TWO HSCT MACH 1.7 LOW SONIC BOOM DESIGNS*

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SUMMARY

The objective of this study was to provide low sonic boom concepts, geometry, and analysis to support wind tunnel model designs. Within guidelines provided by NASA, two High Speed Civil Transport (HSCT) configurations were defined with reduced sonic boom that have low drag, high payload, and good performance. To provide information for assessing the feasibility of reduced sonic boom operation, the two designs were analyzed in terms of their sonic boom characteristics, as well as aerodynamics, weight and balance, and performance characteristics. Low drag and high payload were achieved, but both of the blended arrow-wing configurations have deficiencies in high lift capability, fuel volume, wing loading, balance, and takeoff gross weight. Further refinement of the designs is needed to better determine the commercial viability of low boom operation. To help in assessing low boom design technology, the two configurations were defined as wind tunnel models with altered aft-bodies for the wind tunnel sting mounting system.

INTRODUCTION

The primary objective of this study was to define wind tunnel models of two configurations for sonic boom testing. The goal of the wind tunnel test is to verify experimentally the low-boom characteristics with 12-inch models that incorporate the effects of wing camber, nacelles, and fuselage area-ruling. The aft-body of the model must be altered, however, to provide for the sting mounting system.

Previous NASA-sponsored studies at Boeing have included these effects (References 1 to 7), and have helped to define practical HSCT configurations with reduced sonic boom characteristics. In the current work, two low-sonic-boom configurations were designed for overland cruise at M1.7 and overwater cruise at M2.4. The major objective was to explore the effect of sonic boom waveform shape. One configuration was designed to the well-known "flat-top" waveform, while the other was designed to the "hybrid" waveform developed at Boeing (References 6 and 7). Figure 1 compares the two target low sonic boom waveforms with a conventional waveform. The hybrid waveform has desirable features from the standpoints of configuration design, sonic boom propagation, and loudness. The hybrid waveform was so named because it combines the features of the "flat-top" and the "minimum-shock" waveforms of Reference 8. The hybrid waveform

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deserves further study because it is a significant development toward achieving a practical low sonic boom HSCT. However, since the peak pressure rises to about 2.0 lb/ft^2, there is some concern that this waveform would produce an unacceptable response for indoor observers (buildings respond primarily to the peak pressure rather than the initial shock wave intensity that is primary for outdoor observers). On the other hand, the "flat-top" waveform has a maximum overpressure of about 1.0 lb/ft^2 and would be more acceptable to indoor observers. Thus the flat-top waveform deserves study as a target waveform and was included in this study.

Reduced sonic boom loudness is achieved by reducing the magnitude or increasing the rise time of the pressure jump across each shock wave in the sonic boom waveform. For an acceptable loudness of about 72 dBA, the shock wave intensity at the ground must be approximately 0.80 lb/ft^2. In the current study, the target sonic boom shock intensity was relaxed somewhat to about 1.0 lb/ft^2 to demonstrate that a low sonic boom configuration can achieve low drag, high payload, and good performance. The performance objectives of the two configurations were as follows:

Range:	5000 nm
Payload:	300 tri-class passengers
Cruise Lift to Drag Ratio:	At least one unit higher than the baseline configuration

Since L/D alone is not a good measure of airplane performance, each airplane was evaluated in sufficient depth to determine an operating empty weight (OEW) and maximum takeoff weight (MTOW) for a 5000 n.mi. mission. This allowed a meaningful performance comparison to a conventional baseline configuration, the 1080-874.

The three configurations to be discussed are as follows:

Model	Waveform	Unrestricted Cruise Mach	Restricted Cruise Mach
1080-874	N-wave	2.4	0.9
1080-910	Hybrid	2.4	1.7
1080-911	Flat-top	2.4	1.7

For convenience, these configurations will be referred to as the -874, -910, and -911.

CONFIGURATION DEVELOPMENT

This section provides a description of the configuration development and configuration characteristics such as aerodynamics, stability and control, weight and balance, performance sizing, and sonic boom.

The two desired low sonic boom waveforms are shown in Figure 1. The real constraints, however, in the Boeing low boom design method are the corresponding Whitham F-functions shown in Figure 2.

Configuration Description

The two low-boom configurations share some features of the baseline 1080-874 configuration, including the following:

- Blended wing-body philosophy
- Aft fuselage fuel tank
- 4 PWA STJ-945 engines (year 2002 turbine bypass afterburning turbojet)
- 4-post landing gear

The baseline configuration -874 is shown in Figure 3, and the drawings of the low-boom configurations -910 and -911 are shown in Figures 4 and 5. The -911 has no horizontal tail and therefore the elevator and trimming functions are performed by the wing trailing edge flaps.

Aerodynamics

High Speed Design and Analysis

The sonic boom constraint is severe and directly affects every configuration component. The low boom design method used at Boeing has been summarized recently in References 6, 7, and 9. There is a complex interplay between many design elements. The wing planform must provide a gradual, smooth lift distribution and low drag. The camber and twist were designed for a C_L of about .09, with a sufficiently positive C_{MO}, at a Mach number of 2.1. The wing thickness distribution was defined by considering landing gear requirements and rear spar depth at the outboard nacelle. The wing thickness to chord ratio values are relatively low, contributing to low wing wave drag. The nacelles and empennage contribute volume and lift and must be located and shaped appropriately. The fuselage area distribution was defined last. In practice, several iterations with the wing planform were required to achieve acceptable wing-body wave drag, which is important for optimum performance. The sonic boom constraint provides an automatic area-ruling effect and low wing-body wave drag can be obtained, provided the proper wing planform is chosen.

Both of the low boom configurations have significantly reduced drag compared to the baseline configuration. The -911 is close to the optimum that can be obtained with or without a sonic boom constraint, while the wave drag of the -910 could be improved somewhat by modifying the inboard strake and forebody.

Two innovative concepts were introduced on the -910 configuration to obtain the desired low-boom Whitham F-function: tailoring of the nacelle forecowl shape and deflecting the leading edge flaps. Figure 6 shows the effect of these two design modifications on the F-function.

The nacelle forecowl shaping is simply the reduction of initial forecowl angle to reduce shock strength and corresponding increase of the aft forecowl angle to retain the same maximum nacelle diameter required for accessories. The drag penalty for this change is small. The correct shaping of the nacelle forecowls when combined with the appropriate staggering of the nacelles and careful design of the boundary layer diverters provides significant flexibility in closing to the desired F-function.

Low boom configurations have required planforms that provide long lifting lengths. These planforms, however, have many undesirable characteristics in terms of wing weight, low speed aerodynamic performance, and configuration integration. The -910 configuration employs leading edge deflections to distribute the lift in such a way that the equivalent area due to lift provides a smoothly varying equivalent area when combined with the equivalent area due to volume. The summation of the F-function due to lift and the F-function due to volume illustrates this point as shown in Figure 7.

Low Speed Design and Analysis

The low speed performance of the -910 low sonic boom configuration is based on the assumption that flap settings can be programmed to provide optimum lift-to-drag ratio (L/D) for varying conditions during climbout. Programmed flap climbout polars for the tailless airplane (-911) were not produced, however, since climbout L/D optimization would not reduce airplane size because it is limited by approach speed and takeoff field length constraints.

Wing apex vortex fence deployment at landing flare was assumed on the tailless airplane, as on the baseline airplane (-874). Because utilization of a vortex fence offered no benefit to 1080-910 airplane sizing, it was removed for a weight reduction.

The procedure for calculating the lift and drag characteristics of the low sonic boom configurations consisted of adding computed increments to an established data base. The reference data base selected for low speed characteristics prediction is the estimated full scale data base for the Model 2707-300 airplane built up from high Reynolds number testing conducted in the spring of 1970 (Reference 10). Increments due to configuration wing differences relative to the 2707-300 are determined by comparing computed characteristics. The NASA computer program, AERO2S (Reference 11), is used for the drag due to lift computations since it includes the effects of the leading edge separation vortex and leading edge suction limitations together with a wing potential flow solution. Additional corrections to the Model 2707-300 data base include differences in skin friction, elimination of nose cab droop, and thrust (where appropriate).

The attitude limits for the tailless airplane (-911) are higher to compensate for the loss in trailing edge flap lift. The tailless -911 required an increase in landing gear length of 54 inches to achieve the 160 KEAS approach speed limit at maximum landing weight. The lengthened gear produces an OEW increase of about 5400 lb. Landing gear length has a significant effect on takeoff field length and approach speed because of its effect on rotation angle capability. An increase in wing-body incidence angle could be used to shorten the landing gear somewhat, but with a cruise drag penalty.

The lift-to-drag ratios for climbout and approach were determined from respective polars for each configuration. Leading and trailing edge flaps vary for climbout and approach to maximize L/D at each condition. Climbout points are selected for a speed (V_2+10) corresponding to the lift coefficient for a second segment climb plus 10 knots. For approach, the values of L/D correspond to a gear extended speed that will result in an attitude limited touchdown after a 3% speed bleed-off. Pertinent information comparing each of the configurations at these two conditions is presented below.

Model	Climbout		Approach	
	$C_{L_{V2+10}}$	L/D_{V2+10}	CL_{APP}	L/D_{APP}
1080-874	0.63	7.34	0.71	5.68
1080-910	0.63	5.81	0.63	4.05
1080-911	0.45	N/A	0.53	N/A

Stability and Control

The horizontal tail size is determined by calculating the forward and aft center of gravity (c.g.) limits as a variation with tail size and selecting the tail size which provides the required c.g. range. This also determines the main landing gear position since the nose wheel steering criterion requires a certain distance between the aft c.g. and gear position. The forward c.g. limit is based on take-off rotation criterion and the aft c.g. is based on stall recovery.

Since the 1080-911 is a tailless configuration, the longitudinal control evaluation consisted of determining whether the elevons provide adequate control and, if so, how many of the four segments per side are required and if some can be used for high lift. The results show that only three of the four (per side) are required but there is insufficient control to permit using the unused panel for high lift. It was decided to use the three inboard panels for elevons and leave the outboard panel unused, or as a possible low-speed aileron, because of the probable high aeroelastic losses of the outboard panel.

The sized vertical tail of the -911 (528 sq. ft.) is larger than that of the -910 (464 sq. ft.) because of the more aft wing location and more forward vertical tail location of the -911 compared to the -910.

Weight and Balance

The point design configurations were balanced by positioning the wing to achieve desired c.g. ranges. These configurations were then analyzed to provide operating empty weights and weights scalars for aircraft sizing. Scalars were determined for the change in

OEW with MTOW, engine airflow, and wing area. These scalars are described in more detail in Section 8.7.3 of Reference 3. Ballast was required to balance all the point design configurations but was not included in the performance calculations.

Performance Sizing

This section presents the aerodynamic performance results of the "Hybrid" sonic boom waveform -910 and the tailless "Flat-Top" sonic boom waveform -911, with takeoff and climb thrust-augmented Pratt Whitney STJ945 engines. The 1989 baseline model -874 previously supplied in Reference 9 is also included for comparison.

The -874, -910 and the -911 configurations were sized following the same Design Requirements and Objectives (DR&O) criteria as outlined in Reference 12. These requirements include:

- Design Mach = 2.4
- Design Range = 5000 nm
- Takeoff Field Length = 12000 ft.
- Approach Speed = 160 keas
- Transonic Climb Thrust Margin = 0.3
- Cruise Thrust Margin = 0.1
- Climb Time = 0.75 hr.

In addition to these requirements, a 20% Programmed Thrust Lapse Rate (PLR) limit was applied to reduce community noise as described in Reference 5. The 20% PLR is an automatic reduction in thrust initiated at 35 feet altitude which has been found empirically to reduce the "shoulder" of the 85 dBA noise footprint to that extent caused by the takeoff ground-roll. The requirement specifies that the engine maximum climb thrust minus 20% must be great enough to maintain a speed of V2+10 knots while climbing at a gradient which allows the aircraft to attain the minimum altitude for FAR cutback at a distance from brake release that permits the achievement of full spin down when the FAR specified cutback measuring station is reached.

Major characteristics of the sized aircraft are shown in the table below. S_{REF} is the reference wing area in square feet and Wa is the reference engine airflow in pounds mass per second. MTOW and OEW are expressed in pounds.

Model	Waveform	PAX	MTOW	OEW	L/D	S_{REF}	Wa
1080-874	N-wave	279	666860	265120	8.89	6311	426
1080-910	Hybrid	320	823640	362270	9.89	9957	575
1080-911	Flat-top	300	778690	336810	9.83	10014	511

A summary of the configuration and performance results for each sized configuration is given in Figure 8. The different payloads of the configurations, however, make comparisons difficult. An estimate was made using empirical rules to adjust the MTOW for a payload of 279 passengers. The results are shown in Figure 9, with the payload to gross weight ratio of the -910 and -911 both about 10% lower than the baseline -874 at the same payload (279 passengers).

It should be noted that the sized configurations for the 1080-910 and 1080-911 were obtained through only one airplane sizing cycle. Therefore, any performance recommendations or conclusions are preliminary in nature. Future MTOW optimization should include additional sizing cycles to converge design objectives and performance results through refinements in available fuel volume, high lift systems, and wing camber.

Sonic Boom Characteristics

Estimated sonic boom waveforms calculated by the method documented in References 13 and 14 are shown in Figure 10. These were calculated for the initial design conditions of Mach 1.7, 44000 ft. altitude, and the design C_L of about .09.

The performance sizing described previously resulted in significantly higher gross weights than were designed for. Figure 11 compares the initial design and performance sizing conditions. An important consideration is whether the low boom characteristics have been lost because of the heavy gross weight. Figure 12 shows the calculated sonic boom for the heavier start-cruise weights for the -911 configuration. The higher wing lift has produced stronger shocks, but the low boom characteristics have not been lost entirely. Another mode of operation is to fly at the design C_L of the heavier gross weight, by reducing the cruise altitude appropriately. For the -911 this means reducing the initial cruise altitude from 44000 ft. to about 39000 ft. The sonic boom waveform for this case, shown in Figure 12, is very similar to the higher altitude case, but the pressure levels are higher because of the shorter propagation distance to the ground. However, a structural weight penalty would be assessed for flying at this reduced altitude due to increased dynamic pressure.

WIND TUNNEL MODEL DESIGN

Aft-Body Design and Sonic Boom Characteristics

The Boeing low-boom design method is appropriate for designing an altered aft-body, in the same way it is used for designing the full configuration aft-body. The only change is to modify the target sonic boom waveform to produce an open aft-body that matches the desired sting diameter.

Figure 13 shows the target sonic boom waveforms and the estimated sonic boom waveforms for the wind tunnel model configurations. The -911 forebody was also analyzed using a CFD code called STUFF (a parabolized Navier-Stokes solver run in the inviscid mode). The result shown in Figure 13 indicates a bow shock of 1.4 lb/ft^2 instead of the desired 1.0 lb/ft^2 predicted by linear theory methods. This inconsistency is possibly related to the forebody camber and wing body junction regions that were not modelled accurately by the linear theory methods. Thus, design methods based on the linear theory should be used with care, and sonic boom characteristics should be verified by CFD methods.

Aerodynamic Performance Verification

The highly-swept, lightly-loaded wings of the two low-boom configurations provide a significant reduction in drag. At Mach 2.4, for example, the theoretical drag of the -911 is 23% lower than the baseline -874. However, viscous effects can have important consequences on highly swept wings that can negate the theoretical drag reduction. Reference 15 provides a set of design conditions developed from experimental test programs. In general, attached flow must be maintained on the wing upper surface by avoiding the following flow conditions: strong spanwise flow near the wing trailing edge, extremely high leading edge suction pressures, inboard shock separation, and a strong shock near the wing trailing edge. These adverse flow conditions can affect the boundary layer and produce separated flow. The presence of the adverse flow conditions can be determined from examining calculated wing pressure distributions. For this study, TRANAIR was used to calculate wing pressures. A check of the -911 sonic boom design flight condition (M1.7, $C_L = .090$) showed no severe flow problems.

CONCLUSIONS AND RECOMMENDATIONS

Achieving a practical HSCT low-boom configuration with low drag, high payload, and good performance is a formidable design problem. In this study, two low-boom configurations were designed to different sonic boom waveforms for overland cruise at Mach 1.7 and overwater cruise at Mach 2.4. Both configurations met the goal of at least 300 passengers and low drag, but suffered from the increased OEW of the arrow-wing planform and large fuselages.

The following conclusions summarize the results of this study:

1. Of the two configurations, the -910 designed to the hybrid waveform has fewer design problems. The -911 tailless configuration has the advantage of reduced drag compared to the -910, but needs considerable work to improve low speed performance and a serious balance problem due to the aft location of the wing.

2. High payload (at least 300 passengers) and low drag were achieved for both configurations.

3. The OEW and MTOW of the low boom configurations are significantly higher than the baseline for the 5000 n.mi. mission. For the same payload of 279 passengers,

both the -910 and -911 have payload to gross weight ratios about 10% lower than the baseline -874.

4. Wind tunnel model aft-body designs were developed by using the same technique as for the basic airplane design but with a modified target tail shock.

5. A TRANAIR analysis of the -911 wing-body showed well-behaved flow qualities with little chance of flow separation at Mach 1.7.

6. The linear theory low-boom design methods should be used with care and the sonic boom characteristics should be verified by a CFD method.

During this short study, it was not possible to modify the designs to any extent. Refinements are needed to correct design deficiencies for improved performance while maintaining the low-boom characteristics. This should be done before attempting a better assessment of commercial viability. In addition, it would be desirable to modify several of the design goals.

1. Revised design goals
    a. Reduce the target shock wave strength to about 0.8 lb/ft^2 for better acceptability.
    b. Reduce the passenger count to about 280 to 290 to improve low boom design flexibility.
    c. Consider designing for a lower overwater cruise Mach number to reduce the performance penalty for flying Mach 1.7 overland.

2. Design improvements
    a. Increase the available fuel volume by increasing the inboard wing thickness slightly (-910 and -911), and/or by adding fuel further outboard in the wing to reduce required wing area and hence MTOW.
    b. Change landing gear to a 3-post gear, which may provide more volume for fuel and reduced weight (-910 and -911).
    c. Consider reducing the mid-body fuselage cross-sectional area to 4-abreast seating, for lower wave drag and more low-boom design flexibility (-910 and -911).
    d. Reduce the wave drag of the -910 configuration by matching the wing planform with the optimum area-ruled fuselage, within the low-boom constraint.
    e. Revise the camber and twist of the -911 configuration to obtain a better match between the lift coefficient for maximum L/D and the airplane cruise lift coefficient.
    f. Revise the camber and twist of both configurations to improve the low-speed high-lift characteristics. For the -911 this will allow a reduction in the landing gear length that was required for an approach speed of 160 knots. A folding canard should also be considered.
    g. Iterate through the airplane sizing procedure and the sonic boom constrained designs to obtain a better match between optimum performance and the low wing loading that low boom requires.
    h. Investigate ways of reducing the tail shock strength, for example, through horizontal tail loading, aft-body contouring, or secondary air exhausted from the aft-body.

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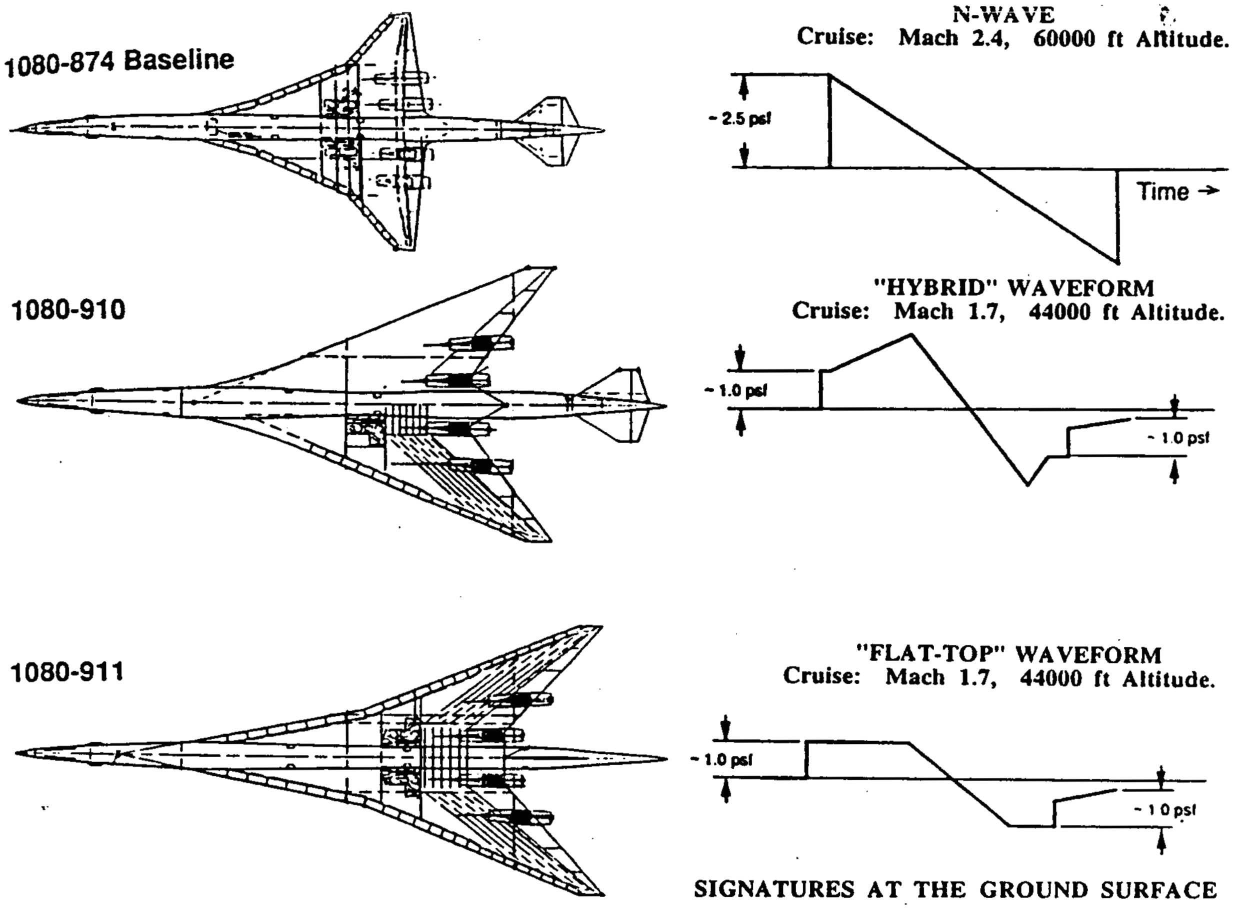


Figure 1. Design sonic boom waveforms.

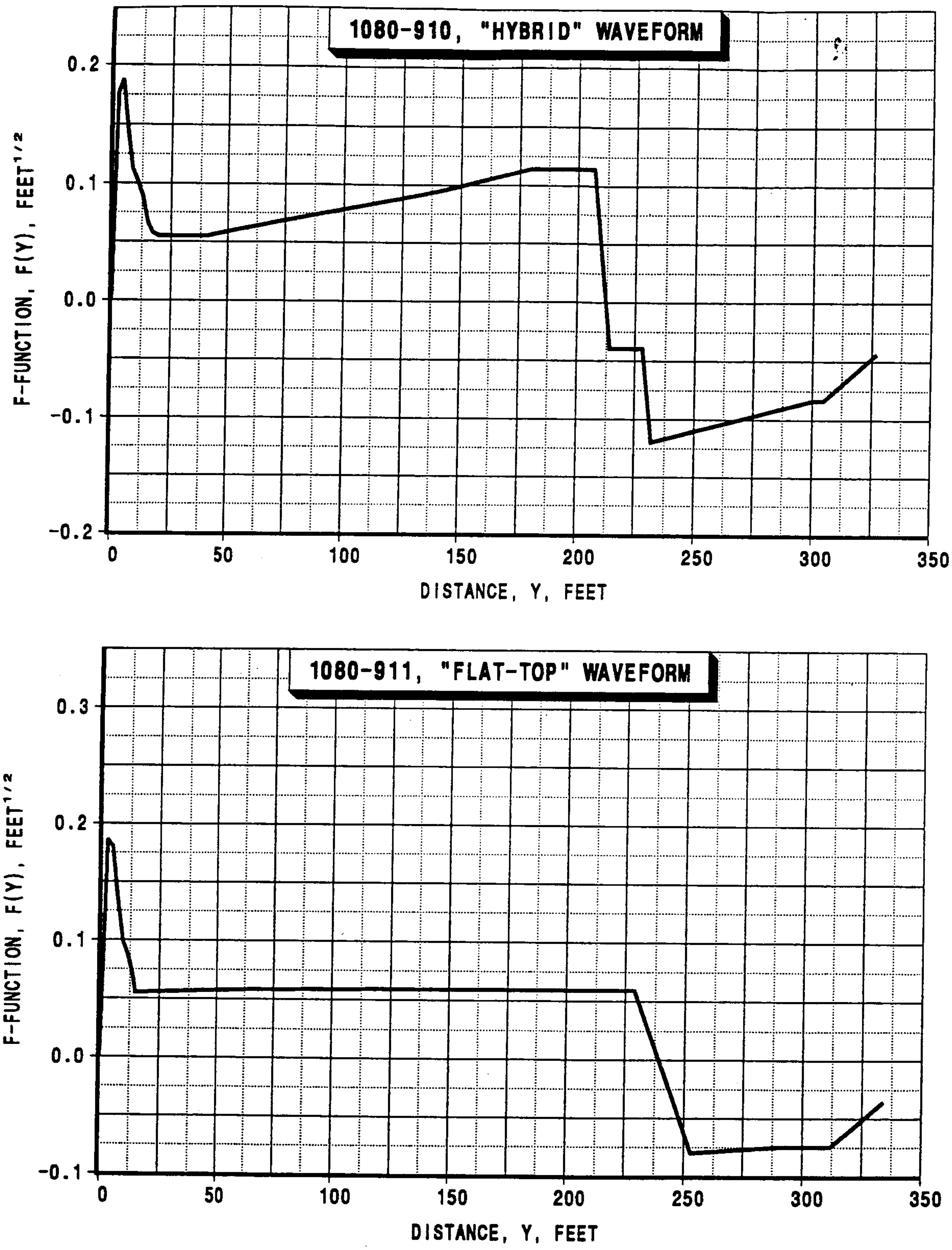


Figure 2. Design Whitham sonic boom F-functions.

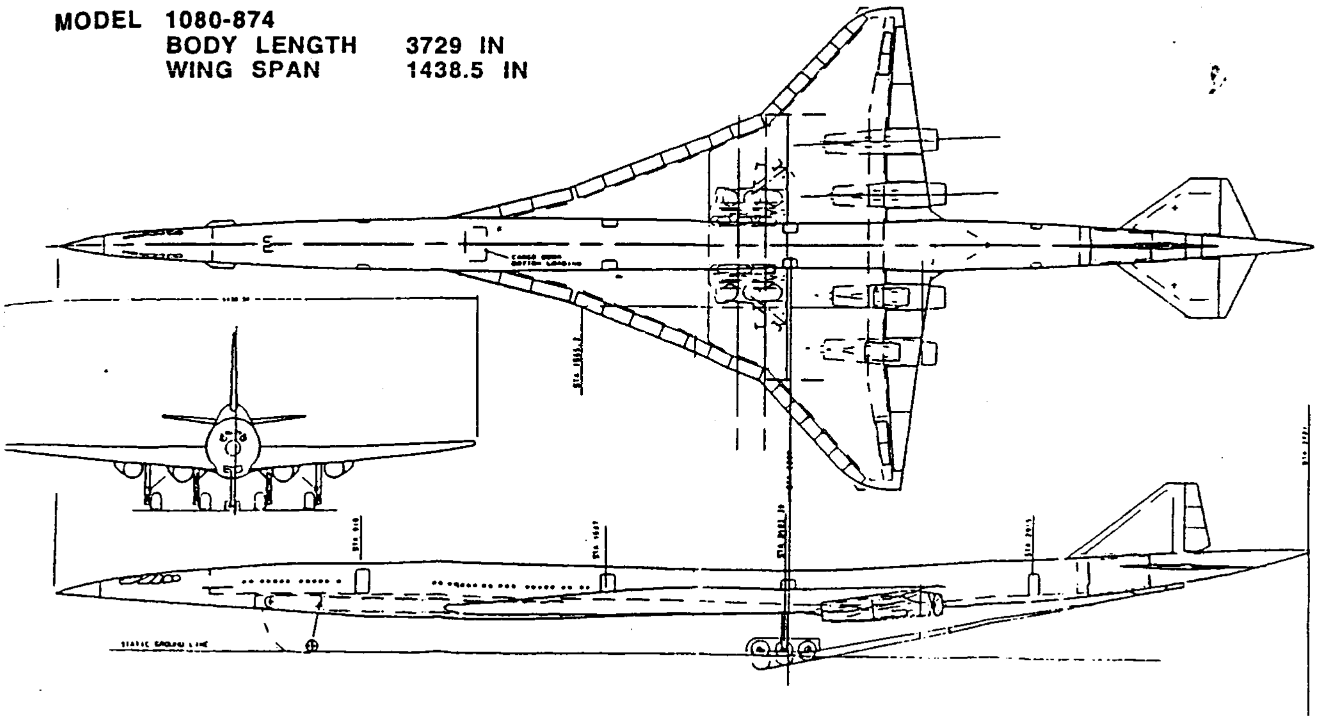


Figure 3. Configuration drawing of Model 1080-874 Baseline.

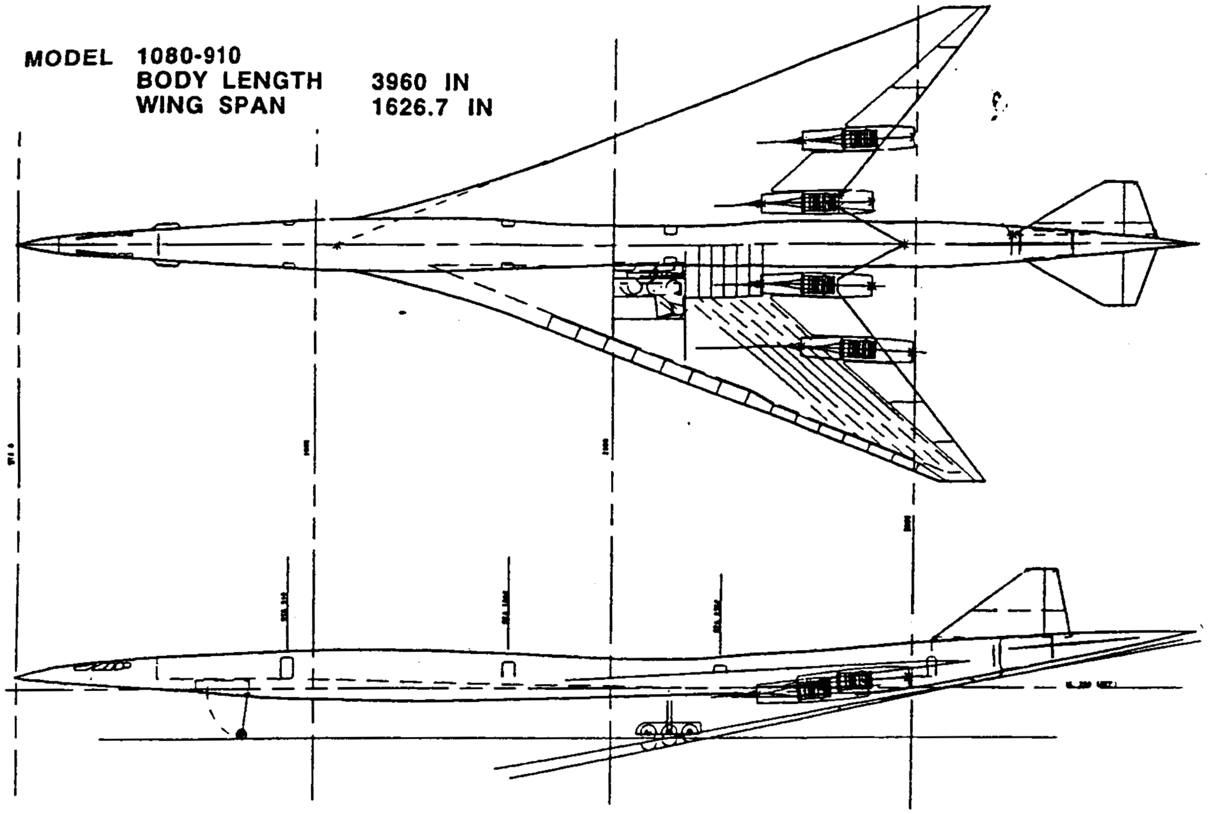


Figure 4. Configuration drawing of Model 1080-910.

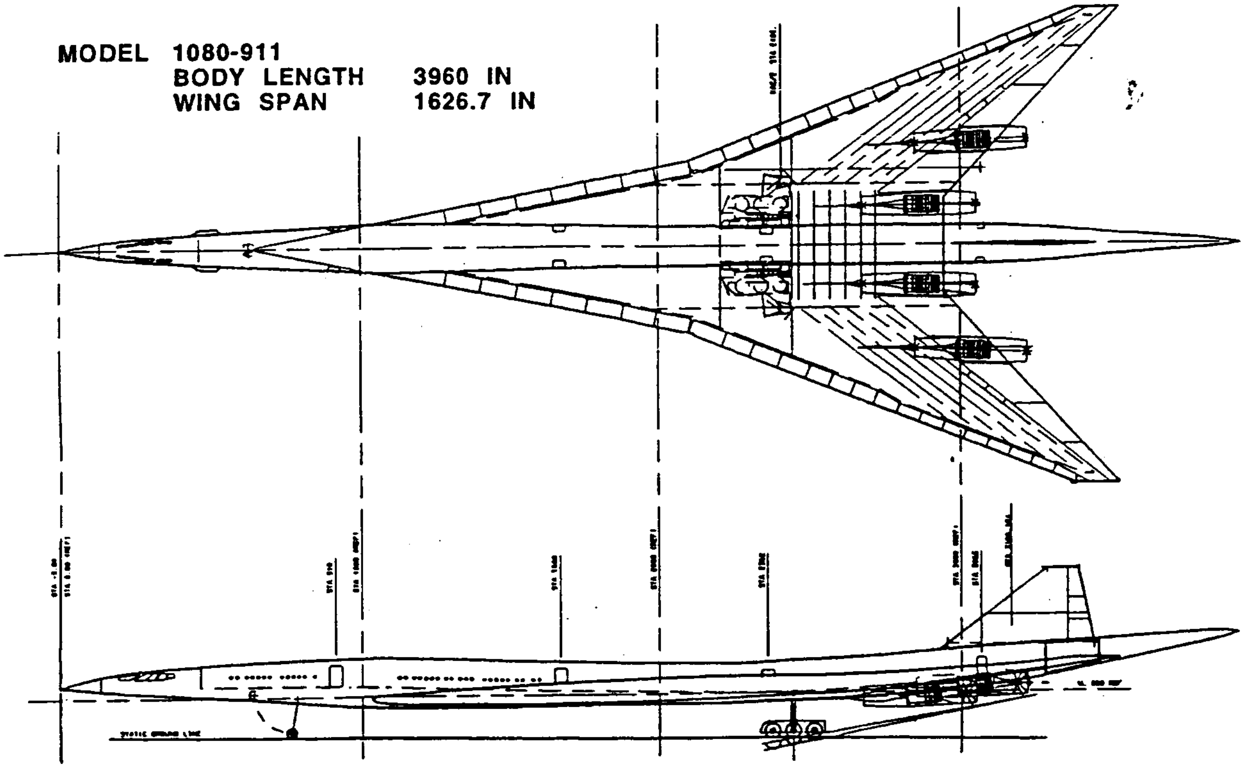


Figure 5. Configuration drawing of Model 1080-911.

1080-910, MACH 1.7, C_L=.095

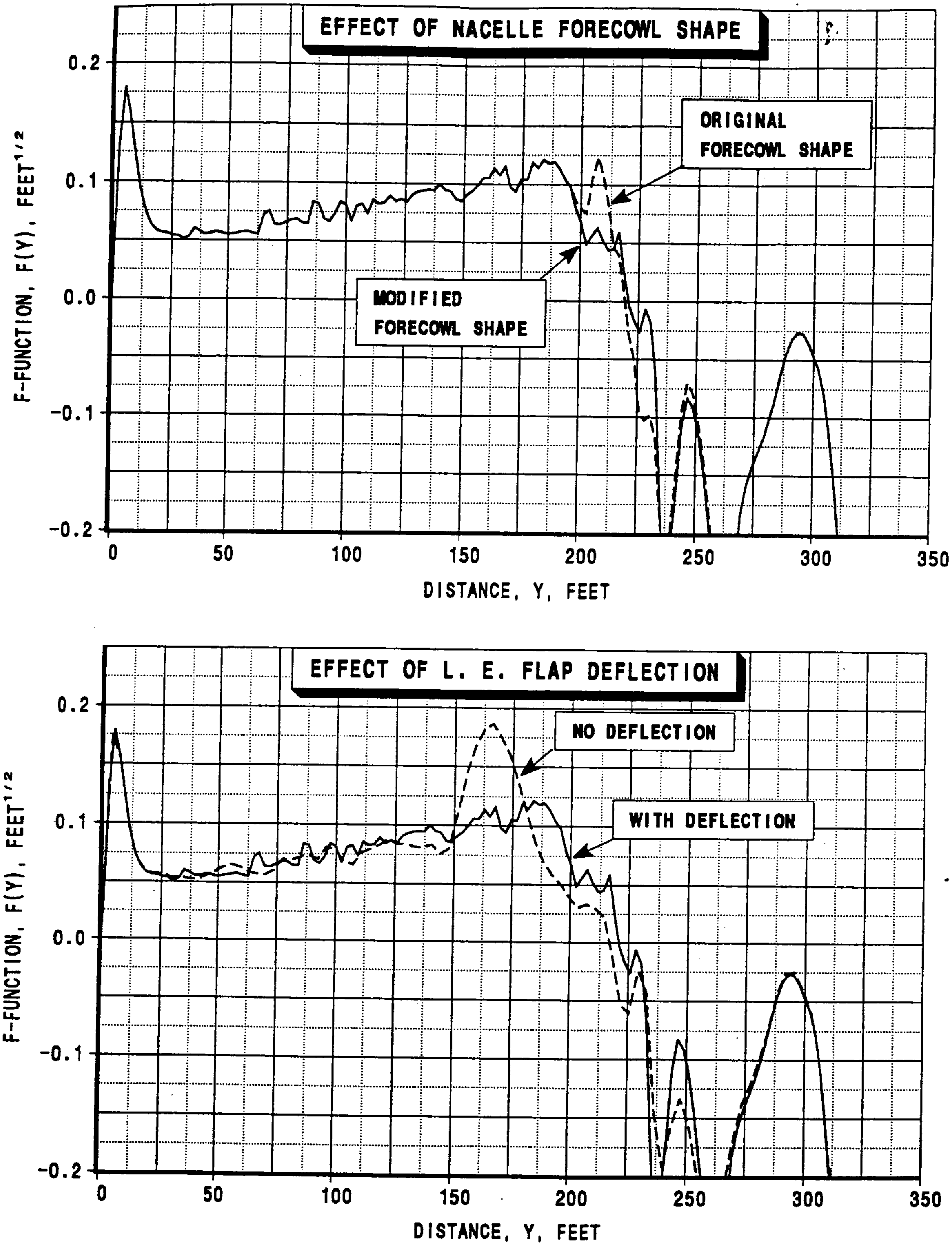


Figure 6. Effect of nacelle forecowl shape and wing leading edge flap deflection on sonic boom F-function.

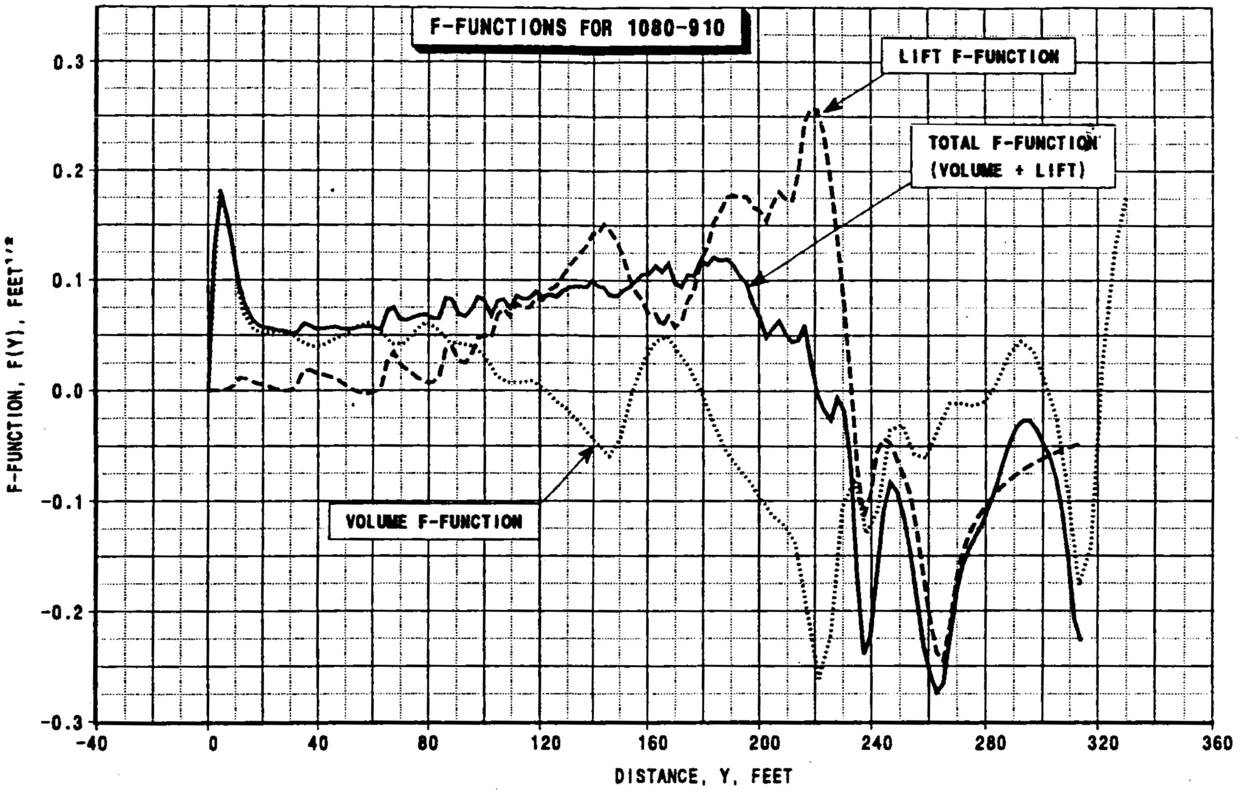


Figure 7. F-functions due to volume, lift, and the total configuration for 1080-910.

Model	Baseline	"Hybrid" Waveform Low Boom	"Flat-Top" Waveform Low Boom
	1080-874	1080-910	1080-911
Cruise Mach Number	2.4	2.4	2.4
Engine (PW, Year 2002)	PWSTJ945	PWSTJ945	PWSTJ945
Thrust Augmentation	Yes	Yes	Yes
Design Range, nm	5000	5000	5000
Design Payload, pax	279	320	300
Design Payload, lb	58590	67200	63000
Max Allow P/L, pax	299	353	333
<u>MISSION SIZED AIRPLANE</u>			
MAXIMUM TAKEOFF WT, lb	***666857***	***823641***	***778685***
Maximum Taxi Wt, lb	669374	826836	781647
Operating Empty Wt, lb	265117	362267	336807
Prop. Pod Wt., lb	50877	69800	61672
Eff. Wing Area, sq. ft.	***6311.3***	***9957***	***10014***
Span, ft.	117.2	135.4	135.4
Horiz. Area, sq. ft.	583	742	0
Vert. Area, sq. ft.	354	464	528
Engine Airflow, pps	***426.0***	***575.0***	***511.0***
SL TOFL (30c), ft (Augmentation)	11666 (20%)	9561 (20%)	12000(20%)
Vapp @ MLW, KEAS	156.1	146.3	160.0
Sized By	FV/PLR	FV/PLR	Vapp/TOFL
<u>Design Mission</u>			
Block Fuel, lb	304670	346705	332292
Block Time, hr	4.45	4.37	4.40
Reserve Fuel, lb	41881	52961	50632
L/D (mid cruise wt)	8.89	9.89	9.83
SFC (mid cruise wt)	1.322	1.329	1.335
End Cruise Alt, ft	62264	65790	65619
Supersonic RF, nm	9256	10244	10136
Fuel Vol Required, lb	365667	417369	401840
<u>Overland Mission</u>			
Overland Range, nm	4322	4450	4115
Overland RF, nm	7449	8875	8024
L/D (mid cruise wt)	14.43	11.48	10.44
SFC (mid cruise wt)	1.0311	1.2611	1.2684
<u>Mixed Mission for 3450 nm, 65% PL</u>			
Cruise Mach Number	M0.9, M2.4	M1.7, M2.4	M1.7, M2.4
Block Fuel, lb	184470	216488	222354
Block Fuel / Pass, lb/pax	1017.2	1040.8	1140.3
Block Time, hr	4.45	3.286	3.84

Legend:
TR - Transonic Thrust Margin
FV - Fuel Volume Limit
TO - Takeoff Field Length Limit
Vapp - Approach Speed
PLR - 20% Programmed Thrust Lapse Rate

Figure 8. Summary of performance results for the -910, and -911, and the baseline -874.

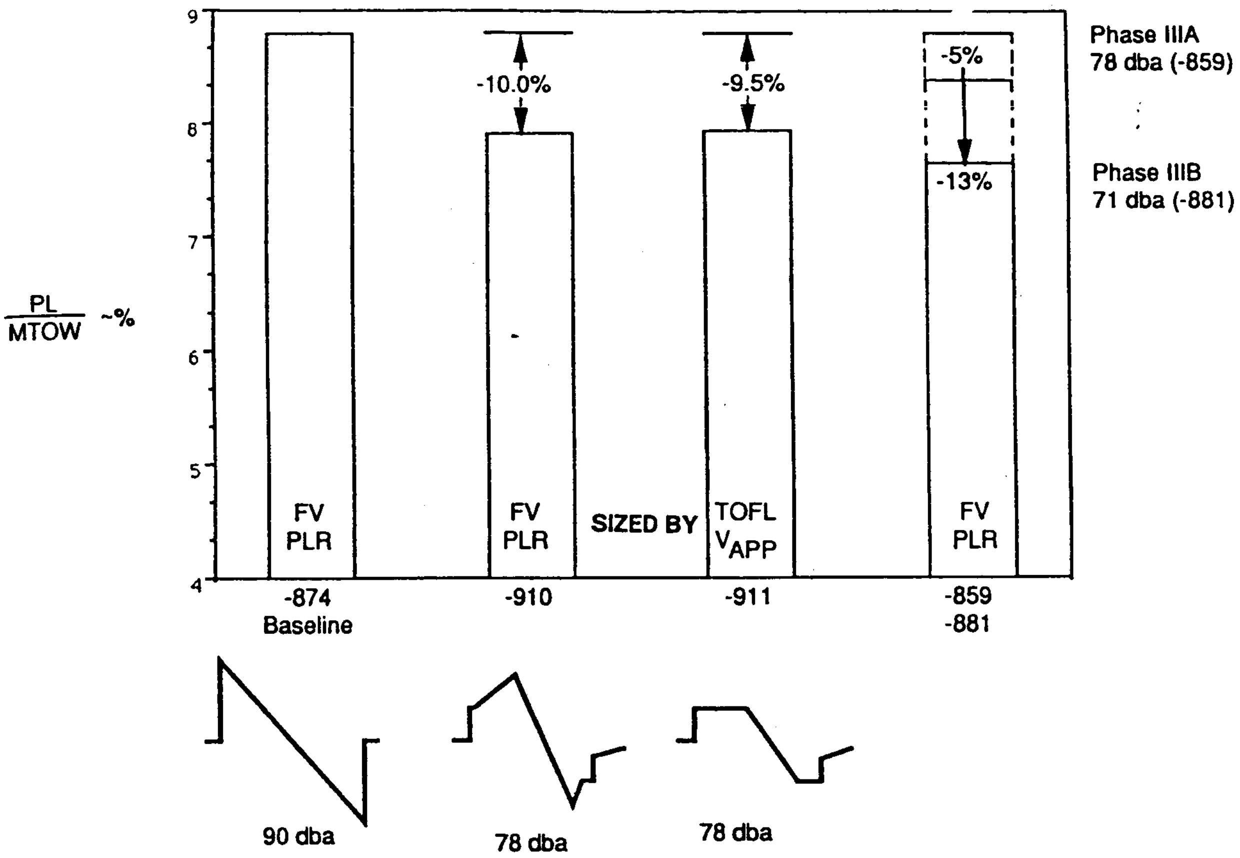
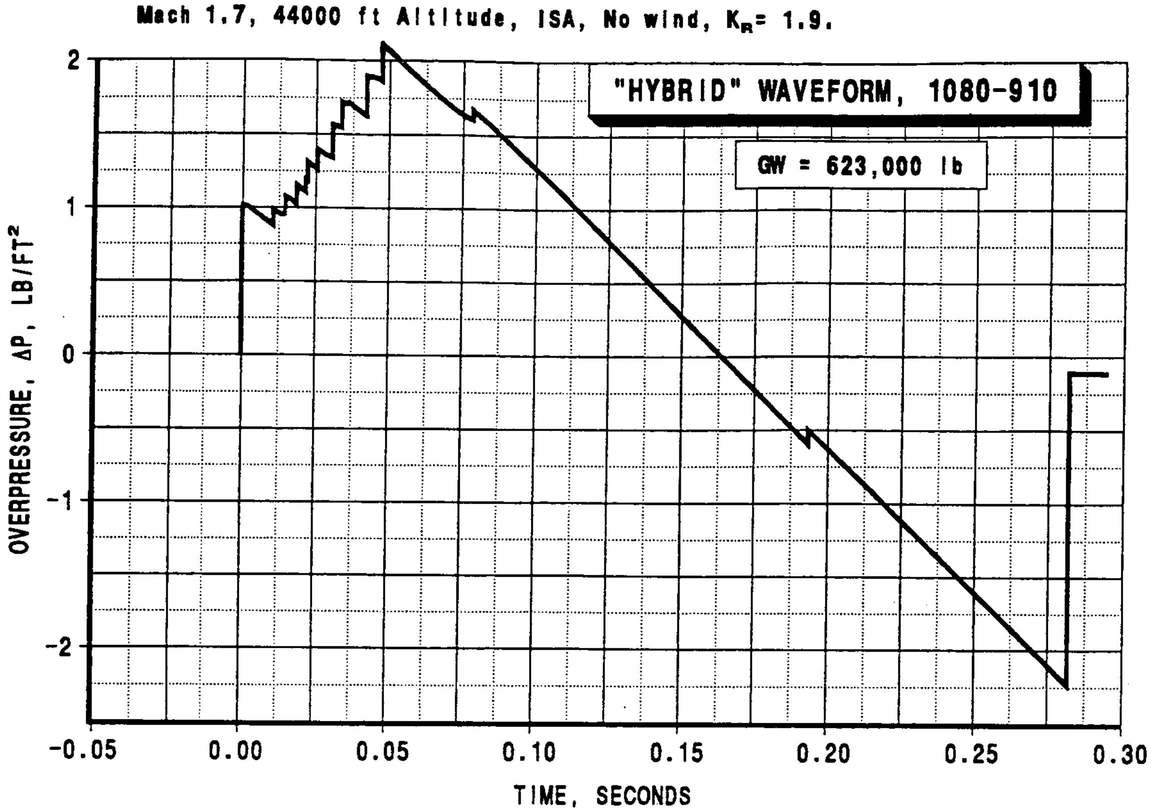


Figure 9. Performance comparison using the payload-to-MTOW ratio.



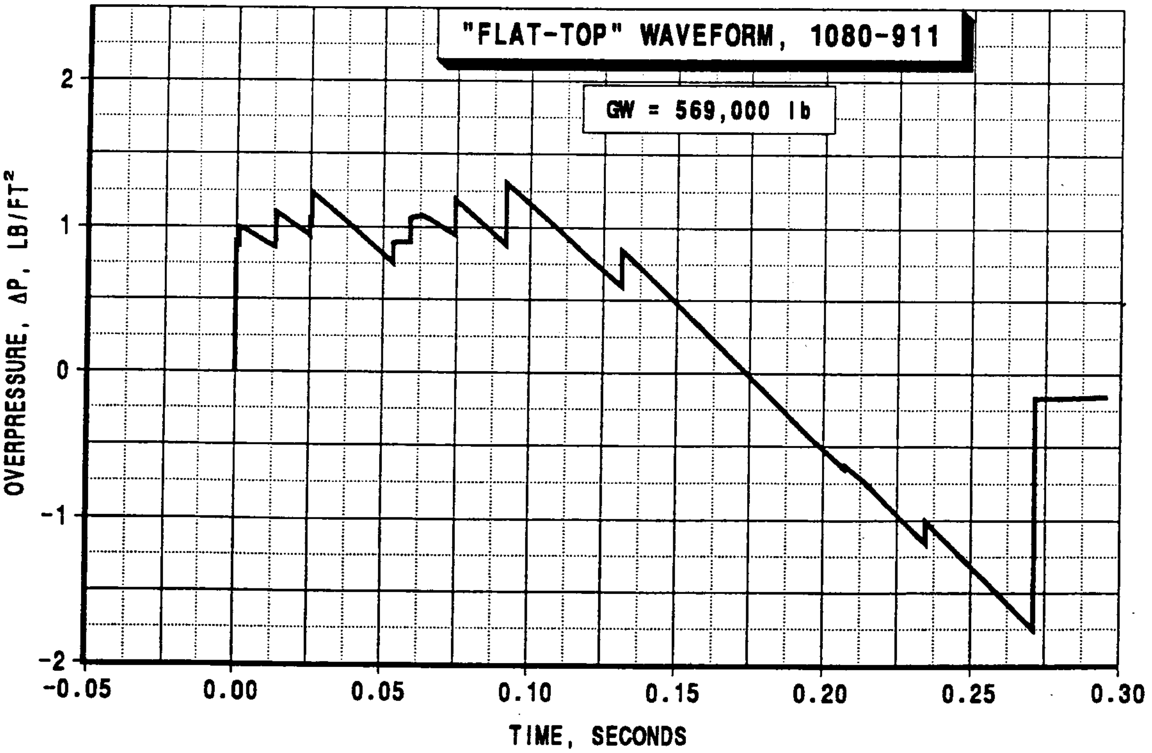


Figure 10. Calculated sonic boom waveforms at the ground surface for the -910 and -911 using modified linear theory methods.

Design Condition	1080-910	1080-911
Initial Design		
Wing Area, S_{REF}, Ft^2	9984	10044
Start - Cruise W, Lb	620000	560000
Start - Cruise CL	.095	.085
Start - Cruise W/S_{REF}, Lb/Ft^2	62.1	55.8
Sized Airplane		
Wing Area, S_{REF}, Ft^2	9957	10014
Start - Cruise W, Lb	767240	720700
Start - Cruise CL	.116	.109
Start - Cruise W/S_{REF}, Lb/Ft^2	76.6	72.2

Note: Design Start - Cruise Altitude is 44000 feet

Figure 11. Comparison of the initial design condition and sized airplanes.

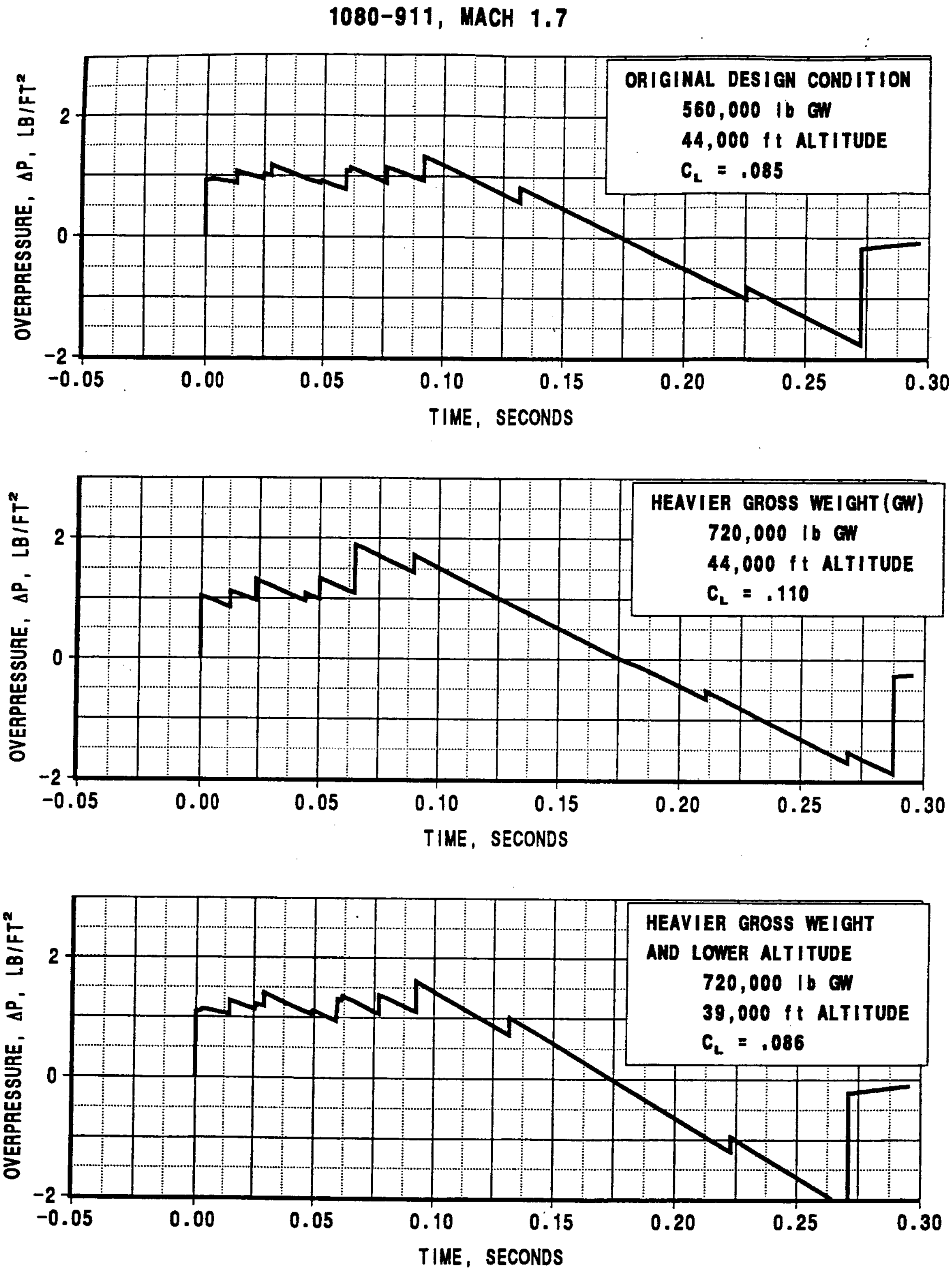


Figure 12. Calculated sonic boom waveforms at the ground surface for off-design cruise conditions for the -911.

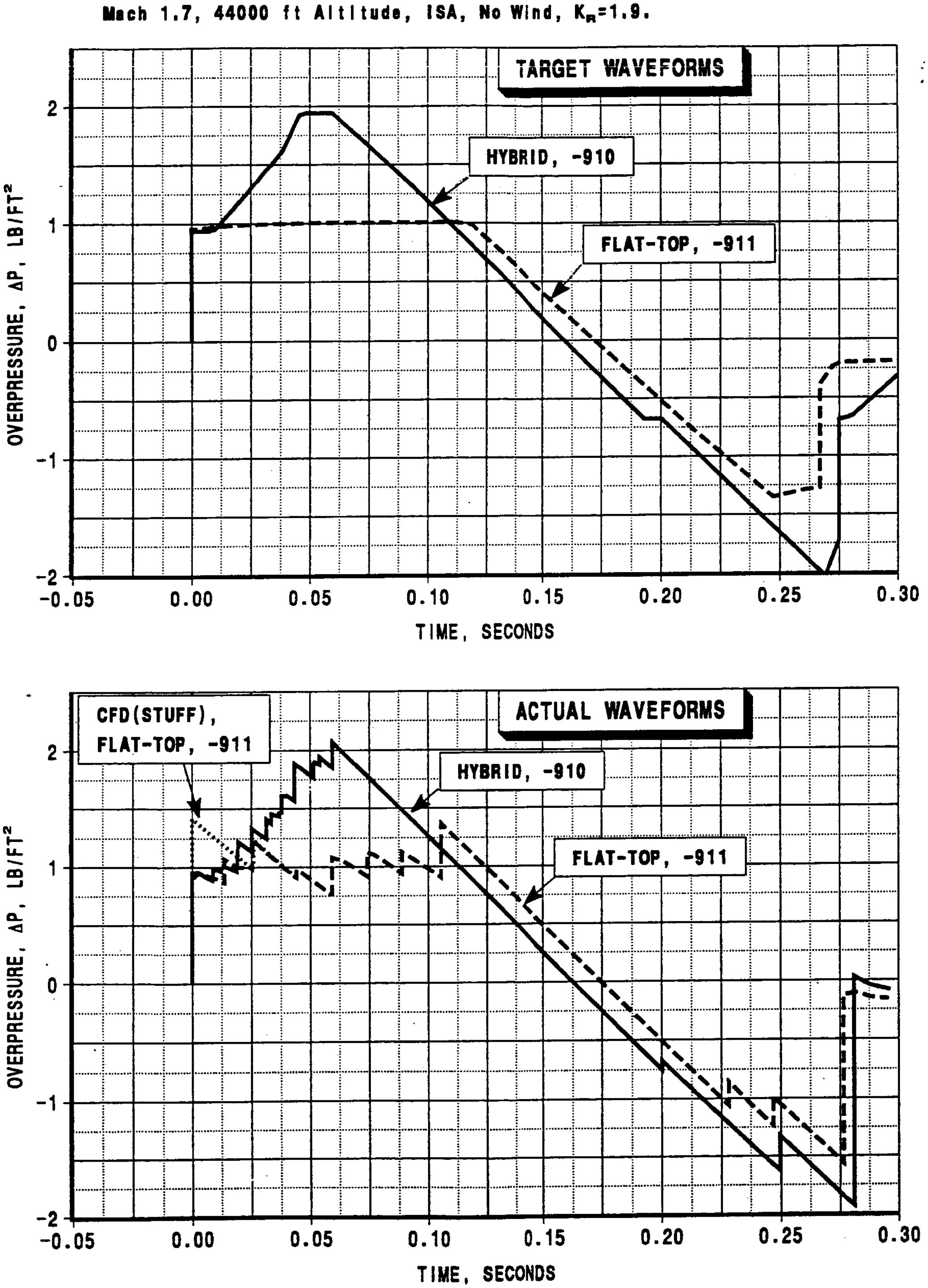


Figure 13. Calculated sonic boom waveforms for the -910 and -911 wind tunnel models. (Full scale conditions and at the ground surface).