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Design and Analysis of Low Boom Concepts at Langley Research Center

By

Christine M. Darden, Robert J. Mack, Kathy E. Needleman, Daniel G. Baize, Peter G. Coen, Raymond L. Barger, N. Duane Melson, Mary S. Adams, Elwood W. Shields, and Marvin E. McGraw

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Outline of Presentation

The objective of the sonic boom research in the current High Speed Research Program is to ultimately make possible overland supersonic flight by a high speed civil transport. To accomplish this objective, it is felt that results in four areas must demonstrate that such a vehicle would be acceptable by the general public, by the airframers, and by the airlines. It should be demonstrated: (1) that some waveform shape has the possibility of being acceptable by the general public; (2) that the atmosphere would not totally destroy such a waveform during propagation; (3) that a viable airplane could be built which produces such a waveform; and (4) that any performance penalty suffered by a low boom aircraft would be counteracted by the economic benefit of overland supersonic flight.

This paper addresses the work being done at Langley Research Center in support of the third element listed above --the area of configuration design. The initial part of the paper will give a review of the theory being used for configuration designs and discuss two theory validation models which were built and tested within the past two years.Discussion of the wind tunnel and theoretical results (linear theory and higher order methods) and their implications for future designs will be included.

DESIGN PROCEDURE

THEORY VALIDATION DESIGNS

WIND TUNNEL TESTS

FUTURE DESIGNS

L/D ESTIMATES

PLUME EFFECTS

SIGNATURES ON FLIGHT PROFILE

Figure 1

Design Approach for Low Boom Aircraft Concept

Two design approaches, both based on the Seebass and George[1,2] sonic boom minimization theory, are being used in the design of low boom concepts at Langley. The first approach is illustrated in Figure 1. The design parameters of aircraft weight, length, Mach number and flight altitude, along with signature parameters which define the type of signature and the bluntness parameter of the signature are used to define a target equivalent area distribution and pressure signature as shown in the upper right corner of the figure. Working initially with an uncambered wing, the designer describes a planform and fuselage shape and iterates on this design until the Mach-sliced equivalent area is near but everwhere below the desired equivalent area. When the equivalent area for the planform and flat plate lift are judged "near enough" to the target, a camber surface is designed to increase the lift of the configuration. Again, the equivalent areas of the design are continually compared to the target equivalent area distribution until the differences in the areas are very slight. Final adjustments to the design are made in the fuselage by use of an Inverse Fuselage Design Procedure which prescribes the fuselage necessary for a given equivalent area distribution.[3] More information on this design procedure can be found in reference 4.

Once the sonic boom constraints have been met, the configuration is then analyzed for performance. If it is judged to have serious performance deficiencies, then changes must be made because of aerodynamic concerns and the configuration recycled through the sonic boom design phase.

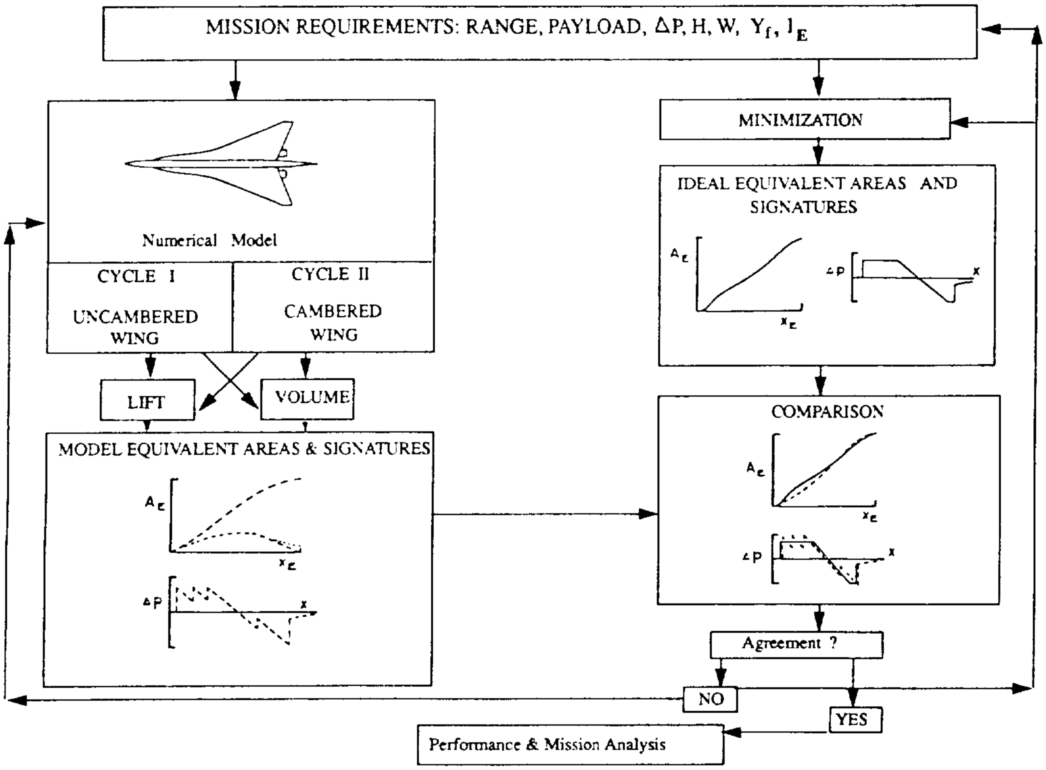


Figure 2

DESIGN APPROACH FOR BLENDED WING-BODY CONFIGURATION

A second approach for designing a blended wing-body configuration with low boom constraints is shown below. In this approach, the designer initially defines the planform of the desired wing-body and the geometry for the nacelles and fin. The camber surface is designed using the procedure of reference 5, and the thickness, twist and dihedral schedules are added. The configuration is then evaluated to determine its equivalent area distribution and its sonic boom signature is calculated using the method of reference 6.

Redesign for low boom is accomplished by a comparison between the F-function of the configuration and the target F-function. The target F-function may be derived from the method of references 1 and 2, or a related method. When the desired F-function and resulting signature have been attained, the necessary equivalent area distribution is defined. The equivalent area due to lift, pods, and fins of the original configuration is subtracted from the target equivalent area distribution so that the only area remaining is the equivalent area due to the wing-body. Final modifications to the design are made with thickness adjustments to the wing body using an inverse design procedure.[7] All of the codes in the above approach have been automated with input and output files consistent with one another. Judgement and interface with the designer is necessary at each step of the design and analysis process.

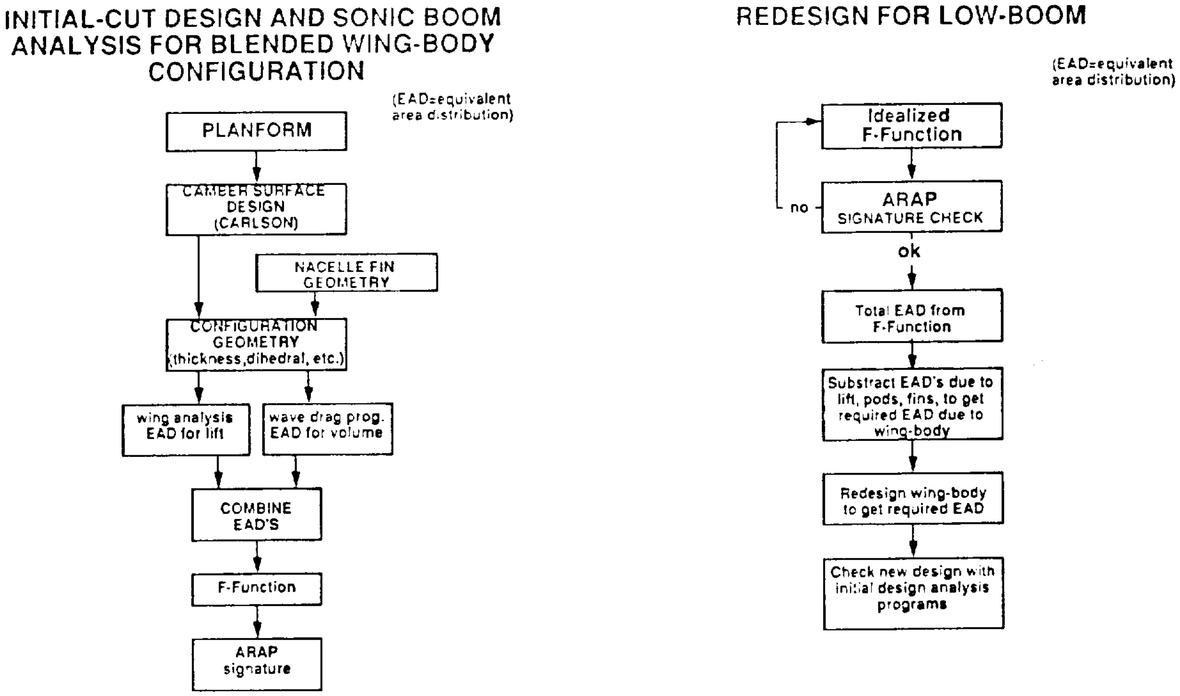


Figure 3

Sonic Boom Wind Tunnel Models

Two wind tunnel models were designed using the first approach shown in this paper[8]. To insure proper definition of the camber and twist distribution of the configuration, these models were designed to be 12 inches in length--the largest sonic boom models ever built at the Langley Research Center. Design conditions for the models are shown in the insets. One configuration was designed to cruise at Mach 2 at an altitude of 55,000 feet. The assumed weight at beginning cruise was 550,000 lbs and the full scale length was 323 feet. As shown, this configuration was designed to give a flat-top signature at design cruise conditions, with a bow shock overpressure of slightly less than 1 psf. The second model was designed for cruise at Mach 3 and an altitude of 65,000 feet. The beginning cruise weight was assumed to be 600,000 lbs and the full scale length, 313 feet. This concept was designed to give the minimum shock, or "ramp" signature at cruise conditions--again with a bow shock of slightly less than 1 psf. The models were fabricated in two pieces with an integrated sting. They both featured twist and camber and had four axisymmetric flow-through nacelles and a vertical fin.

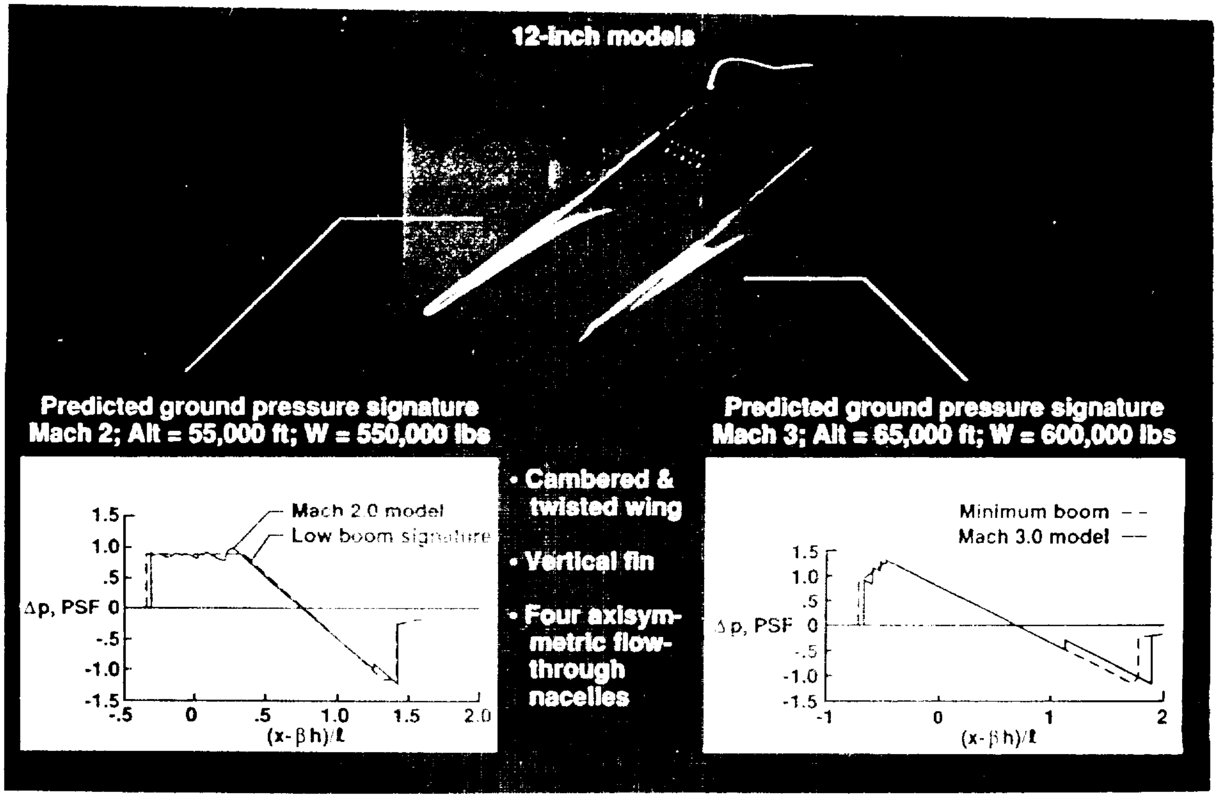


Figure 4

Wind Tunnel Tests

Existing sonic boom extrapolation methods are based on the assumption that disturbances are axisymmetric and thus 3-dimensional effects would be ignored. Because of this limitation, previous sonic boom wind tunnel signatures were measured at 3-5 body lengths away to insure that all three dimensional effects had settled. For the Langley Unitary supersonic wind tunnel which is 4X4 feet in cross section, the needed measuring distance has restricted the model size to 4 or 5 inches in length. Because an accurate representation of camber, twist and thicknesses of the current low boom configurations was felt to be essential to the validation of the theory, the decision was made to build the current wind tunnel models at 12 inches--more than twice the size of any previous sonic boom model at Langley. This size helped to alleviate the problem of fabricating an accurate representation of the concept, but aggravated the problem of accurate extrapolation. At Mach 2, measurements in the Langley tunnel would be at most 2 body lengths away with possible 3 dimensional changes still occurring. While CFD or other nonlinear 3-dimensional extrapolation methods are being developed and validated, the need to also obtain signatures at 5-6 body lengths was very important. Thus arrangements were made with the NASA Ames Research Center to test the low boom configurations in their 9 X 7' and 8 X 7' supersonic wind tunnels. These measurements would insure proper extrapolation with the larger, more accurate model. Tests on the low boom models were held at Ames in October 1990, and at Langley in December 1990 and January, 1991.

NASA AMES 9X7 UNITARY-- October, 1990
Mach 1.68, 2.00, 2.50

NASA LANGLEY 4X4 UNITARY
Test Section I-- December, 1990
Mach 2.5, 2.96

Test Section II - January, 1991
Mach 2.0, 2.5

Figure 5

Sonic Boom Test Setup

Test setup for the Mach 3 low-boom concept in test section 2 of the Langley Unitary Plan Wind Tunnel is shown in this figure. The model and a specially made angle-of-attack mechanism are mounted to the permanent tunnel strut system using a specially made sting. The model was capable of 33 inches of linear travel because of the strut mechanism, and up to 180 degrees of role because of an additionally installed roll coupling. The model was tested at a roll angle of 90 degrees. The model and its support mechanism were also capable of lateral movement because of the permanent strut system. Measuring probes were mounted to a solid tunnel door which had replaced the usual windowed door for the sonic boom tests. The reference probe was mounted such that it was not within the disturbance field of the model at any of its anticipated locations within the tunnel. The measuring probe was located such that it would be within the field of the complete signature of the model as the model moved forward. The measuring probe was mounted to a motorized track which allowed 6 inches of linear movement and thus increased the flexibility of the body lengths at which signatures could be taken without shutting down the tunnel and manually moving the probe.

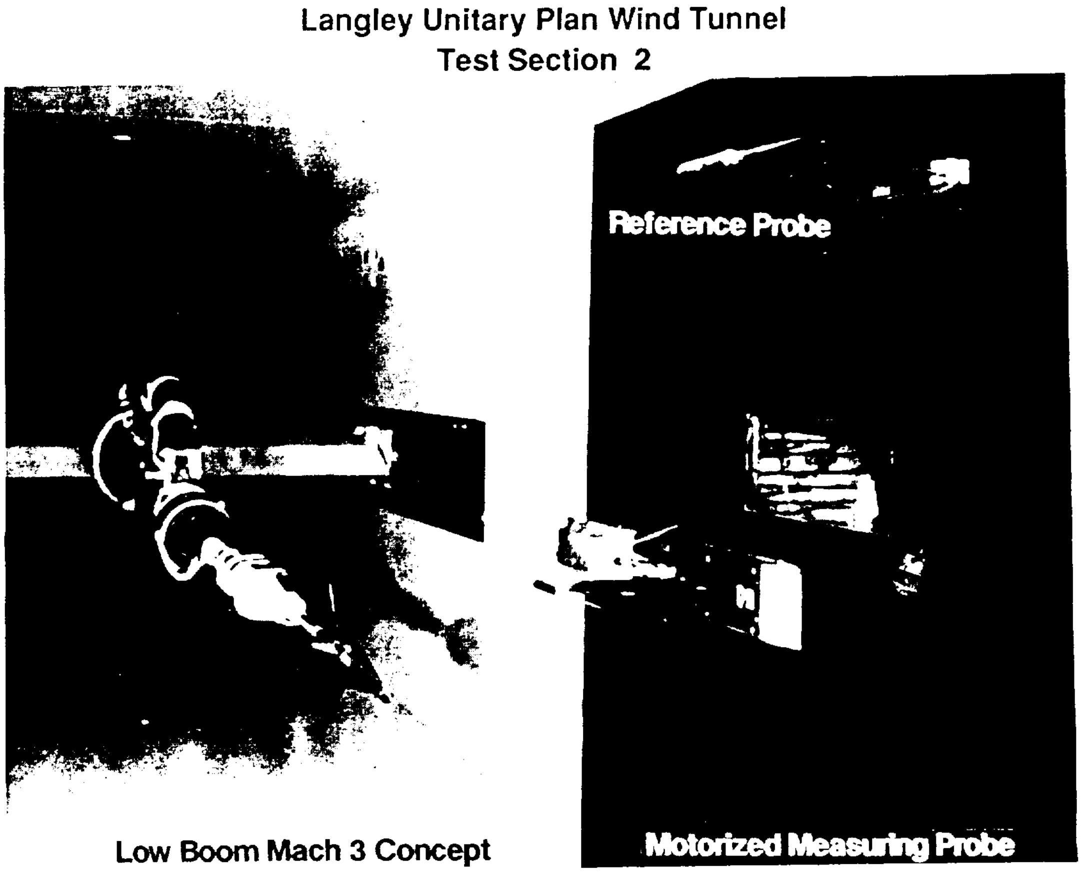
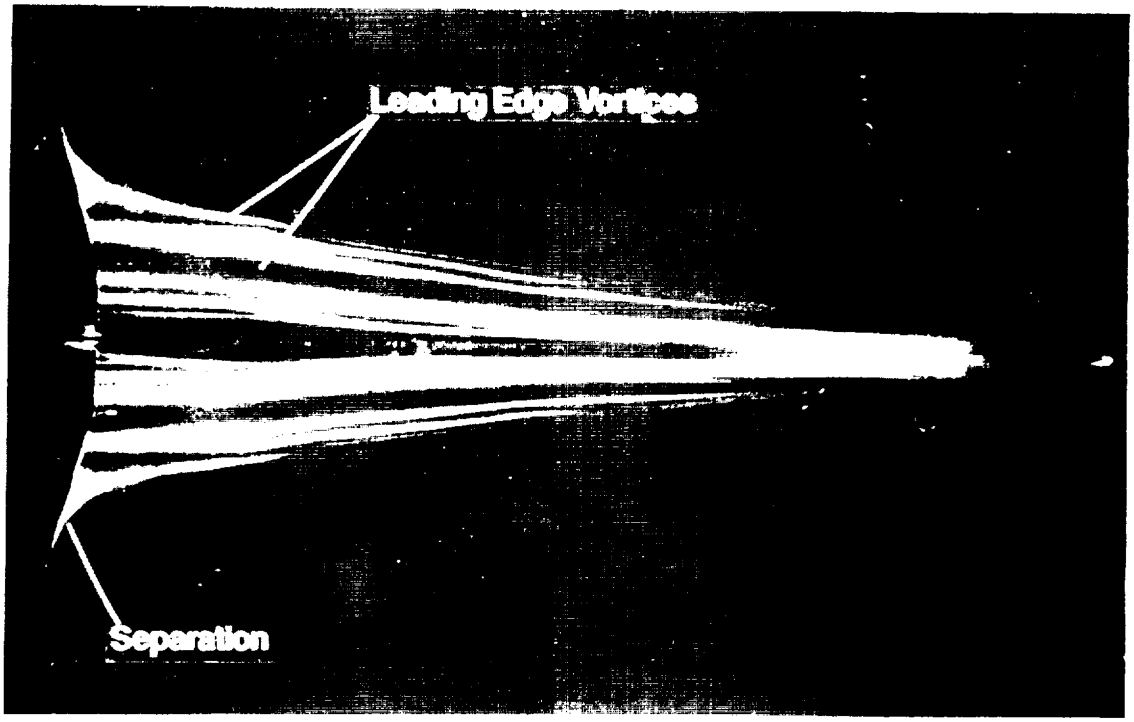


Figure 6

Oil Flow Photograph

Flow visualization [illegible] included this oil flow photograph of the Mach 3 concept. Oil mixed with fluorescent dye is painted on the model and the model installed in the tunnel. When design test conditions are achieved, a vapor light is focussed on the model. Flow patterns on the surface of the model can be observed by the oil patterns which develop.For this model, at a test Mach number of 2.96 and an angle of attack of 1.96 degrees, one can see that the surface flow pattern is very complex. One would like to see very clean attached flow which is indicated by smooth patterns in a linear direction from front to back with very little puddling of the oil. Instead, there are patterns of slanted flow moving in a defined region from front to back which indicates leading edge vortices on the surface. The puddling of the oil near the trailing edge also indicates that some separation is occurring.

Low Boom Model
Design Mach Number = 3



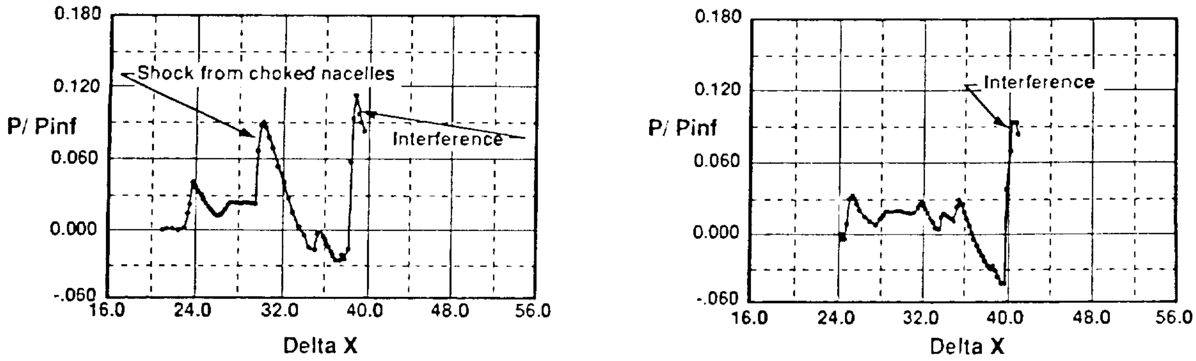
Mach 2.96 Angle of Attack = 1.96°

Wind Tunnel Results

Initial wind tunnel data indicated two unexpected results. Midway along the positive portion of the signature a large shock occurred in an area where the signature was expected to be relatively flat. Toward the end of the signature a second shock occurred before the complete resolution of the tail shock. Upon further investigation, it was decided that the final shock was the result of interference from the angle-of-attack mechanism which caused a stronger shock than anticipated. It was not clear where the first unexpected shock was originating until the nacelles were removed to provide signatures for the validation of Euler code computational calculations. The disappearance of the shock for the configuration without nacelles indicated immediately that flow was not being achieved in the small (.2 inch diameter) flow-through nacelles, and that there was a standing shock in front of the nacelles. Attempts to open the nacelles more and sharpen the front edges to try an achieve flow did not alleviate this shock. All tests at NASA Ames were done with nacelles on. The nacelles were only removed during the tests at Langley.

MACH 3 LOW BOOM CONFIGURATION
Radial distance = 8 inches
N = 3.1 lbs. PINF = 147.3 psf

NASA Langley Unitary Wind Tunnel
Test Section 2
Mach number = 2.96



With Nacelles

Without Nacelles

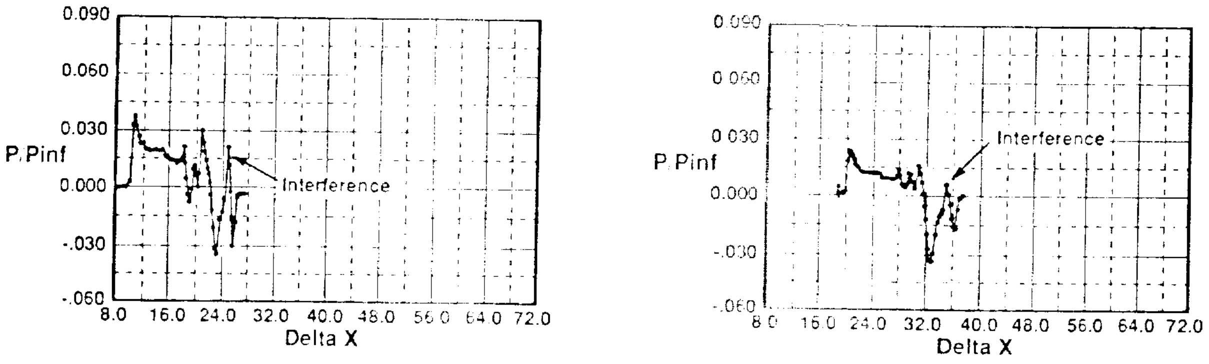
Figure 8

Wind Tunnel Results

Pressure measurements at two radial distances for the Mach 2 configuration are shown in figure 9. Signatures at several distances are desirable for two reasons. With the current emphasis on sonic boom predictions using Computational Fluid Dynamics (CFD) methods, signatures at several distances are needed to validate those codes in regions where grid density and/or grid spreading could reduce accuracy. Signatures at several radial distances are also desired to observe the manner in which the signature changes as it propagates outward. The signatures shown were measured at 6 inches and 12 inches or at 1/2 and one body lengths. Attenuation of the pressure levels at the forward part of the signature are very evident as the signature propagates outward. There is damping of the compressions and expansions which occur just ahead of the major expansion, but the most negative portion of the major expansion does not attenuate. The largest changes in the character of the signature seem to be occurring in the region of the signature where 3-dimensional effects of the lifting surface would occur.

MACH 2 LOW BOOM CONFIGURATION
Without Nacelles
N = 5.1 lbs. PINF = 160.2 psf

NASA Langley Unitary Wind Tunnel
Test Section 1
Mach number = 2.0



Radial Distance = 6 inches

Radial Distance = 12 inches

Figure 9

Comparison of Measured and Extrapolated Wind Tunnel Data

To investigate the accuracy of extrapolating very near-field pressure signatures, the signature measured at 1/2 body length was extrapolated[9] to one body length and compared with the signature as measured at one body length. The results of the comparison are shown on this figure. Note that in the forward portions of the signature where volume is the major portion of the equivalent area the agreement between the measured and extrapolated data is excellent. The latter half of the signatures differ significantly, however. For the first two shocks and expansions, the extrapolated signature is less than that measured; the slopes of the expansion regions differ considerably and the measured signature has the larger expansion. These differences would indicate that an axisymmetric propagation method does not account for all of the flow field phenomena; i.e. the flow in that region is highly three-dimensional. Signatures at greater distances are needed to ascertain just how far radially one must be before there are no 3-dimensional effects.

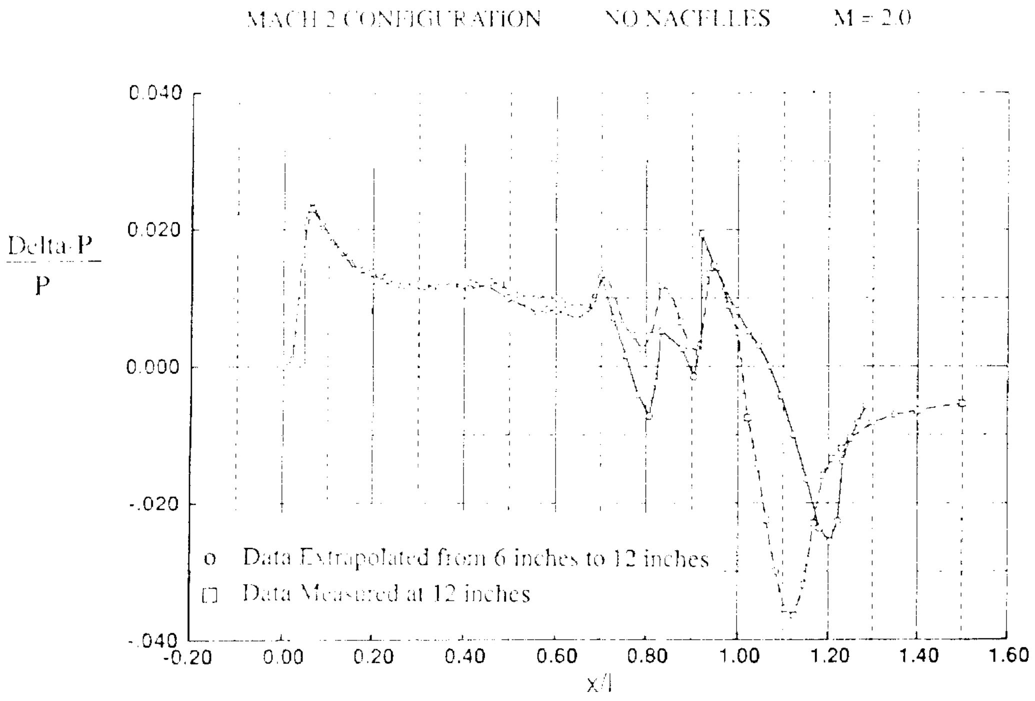


Figure 10

Comparison of Ground Signatures

An example of the differences in the ground signatures when wind tunnel data is extrapolated from two different distances is seen in figure 11. The signature on the left was extrapolated from data taken at 1/2 body length and the data on the right was extrapolated from data taken at one body length. For this Mach 2 configuration which was designed to prevent shock coalescence, the bow shock levels of the ground signatures are nearly the same. The most significant differences in the two signatures are just before the expansion where three-dimension effects are strongest in the near-field signature, and the length of the signature. Since current indications are that loudness is a better indication of sonic boom disturbance than bow shock level[10], these differences in the latter portion of the signatures could lead to significant differences in their loudness.

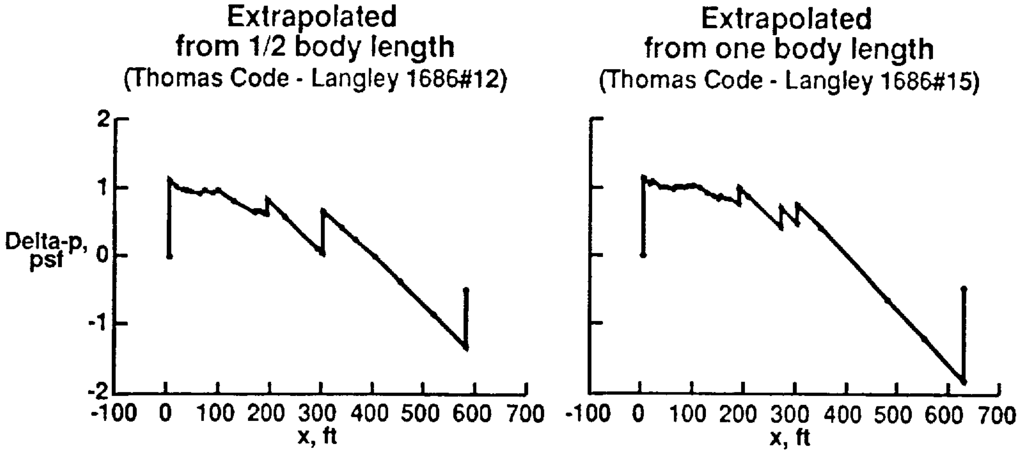
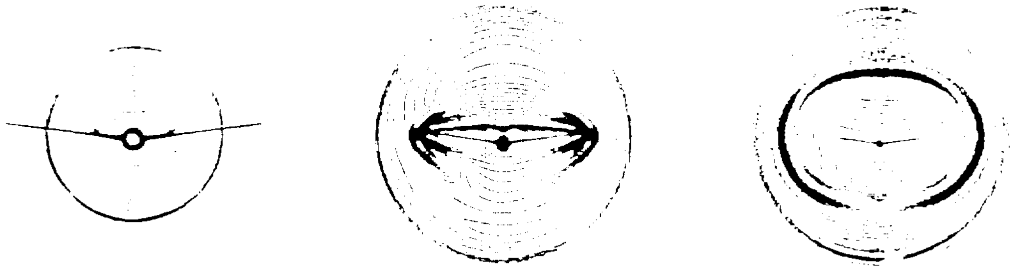


Figure 11

Flow Field Cross Sections

Perhaps an explanation of the flow field phenomena around the shaped, low-boom configurations can be explained with figure 12, which shows a flow field cross section for a low boom configuration at three axial locations as predicted by an Euler computational method[11]. Note that at mid aircraft, the flow field is relatively clean, with only the bow shock being prominent. At the aft end of the aircraft, very strong shocks emanating from the region of the wing are evident. As one moves further downstream, the flow field immediately beneath the configuration is still very clean, but the strong shocks generated by the wind are moving toward the flight path. It is probably the strong effect of the wing that is being seen in the wind tunnel data just ahead of the expansion region. These results would indicate that for low boom configurations where the primary effort has been to reduce disturbances in the flight path, the non-zero azimuth angles can not be ignored either for ground level signatures or for the influences they have on the flight path signatures.


Low Boom Configurations

Mid- Aircraft

Aft End

Body Length Downstream

Figure 12

Comparison of Extrapolated Wind Tunnel Data and Target Signature

A comparison of extrapolated wind tunnel data taken at one body length from the Mach 3 configuration with test conditions of Mach 2.96 and normal force 3.06 lbs is compared with the target signature for the same flight conditions. As can be observed, the objective was to obtain a bow shock of 0.94 psf followed by an isentropic increase in pressure to 1.45 psf. The extrapolated data does not show this behavior. The bow shock level is 1.8 psf and a second shock increases the pressure to 1.95 psf. There could be several reasons for the discrepancy in the expected signature and the actual signature: (1) linear theory methods used in the design of the configuration become less valid at Mach numbers as high as 2.96[12]; (2) the isentropic rise in pressure is less stable and is therefore more difficult to maintain during propagation; (3) boundary effects which cannot be properly scaled on these 12-inch models may have an effect on the wind tunnel results.

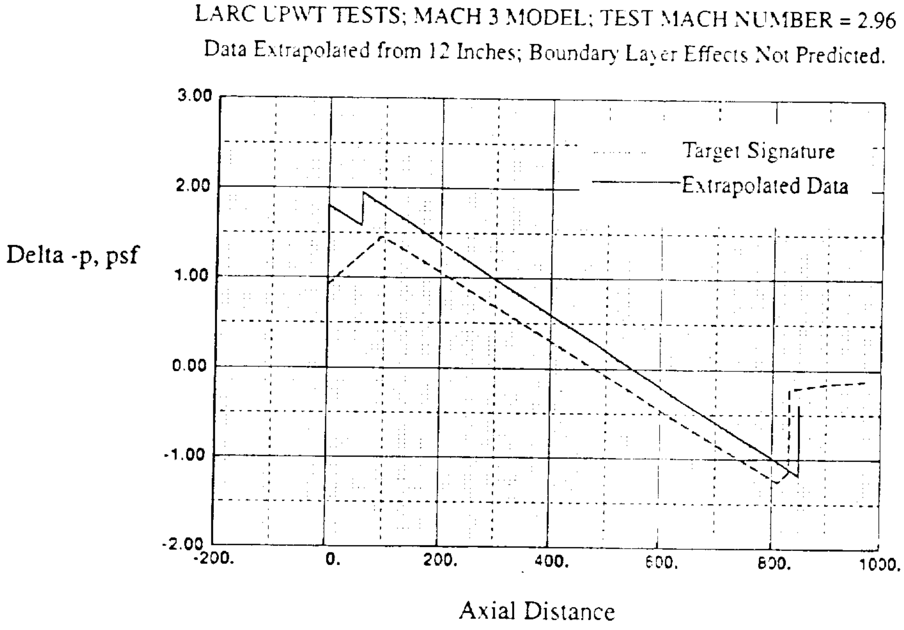


Figure 13

Comparison of Extrapolated Wind Tunnel Data and Target Signature

A comparison of the extrapolated wind tunnel data and the target signature for the Mach 2 configuration is seen in figure 14. Also shown on the signature is the signature predicted from the geometry using linear theory methods. Test conditions were Mach 2 and normal force 5.1 lbs. As can be seen, the agreement between the forward part of the extrapolated wind tunnel signature and the target signature is excellent. The largest discrepancies are in the region near the expansion where uncertainty about 3-dimensional effects still exist and in the overall length of the signatures. If significant changes do not occur in wind tunnel results taken at 3 to 4 body lengths, then these results appear to validate the minimization theory for these twisted and cambered configurations at Mach 2.

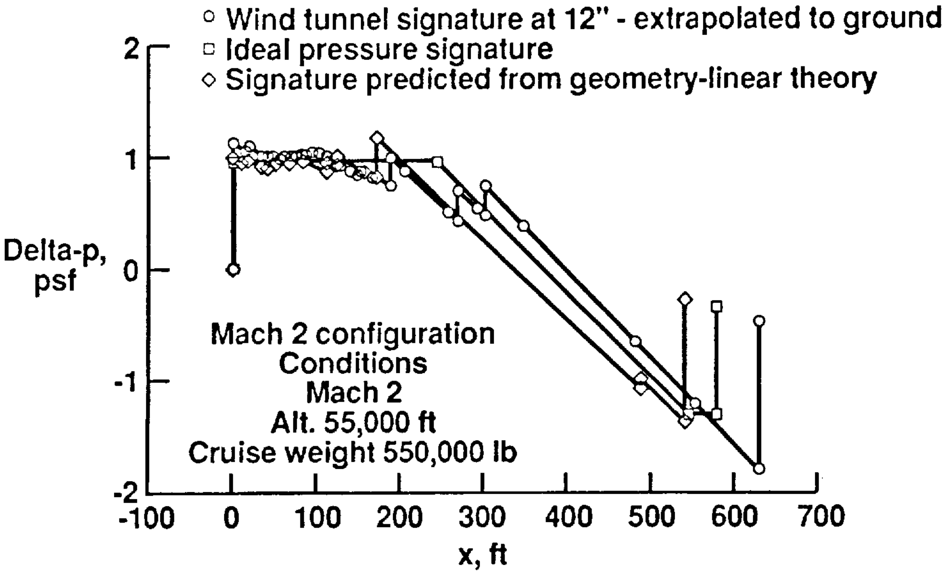


Figure 14

Theoretical Bow Shock Overpressures

Several factors have contributed to the decision for the range of Mach numbers to be considered in the next cycle of low boom designs. Included among those factors are: (1) initial indications that ozone considerations may lead to cruise altitudes of around 45,000 feet; (20 the wind tunnel results which indicated that the linear theory design methods may be invalid at higher Mach numbers; and (3) the decision in the High Speed Research (HSR) program that future designs would center around Mach 2.4. An additional factor is shown on figure 15. Shown on this figure are two carpet plots which include results of the minimization code for a minimum shock type signature. The plot on the left shows for the condition Mach 1.6, the equivalent length necessary for a given bow shock overpressure at a given altitude. This figure shows that to achieve the lowest bow shock level at the shortest length, one would cruise at the lowest altitude. An increase in altitude increases the length necessary. The second carpet plot shows that for an altitude of 44,000 feet one would cruise at the lowest Mach number to achieve the lowest bow shock level at the lowest length. Using as guidance information from this plot as well as guidance from the other factors, the choice was made to choose Mach number between 1.6 and 2 for the second cycle of low boom designs in which the emphasis will be placed on integrating performance.

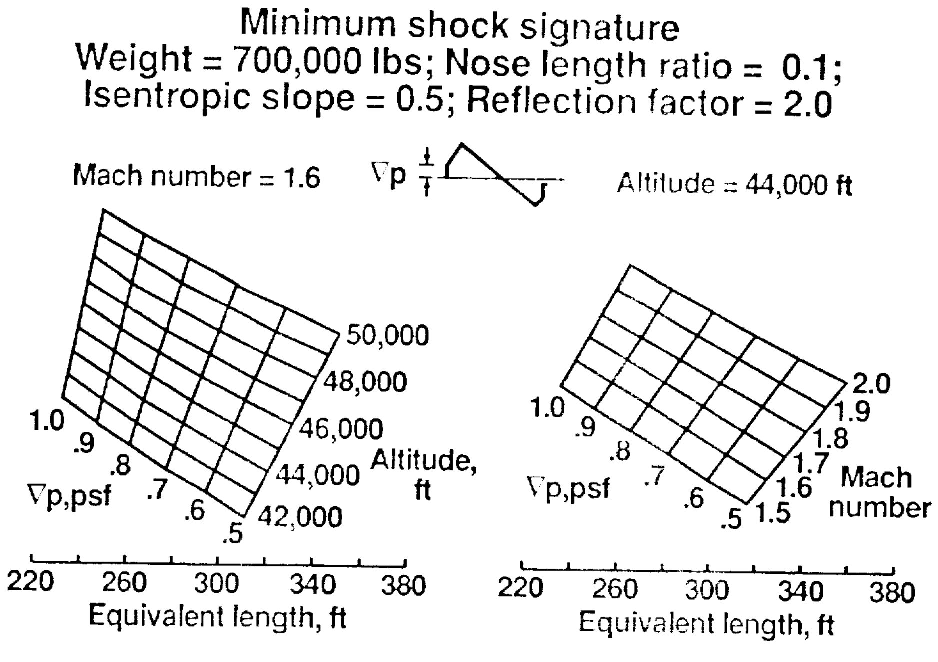


Figure 15

Sonic Boom Design Efforts

Target conditions and a preliminary planform chosen as Mach 1.6 low boom design are shown on figure 16. The target signature shown is one conceived at Boeing Airplane Company as one method of improving the stability problems of the minimum shock signature but still maintaining some of the weight advantage allowed by that signature. Target design flight conditions include Mach 1.6, 45,000 ft altitude, a beginning cruise weight of 650,000 lbs and an overall length of 323 lbs. The theoretical equivalent area distribution and its resulting pressure signature with a bow shock of approximately 0.85 psf are shown. Signature conditions listed are input parameters which define some of the variable parameters in the minimization code. The configuration planform shown is still in its developmental stage.

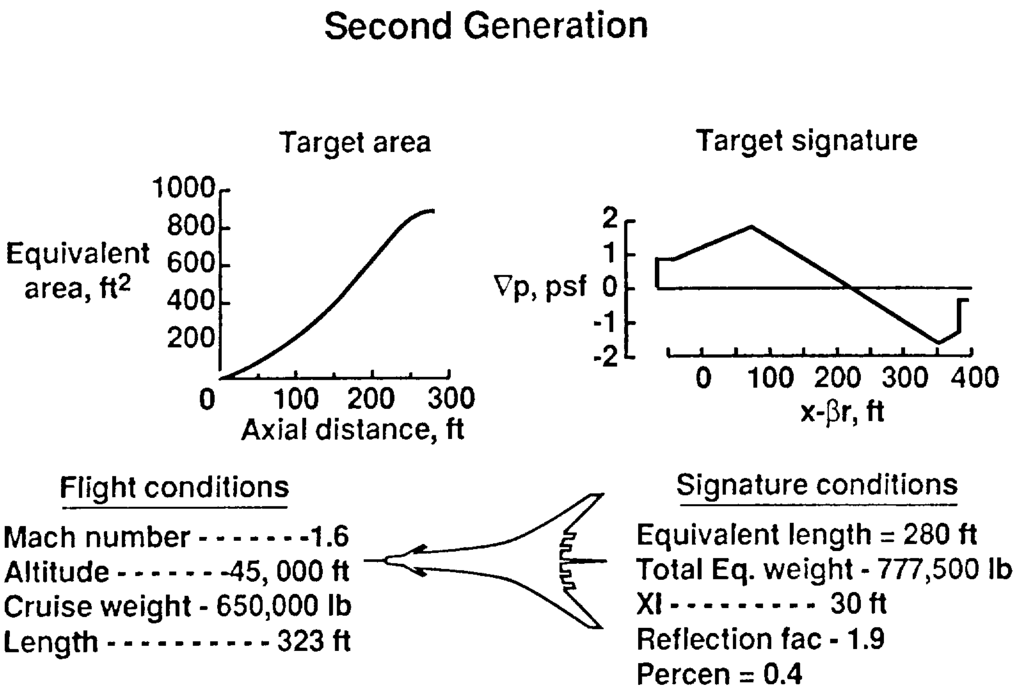
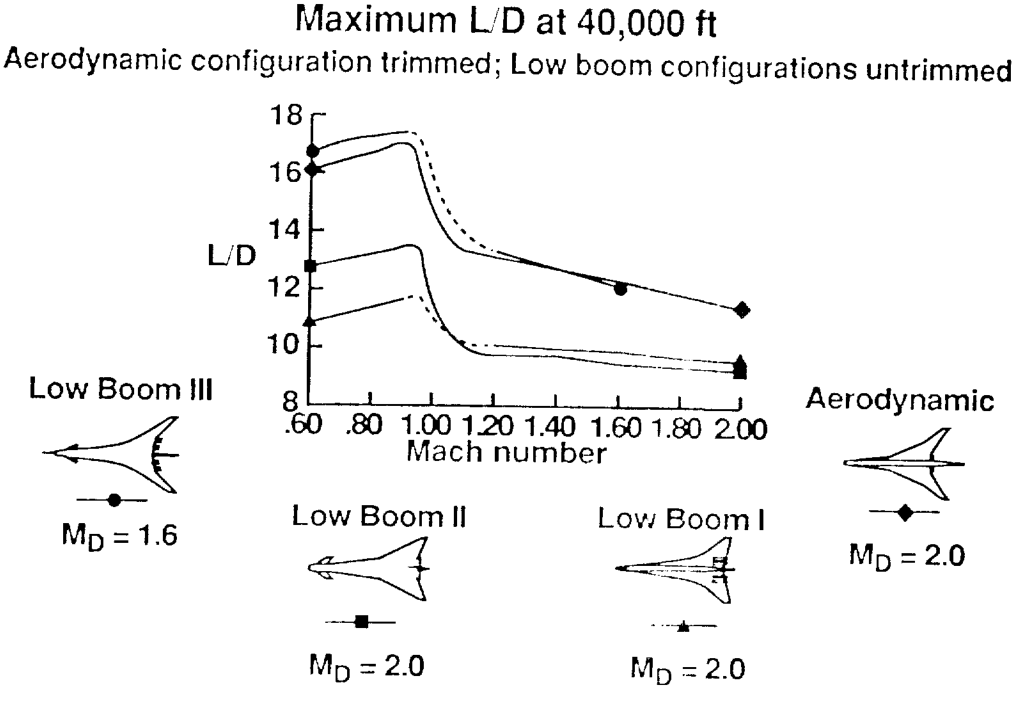


Figure 16

Performance Comparisons

The ultimate goal of the configuration minimization portion of the sonic boom program, is to develop a low-boom configuration which would be competitive with a baseline configuration which has no low boom constraints but which would have to cruise subsonically overland. Shown in figure 17 is an L/D comparison of a baseline Mach 2 concept with no low-boom constraints, but which has been optimized aerodynamically and three low boom configurations. The Low Boom I concept was designed as a theory validation model and very little effort was placed on the performance. Low Boom II represents an intermediate design effort which was subsequently dropped because of performance estimates and Low Boom III is the current 1.6 design being worked. This figure does not separate Mach numbers effects from these results but does give an indication of improved performance for the low boom designs. Also these results are for a trimmed aerodynamic concept but for untrimmed low boom configurations. L/D estimates for Low Boom I are quite poor when compared to the Aerodynamic baseline. Design efforts on the Low Boom II concept improved the subsonic characteristics significantly but the supersonic performance estimates were still quite low. Very preliminary estimates of L/D for the current Mach 1.6 design show significant L/D improvements--subsonically better than the baseline and nearly equal to the baseline at its design Mach number of 1.6. Recall that the results for the Mach 1.6 design are very preliminary and are subject to change. They are shown only to indicate that with effort toward systems integration, the performance of the low boom designs should improve.


Maximum L/D at 40,000 ft

Aerodynamic configuration trimmed; Low boom configurations untrimmed

Figure 17

Effect of Engine Plume on Sonic Boom Signatures

Concern has been expressed about the effect of the engine plume on the sonic boom signature of shaped configurations. To get an estimate of its effects, an Euler code was used to calculate the plume of the low boom Mach 3 concept based on the pressure ratios defined for the in-house Mach 3 engine[13]. In normal sonic boom calculations, the plume is approximated by a cylindrical extension. Shown on figure 18 are comparisons of the sonic boom signature for the Mach 3 configuration cruising at Mach 3 at 60,000 ft initially with the cylindrical plume and beside it with the calculated plume. It can be seen that for the nozzle defined, the plume at 60,000 feet completely obscures any benefit of shaping. The pressure signature for the same Mach 3 configuration cruising at Mach 2 and 55,000 feet is shown on the second line. Although some effect of the plume is still evident, it is much less than the effect at 60,000 feet. Initially these results were used to conclude that the effect at Mach 1.6 and 45,000 feet would be not be noticeable. It was found however, that a different engine was necessary for those conditions and when actual calculations were made, the effect of the plume at 45,000 feet was comparable to that shown at 55,000 feet. Clearly plume effects cannot be ignored during the design process.

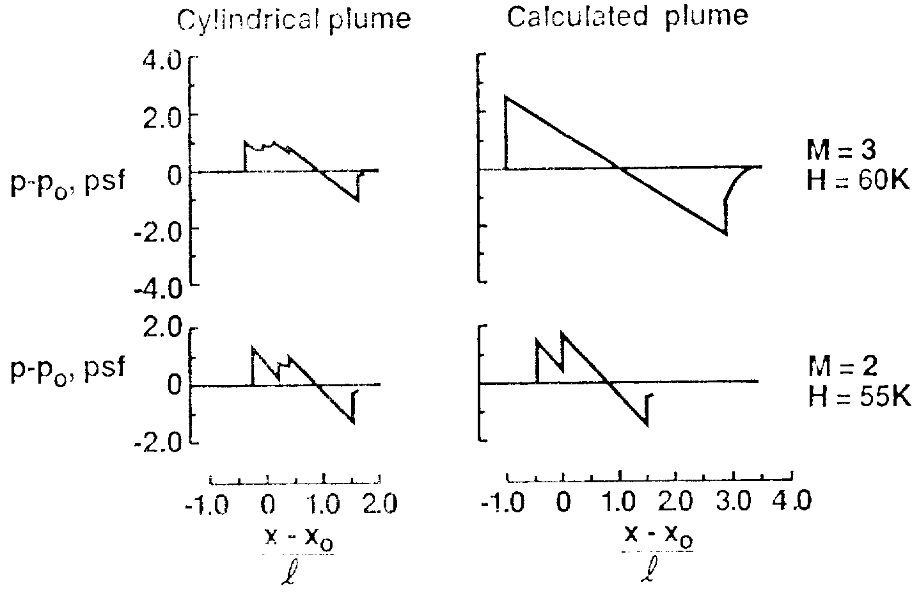


Figure 18

Sonic Boom Contours as a Function of Mach Number and Altitude

The sonic boom prediction method using modified linearized theory methods has been automated and integrated into an in-house performance code[14]. Results of sonic booms at various altitudes for the Low Boom I configuration are shown as contours on figure 19. These boom levels were calculated for steady state conditions but it was found that acceleration and climb rates typical for a transport configuration did not significantly change the results. Climb profiles for optimum performance and with boom constraints are shown on this figure.

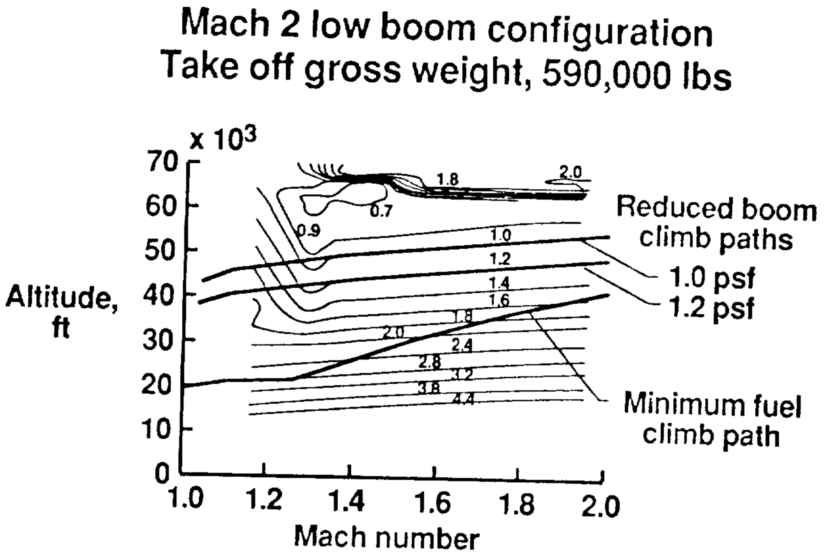
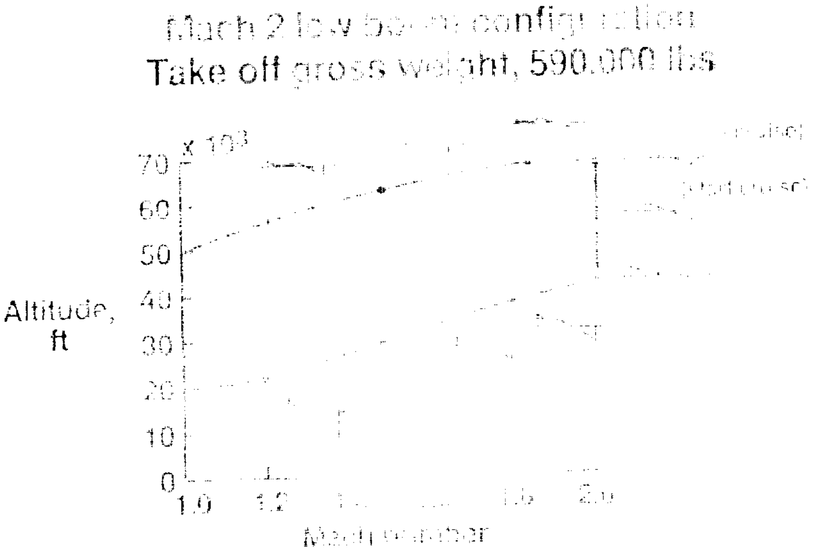


Figure 19

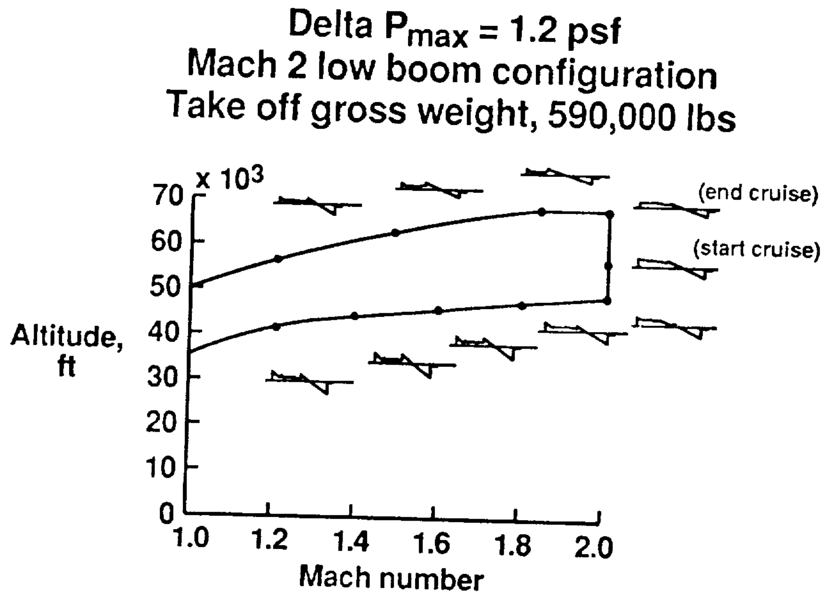
Ground Pressure Signatures for Optimum Performance Flight Profile

Shown in figure 20 are the ground level signatures for the low boom Mach 2 configuration as it climbed to cruise along the optimum performance flight path. All signatures are plotted to the same scale for comparison. Note that for the cruise portion of the flight the signature achieves it flat top shape as predicted but during climb, shock levels as high as 2.6 psf are generated.



Ground Sonic Boom Signatures for Restricted Flight Profiles

Shown in figure 21 is the flight path necessary and sonic boom generated when the sonic boom bow shock level is restricted to 1.2 psf. As can be seen, to limit the boom to 1.2 psf, supersonic speeds must not be achieved until 35,000 feet. For this flight profile, there is a 2% penalty in total range when compared to the performance profile.



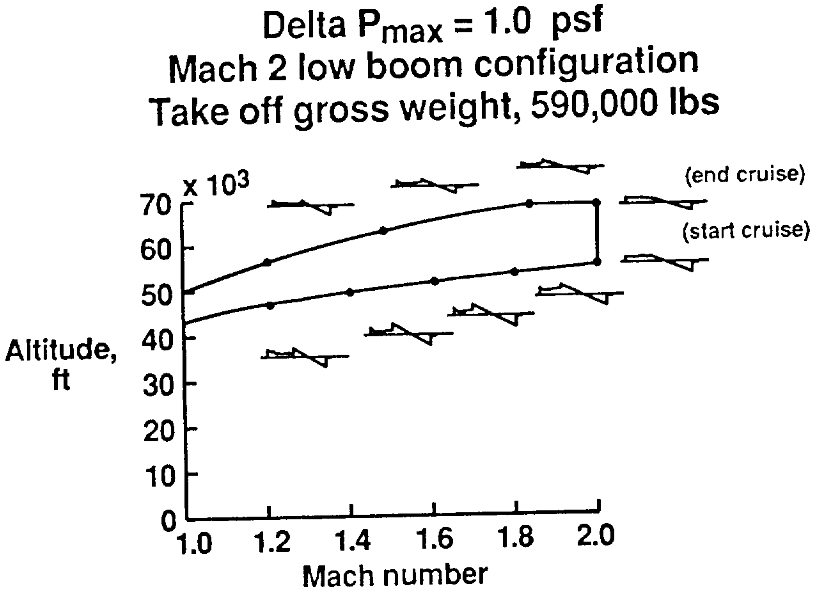
Delta P_{max} = 1.2 psf
Mach 2 low boom configuration
Take off gross weight, 590,000 lbs

Figure 21

~~C-3~~

Ground Sonic Boom Signatures for Restricted Flight Profile

To limit the boom to 1.0 psf., figure 22 shows that the configuration must be at approximately 43,000 feet before going supersonic. This profile results in a 5% range penalty when compared to the optimum performance path. It is evident from these results that the entire flight profile of the low boom configuration must be considered when evaluating its economic performance.



Delta P_{max} = 1.0 psf
Mach 2 low boom configuration
Take off gross weight, 590,000 lbs

Figure 22

C-3

Concluding Remarks

Wind Tunnel results indicate theory validation, especially at Mach 2, but signatures at greater distances needed.

Next designs will target lower Mach numbers and will stress integration of performance and low boom characteristics.

Next designs will be tested for low boom and performance.

Plume effects and entire mission profile must be considered in the design and evaluation of configurations.

Figure 23

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