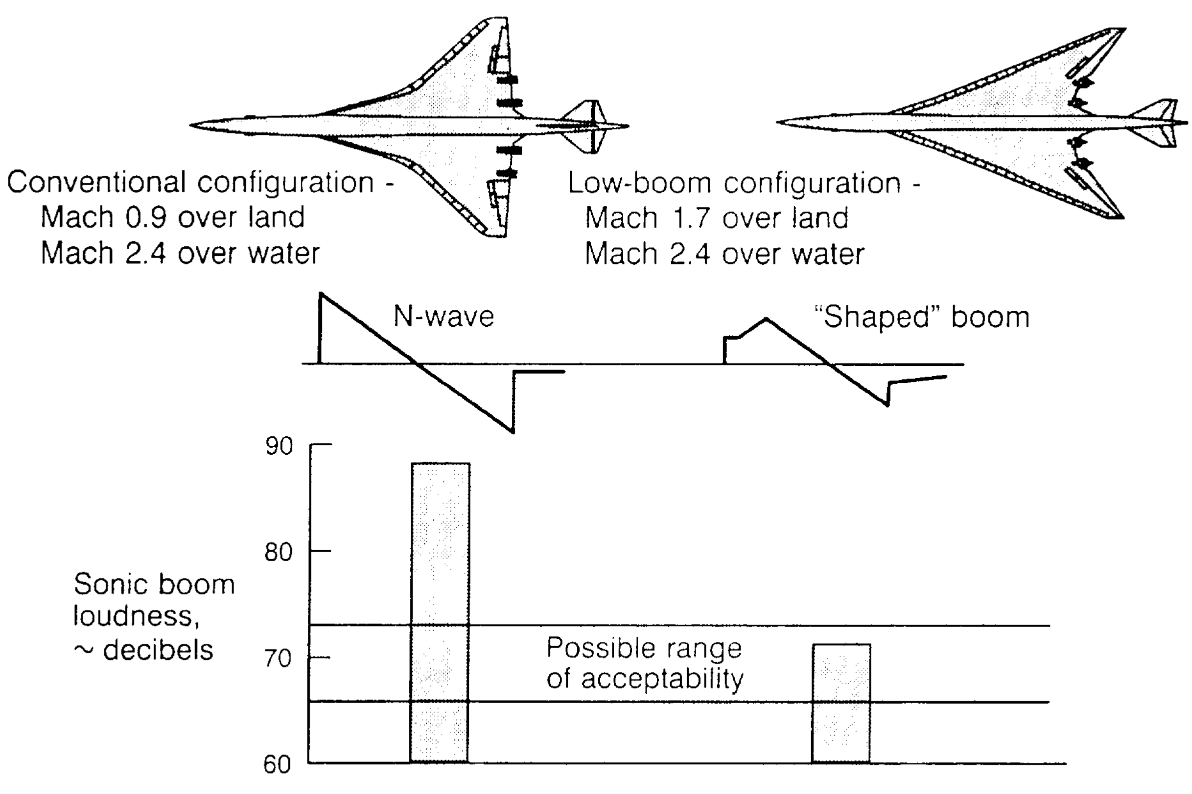

Figure 2. Conventional and low-boom concepts compared.

TARGET SONIC BOOM WAVEFORMS , PHASE III

In HSCT Phase III, configuration III was designed with the objective of meeting the 72 dBA target with 1.0 lb/ft^2 shocks at Mach 1.5 cruise with a "ramp" waveform, shown below (refs. 2 through 5). The design loudness of 72 dBA was not met, however, due to the stronger-than-desired tail shock and intermediate shocks. In Phase IIIA, the target waveform for Mach 1.7 cruise was revised to be a "delayed ramp" waveform with 0.90 lb/ft^2 shocks, resulting in configuration IIIB. Again, however, the calculated loudness of 77 dBA did not meet the loudness goal, primarily because of an update to the shock-wave rise-time effect.

In Phase IIIB, the target shock strengths were reduced to 0.75 lb/ft^2 to achieve the 72 dBA target loudness. In addition, the target waveform was revised slightly, as shown below.

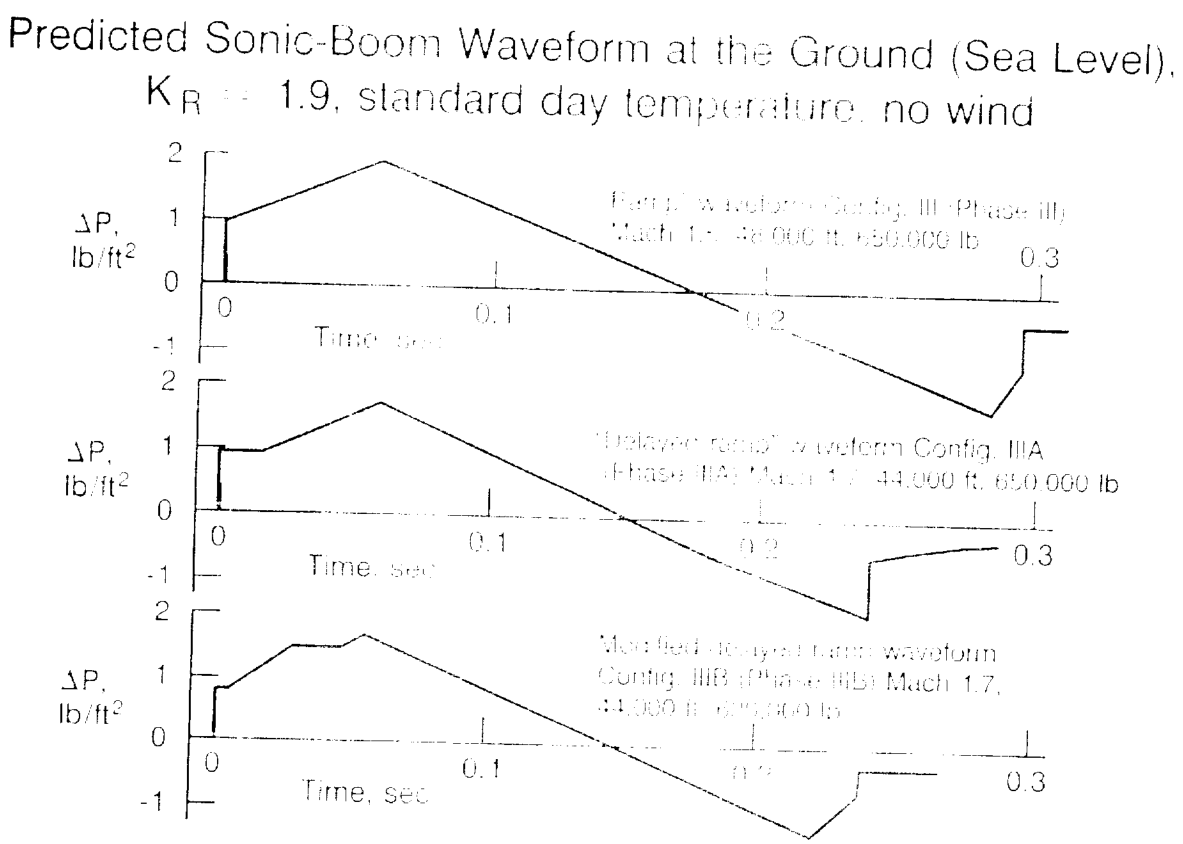

Figure 3. Target sonic boom waveforms.

AIRPLANE DESIGN FOR REDUCED SONIC BOOM LOUDNESS

The sonic boom design constraint was imposed in the form of an overall target distribution of the Whitham F-function, which is directly related to the target sonic boom waveform at the ground. The target F-function fundamentally defines the airplane lift and volume aerodynamic characteristics close to the airplane (Ref. 6). The sonic boom disturbance at the ground includes the effects of atmospheric propagation (Refs. 6 and 7). Figure 4 shows the overall target F-function and the associated sonic boom waveform at the ground.

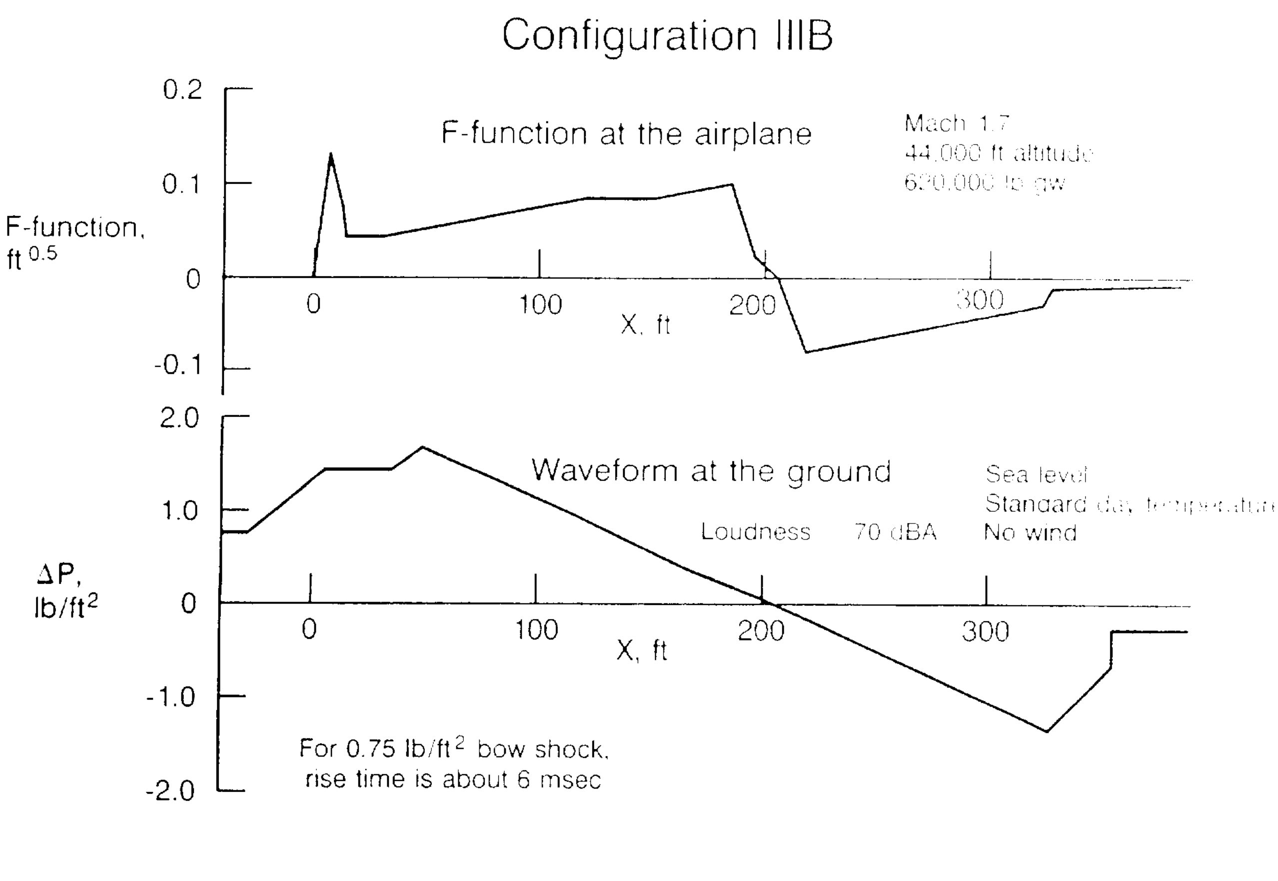

Figure 4. Target F-function and waveform.

DESIGN PROCEDURE FOR LOW SONIC BOOM

Figure 5 outlines the design process that was used in Phase IIIB to define configuration IIIB. Many iterations in geometry were required to approach the desired overall airplane F-function. The lift and volume contributions of each airplane component (wing, body, nacelles, horizontal tail, and vertical tail) must be located and shaped appropriately, while considering any mutual interference effects. Each design iteration led to a correction in the actual airplane F-function and a directly-related correction to the geometry.

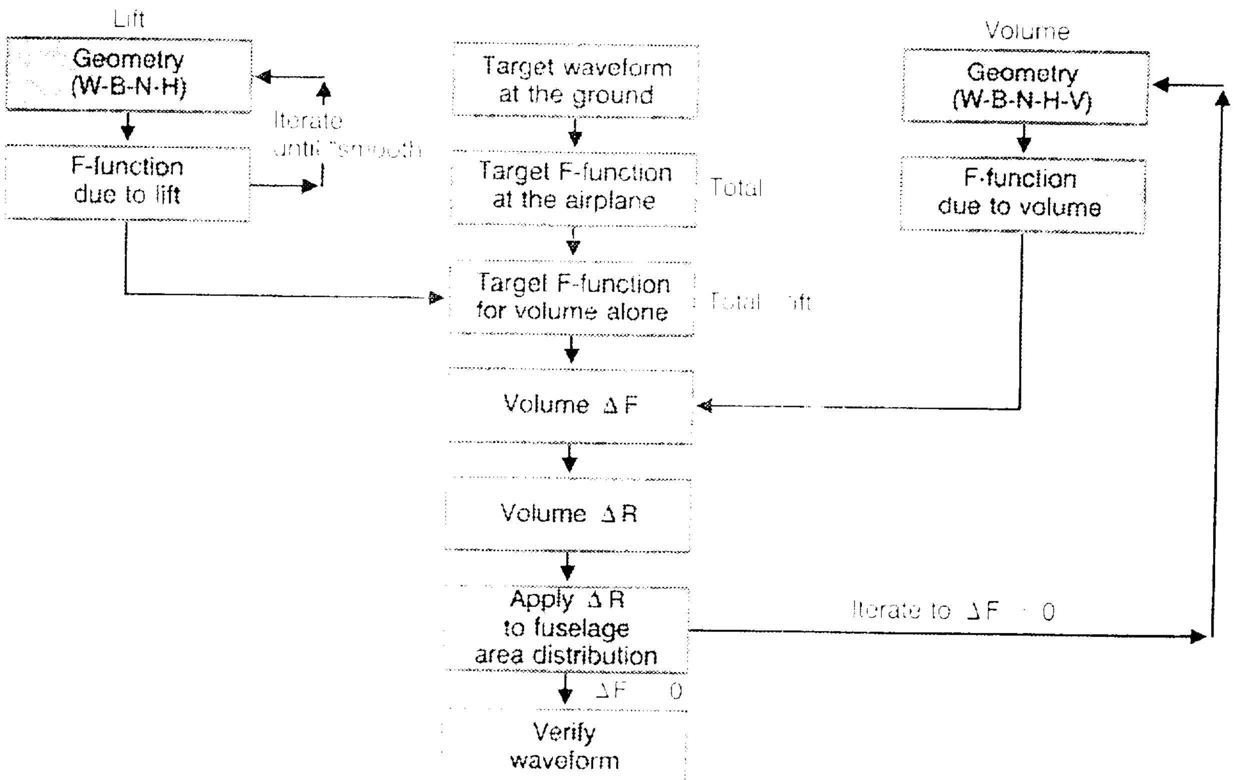

Figure 5. Design procedure for low sonic boom.

WING DESIGN AND NACELLE LIFT EFFECTS

Because the sonic boom from large, heavy cruise vehicles is lift-dominated, the most important airplane component is the wing planform and the lift distribution that it produces. Accordingly, previous Phase III studies have focused on arrow-wing planforms, wing leading-edge strakelets, and appropriate wing camber and twist designs. However, another aspect of the lift distribution is the lift produced by the nacelles, mounted aft on the wing lower surface. The positive pressures from the nacelle forebodies pressurize the wing lower surface, producing a beneficial lift force of up to 10% of the total lift. Because the effect is strong and localized, it should be considered eary in the design phase. The Phase IIIA configuration required a rather severe fuselage area-ruling to counteract the non-smooth lift distribution in the vicinity of the nacelles.

Therefore, one of the major goals of Phase IIIB was to achieve a smooth overall lift distribution, considering the nacelle lift-interference effects. This was accomplished as follows: 1), use of new baseline nacelles, having a smaller area growth, and 2) revised wing camber and twist design, with a reflex in the camber surface near the nacelles.

Figure 6 shows the improvement in the F-function due to lift, by comparing the F-functions of the IIIA configuration and the new IIIB design. These F-functions were calculated by converting the lift distributions into the equivalent bodies of revolution for the start-of-cruise condition, according to the standard sonic boom methods (Refs. 7 and 8).

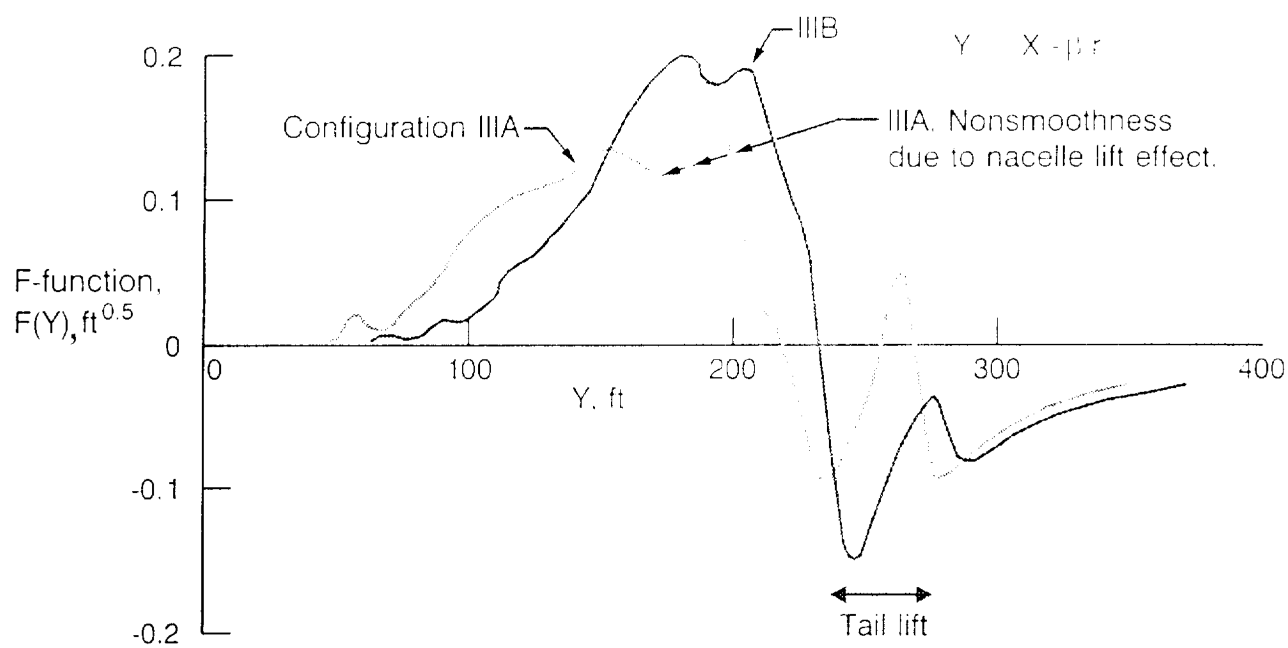

Figure 6. Calculated F-functions due to lift.

AREA DISTRIBUTIONS AND F-FUNCTION DUE TO VOLUME

The details of the volumetric components were defined next, beginning with the fuselage forebody. The forebody shape is important because it produces the initial 0.75 lb/ft^2 shock wave and the constant-pressure region of the target sonic boom waveform. It was defined by the method of Reference 9, with a slight reduction of forebody cross-sectional area to account for forebody lift. Figure 7 shows the area distribution and F-function produced by all of the volumetric components.

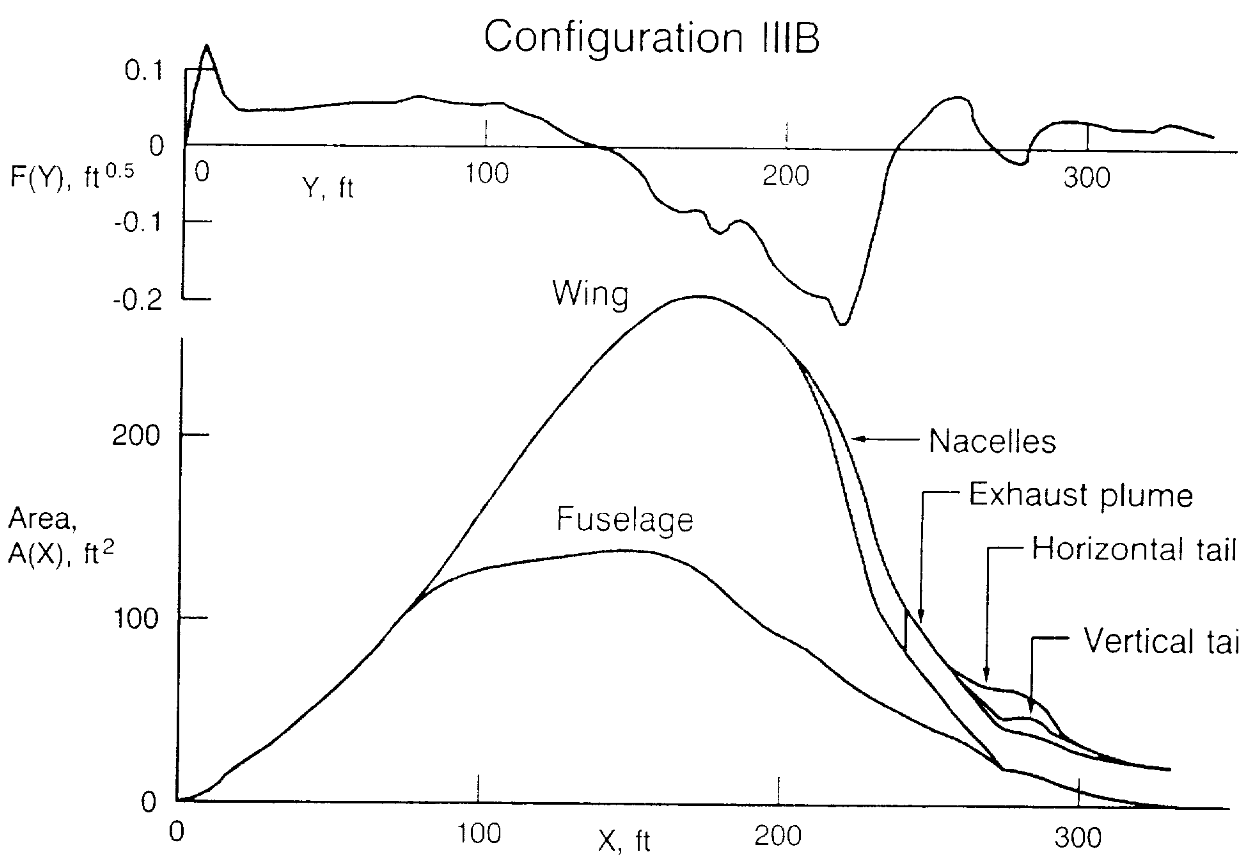

Figure 7. Area distributions and F-functions due to volume.

FUSELAGE AREA DISTRIBUTIONS

The fuselage area distribution shown in Figure 8 is quite different from previous low-boom configurations, because of the 0.75 lb/ft^2 constraint and the smoother lift distribution. The aft-body shape in particular is impacted by the more severe sonic boom constraint, resulting in reduced seating capacity (only 237 mixed-class or 252 all-tourist passengers). This fuselage shape could be improved, in terms of seating capacity and also wave drag, by modifying the wing planform and lift distribution. In addition, the aft-body design needs more investigation.

Figure 8 shows the severe area-ruling of the IIIA configuration in the vicinity of the nacelles, due to the non-smooth lift distribution. This effect was reduced considerably for configuration IIIB.

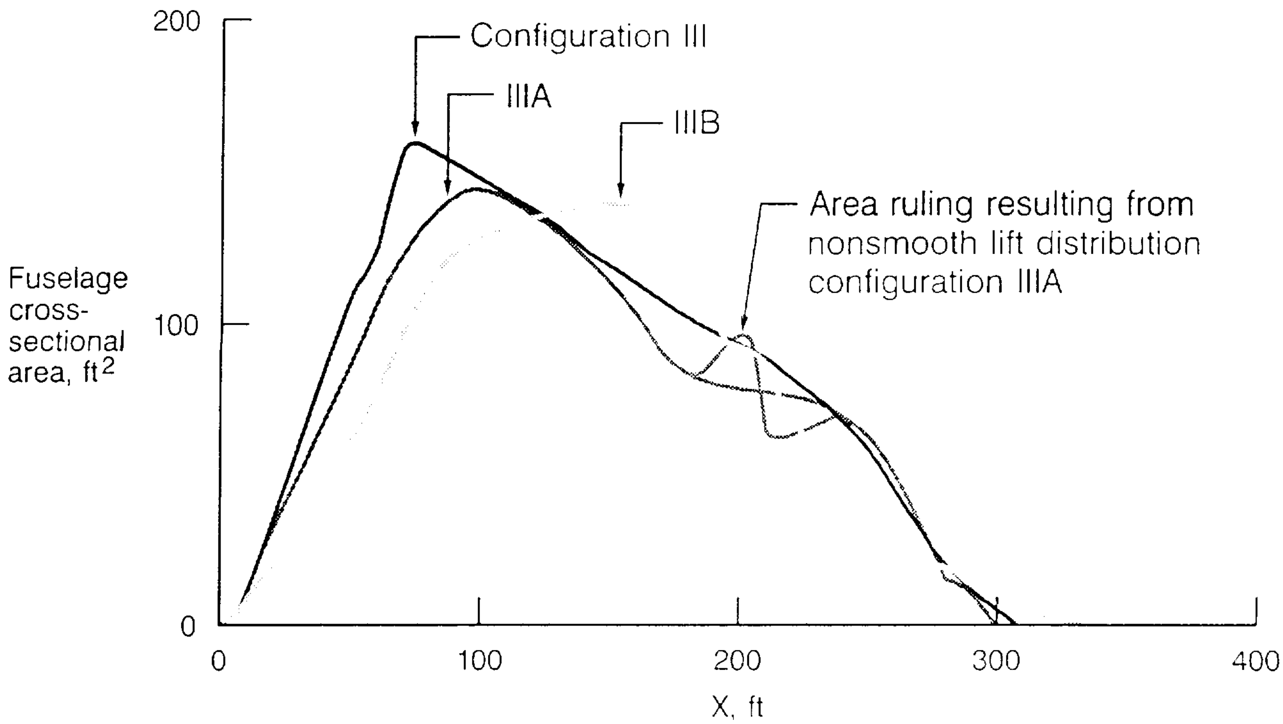

Figure 8. Fuselage area distributions.

LOW SONIC BOOM DESIGN, CONFIGURATION IIIB

The drawing of the uncycled configuration, the Model IIIB, is shown in Figure 9. This drawing was used as the basis for developing the sonic boom characteristics, as well as the inputs and scalars for the performance sizing program.

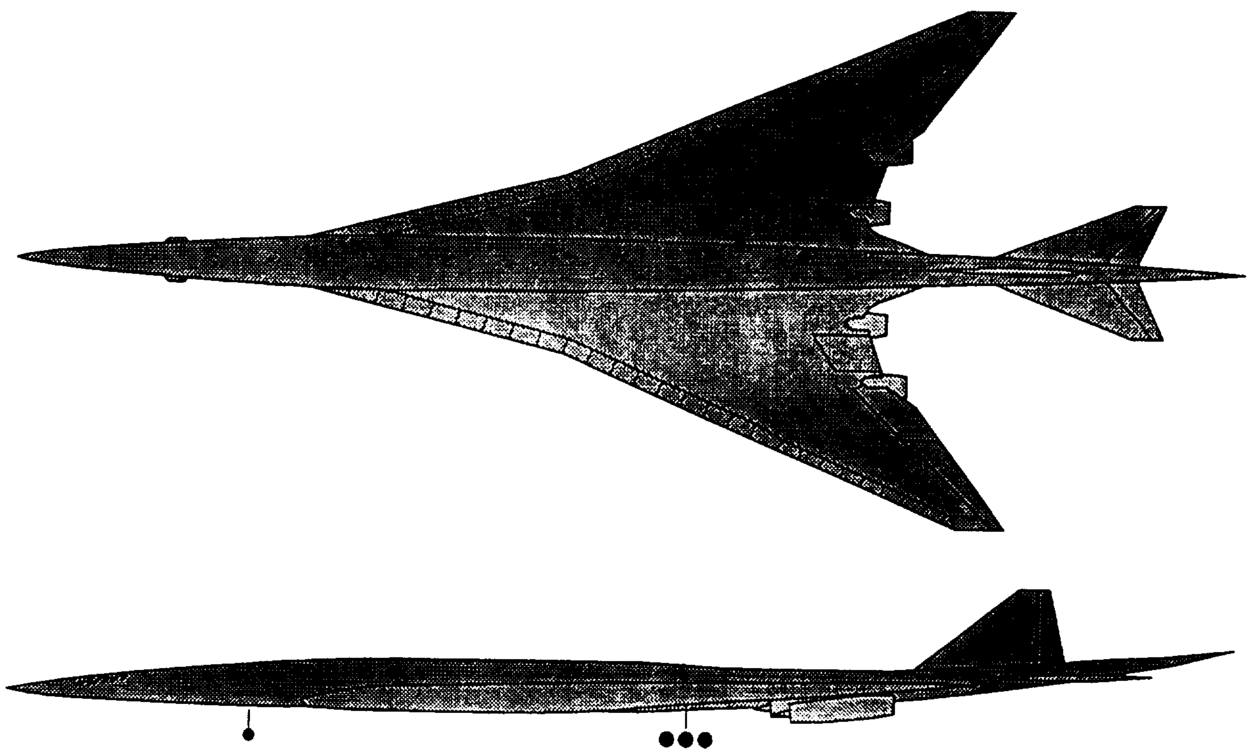

Figure 9. Model IIIB, General Arrangement.

SONIC BOOM CHARACTERISTICS

The Mach 1.7 overland cruise sonic boom waveform at the ground was calculated for the start-of-cruise condition and is shown in Figure 10. The bow and tail shocks meet the 0.75 lb/ft^2 design goal. Although the waveform exhibits smaller pressure jumps and isentropic pressure increases, the calculated sonic boom loudness is 71 dBA, which is less than the design goal of 72 dBA. The small pressure jumps are not significant for sonic boom loudness.

The calculated loudness is sensitive to the shock-wave rise time. For this study, rise-time values were determined from an empirical analysis of N-wave sonic booms produced by Air Force fighter and SR-71 aircraft. The rise time of the 0.75 lb/ft^2 bow shock is about 6 msec; the smaller shocks have an appropriately longer rise time.

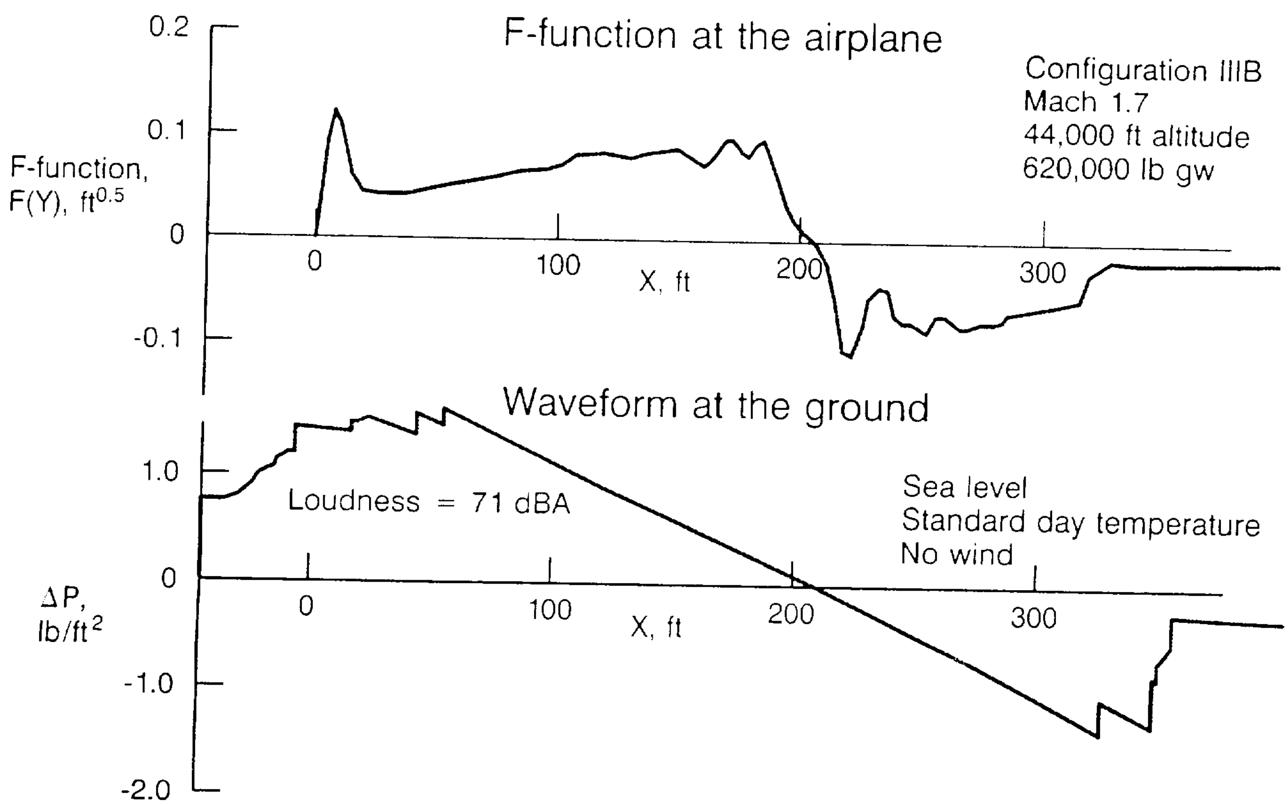

Figure 10. Actual F-function and waveform.

SIZING, PERFORMANCE, AND NOISE CHARACTERISTICS

The airplane is sized for a 5000 n. mi. mission by fuel volume (wing area) and minimum takeoff weight (engine size). Figure 11 compares Model IIIB to its baseline airplane. Despite the large 15% loss in payload from 279 to 237 passengers required to achieve the target 0.75 lb/ft^2 waveform, the takeoff gross weight increased 2%, OEW increased 8%, engine size increased 6%, while block fuel was essentially unchanged. On the other hand, takeoff and landing performance of Model IIIB was substantially improved relative to the baseline due to the low wing loading dictated by the fuel volume requirement. This in turn lead to lower takeoff noise levels for the Model IIIB, -2.7 EPNdB and -1.3 EPNdB at the sideline and community points, respectively.

The performance assessment of the Model IIIB relative to the baseline was done at the average fleet mission of about 3450 n.m., of which about 25% is flown over land. The baseline flies the overland portion of the flight at Mach 0.9, while Model IIIB flies it at Mach 1.7, which reduces the block time by about 0.5 hour.

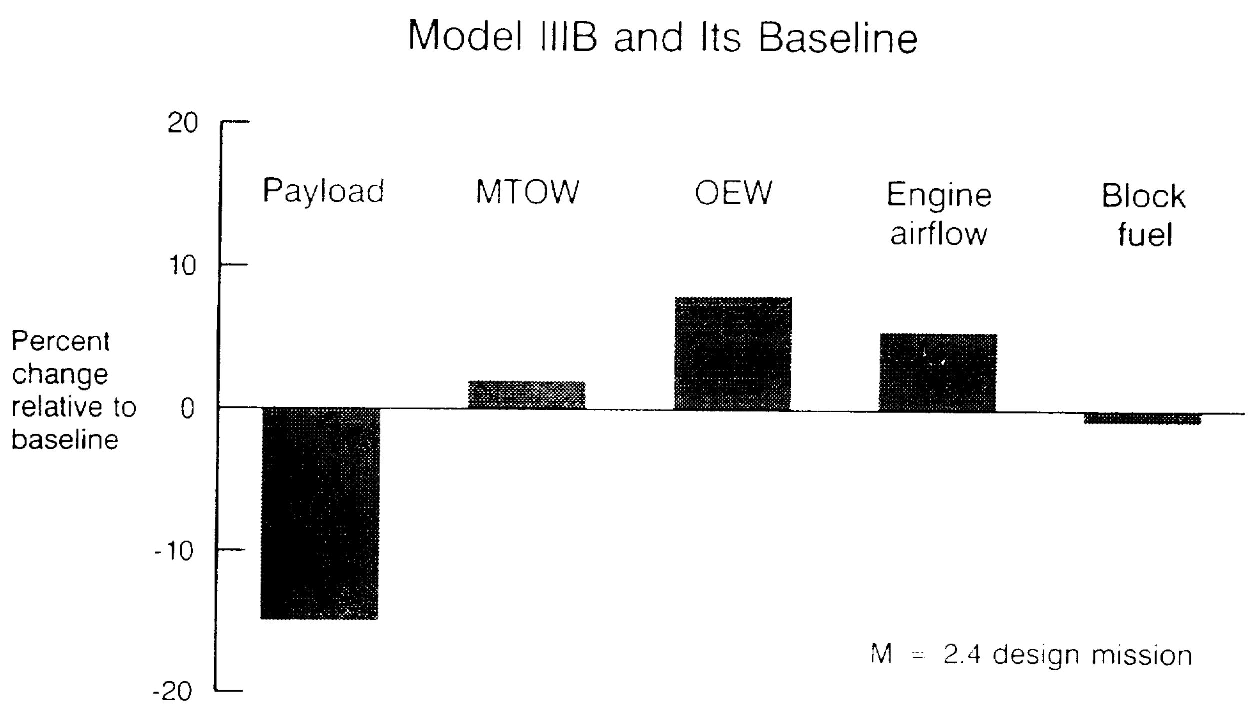

Figure 11. Performance comparison, Model IIIB and its baseline.

SUMMARY OF PHASE III CONFIGURATIONS

During the Phase III low sonic boom studies, several configurations have been designed, with different sonic boom and configuration constraints. Figure 12 gives a comparison of their respective design conditions and constraints. The early studies illustrated the advantages of lower altitude and reduced supersonic Mach number. Higher Mach number, as well as higher altitude, make the low-boom design problem inherently more difficult because far-field propagation pushes the waveform toward the form of the far-field N-wave, rather than the "shaped" low-boom waveforms. Therefore, at higher Mach or altitude, severe configuration changes are required to achieve the shaped near-field waveforms with reduced shock strength. For example, the Mach 2.4 low-boom configuration 2B had significant drag and weight penalties, and a balance problem due to a wing location far back on the fuselage. The Mach 2.4 configuration was not pursued further, because of these formidable design problems.

In Phase IIIA, a new sonic boom target waveform was developed, the "dalayed ramp" waveform, and the cruise Mach number was increased from Mach 1.5 to 1.7. The delayed ramp waveform has several desirable features from the standpoints of configuration design, sonic boom propagation, and loudness.

Overwater Cruise is at Mach 2.4 in all Cases

Phase	Configuration	Sonic boom constraint (target)	Overland start-of-cruise design condition			
			Mach	Altitude, ft	GW, lb	
III	1B	Ramp waveform, ΔP_{SH} = 1.0 lb/ft^2 72 dBA loudness	1.5	48,000	650,000	Special forebody shape, arrow-wing planform with strake, staggered nacelles, etc.
	2B	Same as 1B	2.4	53,000	650,000	Much longer forebody, bigger strake, aft wing location, drag penalty, 20% increase in TOGW.
	III	Same as 1B	1.5	48,000	650,000	Two-post landing gear, 268 PAX. Actual boom loudness 78 dBA.
IIIA	IIIA	Delayed ramp waveform ΔP_{SH} = 0.9 lb/ft^2 72 dBA loudness	1.7	44,000	650,000	Minor configuration changes from III, 253 PAX, 77 dBA loudness.
IIIB	IIIB	Modified delayed ramp ΔP_{SH} = 0.75 lb/ft^2 72 dBA loudness	1.7	44,000	620,000	Smoother lift distribution, new nacelles, modified fuselage with aft-body extension, four-post landing gear, 237 PAX, 71 dBA loudness.

Figure 12. Summary of low-sonic-boom design constraints.

IMPACT OF SONIC BOOM DESIGN CONSTRAINT

For the 5000 n.m. mission, relative to a baseline configuration, the low-boom designs typically have the following characteristics: heavier TOGW, higher L/D, and similar block fuel. These characteristics are compared in Figure 13 for the three low-boom configurations and their respective baseline configurations. The 0.75 lb/ft^2 design (IIIB), however, suffers from reduced L/D and passenger count, as a direct result of the severe sonic boom design constraint. Accordingly, its block fuel per passenger is 17% greater than the baseline.

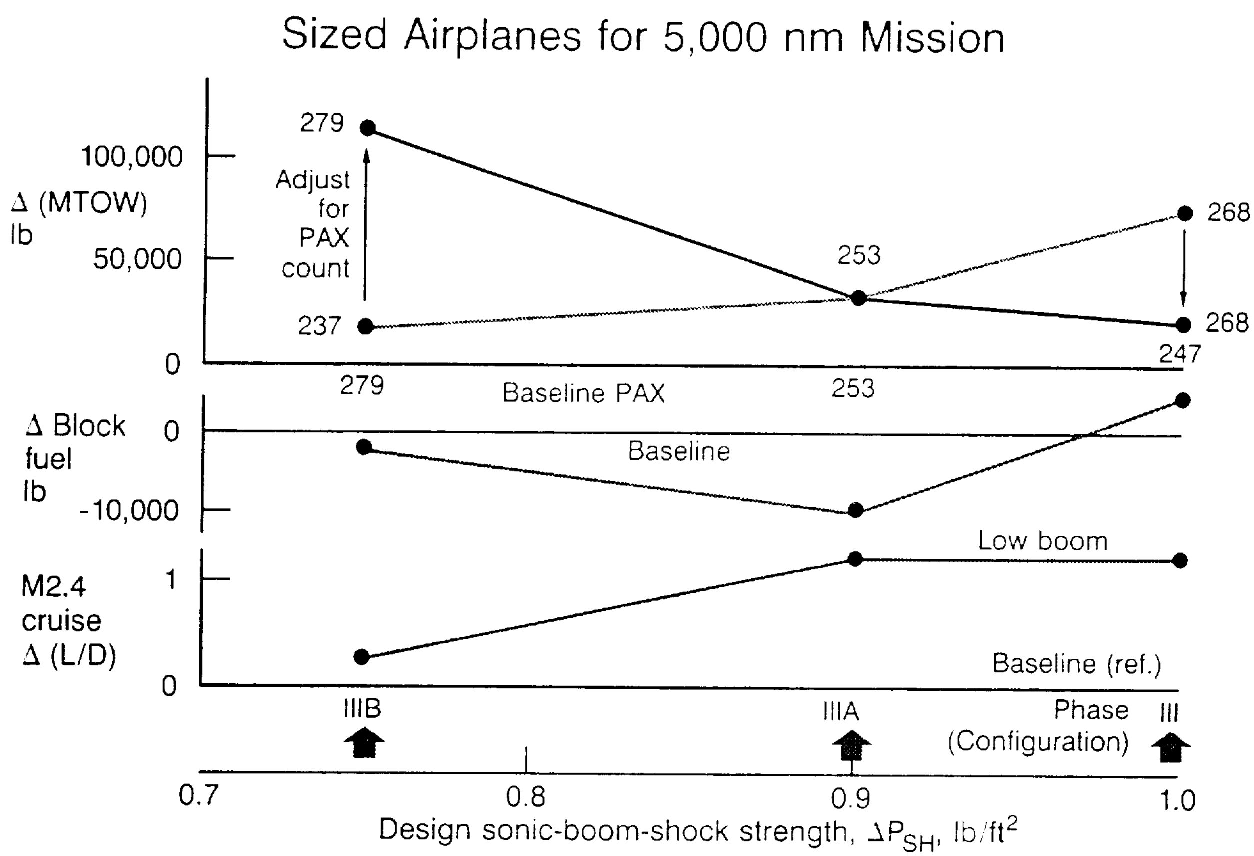

Figure 13. Effect of the level of the sonic boom constraint.

WING LOADING CONSIDERATIONS

In designing for reduced sonic boom, the wing loading, W/S_{REF}, is a particularly important design variable. For conventional configurations, the lift is concentrated over only about 50% of the total airplane length. Such wings have obvious advantages in terms of weight and skin friction drag. For the low-boom configurations, however, the lift must be distributed over a larger fraction of the airplane length and over a larger wing area. For example, the design wing loading of the low-boom configuration IIIB is about 63 lb/ft^2, whereas the wing loading of the baseline configuration is close to 100 lb/ft^2.

The effect of airplane sizing for optimum cruise performance is illustrated for configuration IIIB when it is sized for the 5000n.m. mission. As shown in the table below, the wing area was reduced from 9870 to 8632 ft^2, which increased the wing loading from 63 to 73 lb/ft^2; optimum cruise performance is obtained with the higher wing loading. The increase in wing loading, however, means that the wing lift may then be too concentrated and the low-boom design requirement may no longer be satisfied. This result indicates that there may be an inherent penalty for low-boom configurations because of the sonic boom requirement for a relatively large, lightly-loaded wing. Obviously, another cycle in the design procedure is needed, to develop the best compromise between the low-boom requirements and optimum cruise performance. In all of the Phase III studies, only a single pass was made through the sizing exercise.

	Gross Weight, W, lb At Start-of-Cruise	Effective Wing Area, S_{REF}, ft^2	Wing Loading, W/S_{REF}, lb/ft^2
Design Pt., Config. IIIB	620,000	9870	63
Sized Apl., (5000n.m.), Config. IIIB	628,000	8632	73

CONCLUSIONS

Configuration IIIB was designed for reduced sonic boom loudness at the ground and was compared to a baseline configuration in terms of size, performance, and noise. The following statements summarize the major conclusions:

1) In designing for reduced sonic boom loudness, many design variables must be considered, including flight condition variables and configuration design constraints that conflict with the sonic boom constraints.

2) In the "shaped boom" concept, shock coalescence and waveform aging must be retarded to avoid the N-wave form. Minimum aging occurs at the lower altitudes and lower supersonic Mach numbers.

3) The sonic boom loudness goal of 72 dBA was achieved by keeping the shock waves to less than 0.75 lb/ft^2, based on an empiricaly-derived rise time of six msec.

4) Compared to previous Phase III sonic boom constraints of 1.0 and 0.9 lb/ft^2, the 0.75 lb/ft^2 constraint produced additional penalties in gross weight, drag, passenger count, and performance.

5) A long, slender aft body was required for the 0.75 lb/ft^2 constraint, which resulted in a 15% reduction in seating capacity to only 237 mixed-class passengers (or 252 all-tourist), and a 2% increase in maximum takeoff gross weight relative to the baseline airplane.

6) Takeoff noise was decreased by about 2 EPNdB, due to the low wing loading dictated by the fuel volume requirement.

7) A performance benefit for operating at Mach 1.7 over land, rather than at Mach 0.9, did not materialize because of the large decrease in the ratio of payload to takeoff gross weight.

8) The deficiencies of configuration IIIB in terms of drag, weight, and passenger count can be improved somewhat by additional design work and a better compromise between the low-boom requirements and optimum cruise performance; the more severe design constraint of 0.75 lb/ft^2 makes the design process more difficult.

REFERENCES

1. "High-Speed Civil Transport Studies, Task 3.2 -- Special Factors Assessment, Sonic Booms." Boeing Document D6-53322-3, August 1987, Contract NAS1-18377.

2. Brown, J. G., and Haglund, G. T., "Sonic Boom Loudness Study and Airplane Configuration Development." AIAA Paper 88-4467, presented at the AIAA/ASEE Aircraft Design, Systems, and Operations Conference, Septermber 7-9,1988, Atlanta, Georgia.

3. "High-Speed Civil Transport Study, Airframe Technology," NASA CR 181879, 1989.

4. "High-Speed Civil Transport Study, Special Factors," NASA CR 181880, 1989.

5. "High-Speed Civil Transport Study," NASA CR 4233, September 1989.

6. Hayes, W. D., Haefeli, R. C., and Kulsrud, H.E., "Sonic Boom Propagation in a Stratified Atmosphere, with Computer Program," NASA CR 1299, 1969.

7. Haglund, G. T., and Kane, E. J., "Study Covering Calculations and Analysis of Sonic Boom During Operational Maneuvers, Vol. III, Description of Computer Program and Estimation of Limitation Near Caustics," FAA Report EQ 71-2, Feb. 1971.

8. Middleton, W. D., and Lundry, J. L., "A System for Aerodynamic Design and Analysis of Supersonic Aircraft. Part 1, General Description and Theoretical Development," NASA CR 3351, December 1980.

9. Darden, Christine M., "Sonic-Boom Minimization with Nose-Bluntness Relaxation," NASA TP 1348, 1979.

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