LOW SONIC BOOM DESIGN AND PERFORMANCE OF A MACH 2.4/1.8 OVERLAND HIGH SPEED CIVIL TRANSPORT

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INTRODUCTION

This paper describes the design features of a Douglas Mach 2.4/1.8 Low Sonic Boom High Speed Civil Transport (HSCT) configuration developed for NASA under government contract number NAS1-19345. The configuration is designed to fly over water at Mach 2.4 for highest productivity and economic worth, and fly over land at Mach 1.8 with reduced sonic boom loudness.

SONIC BOOM DESIGN GOALS

Before the design work was undertaken, a study was performed to determine the appropriate Mach number and weight for sonic boom design minimization efforts (figure 1). Based on preliminary acoustic response studies, a loudness goal of 90 PLdB was chosen. The NASA Langley (Christine Darden) SEEB computer code[1] was used to quantify the maximum weight possible for a 90 PLdB waveform. A minimum shock waveform was chosen to maximize the weight allowable. A minimum weight constraint was added based on a non-low boom baseline configuration weight required to meet the mission range and payload desired. As a first order approximation, a 10% increase in weight above the baseline was chosen as an upper weight limit. In previous NASA studies, Douglas was counseled against operating in the no bow shock regime due to concerns over shockless waveforms coalescing into larger front shocks. Further, the equivalent area shapes required to eliminate bow shocks tend to allow very little volume for a practical vehicle. From the design space shown in figure 1, it was decided to pursue sonic boom minimization at Mach 1.8 with a maximum take-off gross weight (MTOGW) of 850,000 pounds.

In addition to using Mach 1.8 for sonic boom minimization, a payload of 300 passengers and range of 5,000-5,500 nautical miles were chosen to match the baseline configuration. Mach 2.4 supersonic cruise over water was chosen to reduce the risk of the low boom design: if the low boom

Sonic Boom Design Space

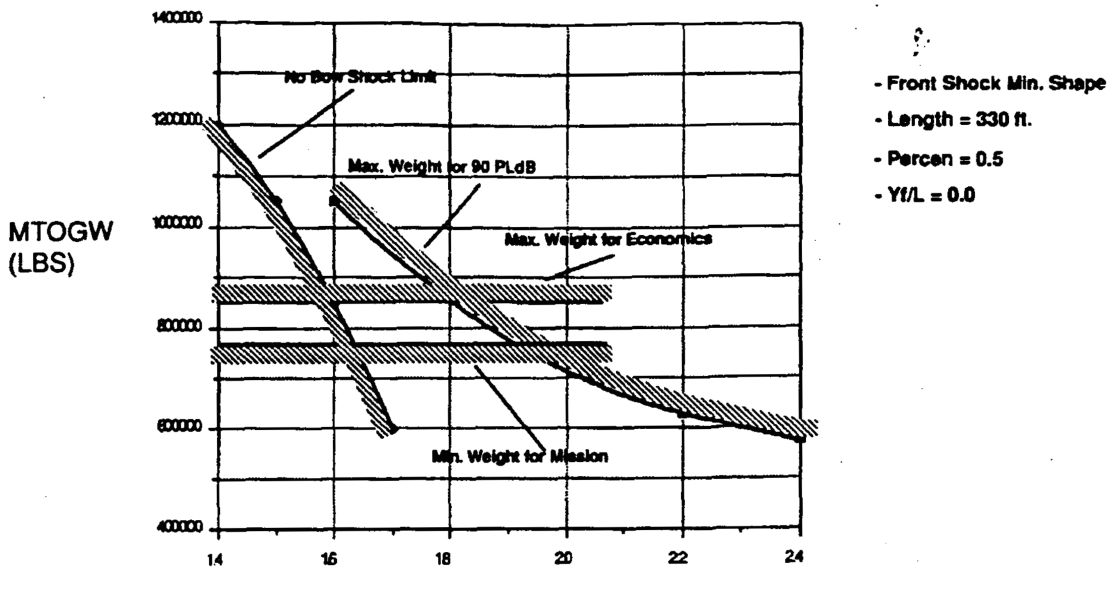

Figure 1

configuration was not allowed to fly supersonic overland, it would still be capable of Mach 2.4 over water; therefore, it retains the baseline's productivity economic advantage over water (compared to subsonic aircraft). Further, the long lifting lengths needed for sonic boom minimization are conducive to the higher sweeps which are beneficial at Mach 2.4.

DESIGN AND ANALYSIS METHODS

Design of the configuration started with a SEEB equivalent area goal based on the chosen Mach number and weight. A linear wing-body-tail panel method calculates the configuration's lift in a trimmed condition. A far-field wave drag program calculates the volume pressure disturbance of the full configuration, wing-body-tails-nacelles. A linear sonic boom propagation method reads in axial lift distributions at several angles-of-attack and Mach angle cut volume distributions at several roll angles. The lift and volume are converted into an 'f' function (as per the Whitham-Walkden theory[2]) and propagated to the ground at several roll angles to form a sonic boom carpet.

Numerous configurations, their permutations and various mutations were analyzed. This study included at least 3 planforms, several twist and camber combinations, 3 horizontal tails, 4 canards, 2 vertical tails, 2 nacelles, and more than 50 fuselages. Many improvements were made in the analysis methods to handle more complex configurations, improve turn-around time, and improve techniques used for numerically calulating slopes and second derivatives as configuration complexity increased.

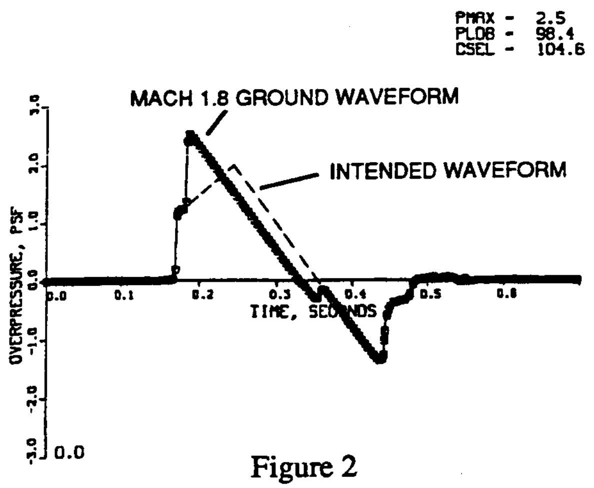

Figure 2

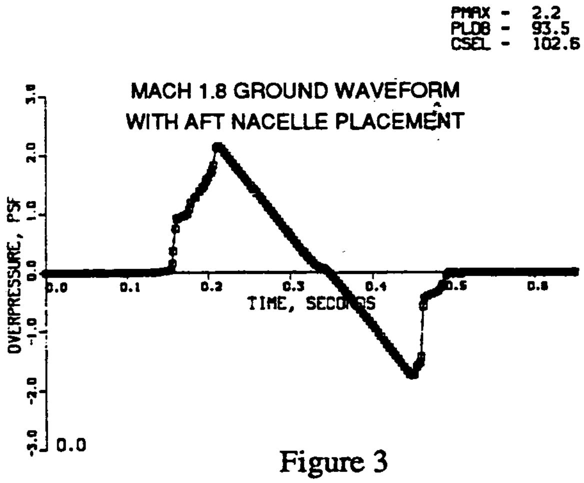

Figure 3

During the many configuation analyses and recent NASA wind tunnel test analyses,[3] the strong effect of nacelles on sonic boom became apparent. Figure 2 shows a comparison of the intended minimum shock waveform with the ground waveform for an earlier version of the 2.4/1.8 configuration. A large pressure spike due to the nacelles "ate up" most of the ramp waveform, creating a second shock that doubled the front waveform loudness. A two part strategy was undertaken to deal with the nacelle pressure spikes: the location of the nacelles was changed, and the accuracy of nacelle effects was increased.

First, the nacelles were moved aft so their pressure spikes would occur behind the front ramp of the waveform. This virtually eliminated the nacelle shock effect on the ground waveform, as shown

NACELLE PRESSURE CONTOURS FROM NASTD CFD SOLUTION

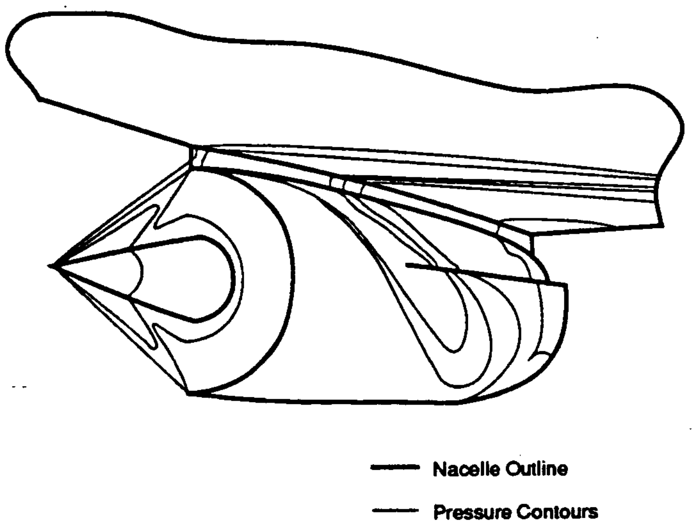

Figure 4

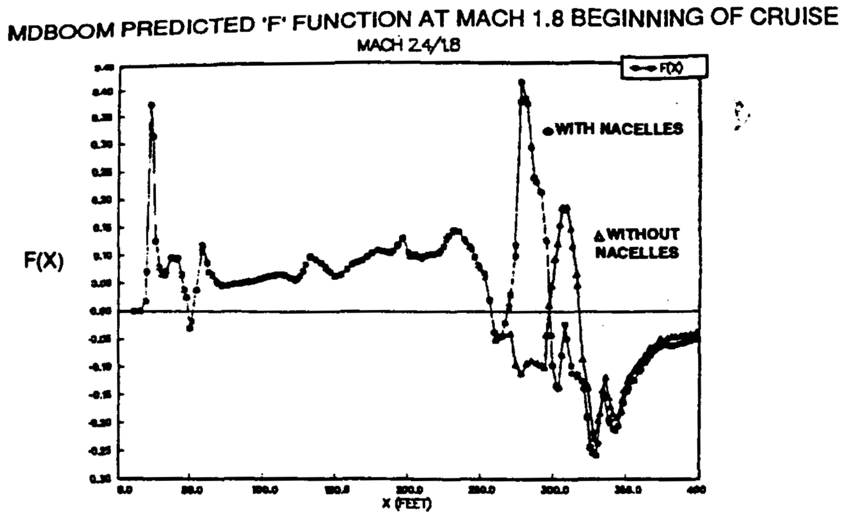

Figure 5

in figure 3. However, it necessitated a large change in the configuration. To get the nacelles back far enough, a change was made to a canard-wing arrangement (instead of an aft tail as on the baseline) and a new planform was developed. This arrangement allowed the airplane balance to be achieved with a more aft wing placement and allowed the typical underwing nacelle mounting arrangement to be retained.

Finally, a new method was developed to improve the modelling of nacelles and nacelle interference effects. CFD runs were made of a detailed nacelle and diverter installation (developed for the NASA Lewis Propulsion Airframe Integration Technology, PAIT, study), as shown in figure 4. The pressure field from the Euler CFD solution (NASTD run by McDonnell Aircraft; St. Louis, MO) is used in the linear 'f' function calculation and this helps in modelling interference effects. The impact of including nacelle effects on the 'f' function calculation is shown in Figure 5. Similar trends have been obtained in recent NASA wind-tunnel tests.[3]

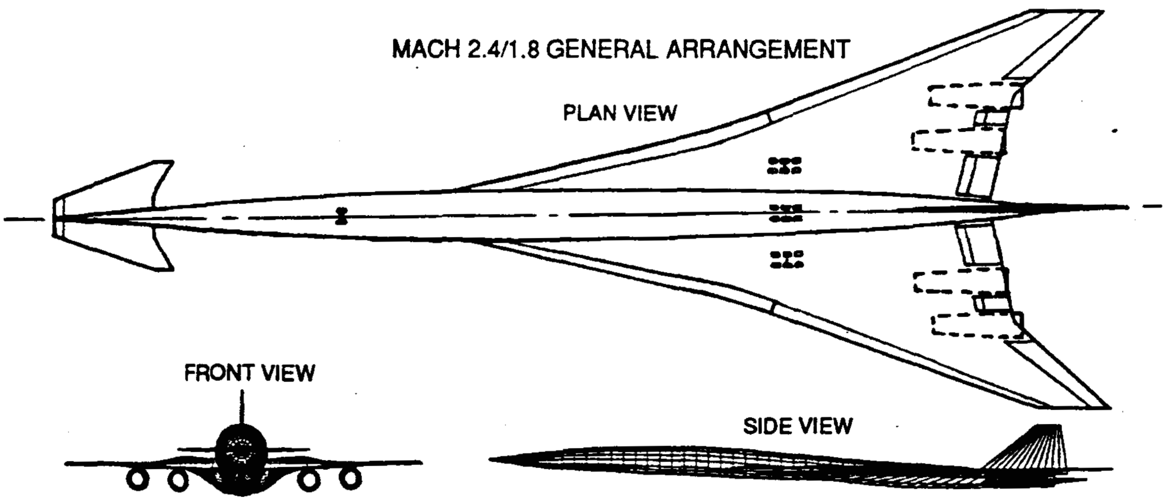

Figure 6

MACH 2.4/1.8 GROUND UNDERTRACK WAVEFORM
AT MACH 1.8 BEGINNING OF CRUISE

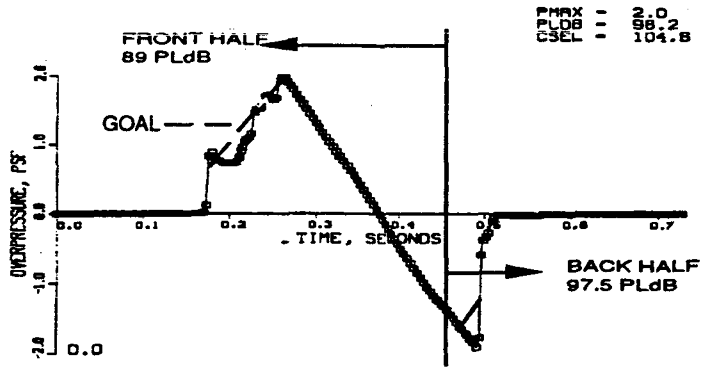

Figure 7

2.4/1.8 CONFIGURATION GENERAL ARRANGEMENT

The latest 2.4/1.8 configuration arrangement is shown in figure 6. As mentioned previously, it has a canard in front. In addition to acting as a trimming and control surface, the canard has a small movable surface on its zero sweep leading edge. This surface is deflected up during low boom operation at Mach 1.8 to help create an effective "nose bluntness" without a blunt area distribution. In this way, the bluntness drag need not be present during Mach 2.4 over water cruise. The wing has a 76/68 degree subsonic swept leading edge and a "gull-wing" dihedral to improve nacelle clearance. The fuselage meets the 300 passengers in a 3-class arrangement goal.

2.4/1.8 CONFIGURATION BOOM LEVELS

Figure 7 shows the beginning of cruise undertrack ground waveform. While the front half of the waveform is close to the 90 PLdB goal, the aft shock brings the total to an annoying 98.2 PLdB. The first question is, "Why did the aft shock get so loud?" The loud aft shock appeared as a result of adding the nacelle CFD pressures created under the back end of the wing. These pressures cause a steep rise in the equivalent area distribution seen as the nacelle pressure spike in the 'f' function (figure 5). As previously mentioned, the effect of the spike is suppressed by the nacelle placement; however, the quick drop off in lift behind the spike causes negative pressure spikes behind the nacelles, which could not be eliminated by fuselage shaping without a large drag penalty. A more gentle drop off in lift is needed to reduce the aft shock strength.

The second question might be, "Why has the minimum shock waveform become a delayed ramp?" The front shock is a little larger than desired because the large canard at the front nose introduces some non-smoothness that is difficult to remove. Also, the design methods have trouble keeping the area distributions smooth wherever lifting surfaces begin and end. And finally, the shape of the ramp was allowed to vary a bit to smooth the fuselage for reduced wave drag.

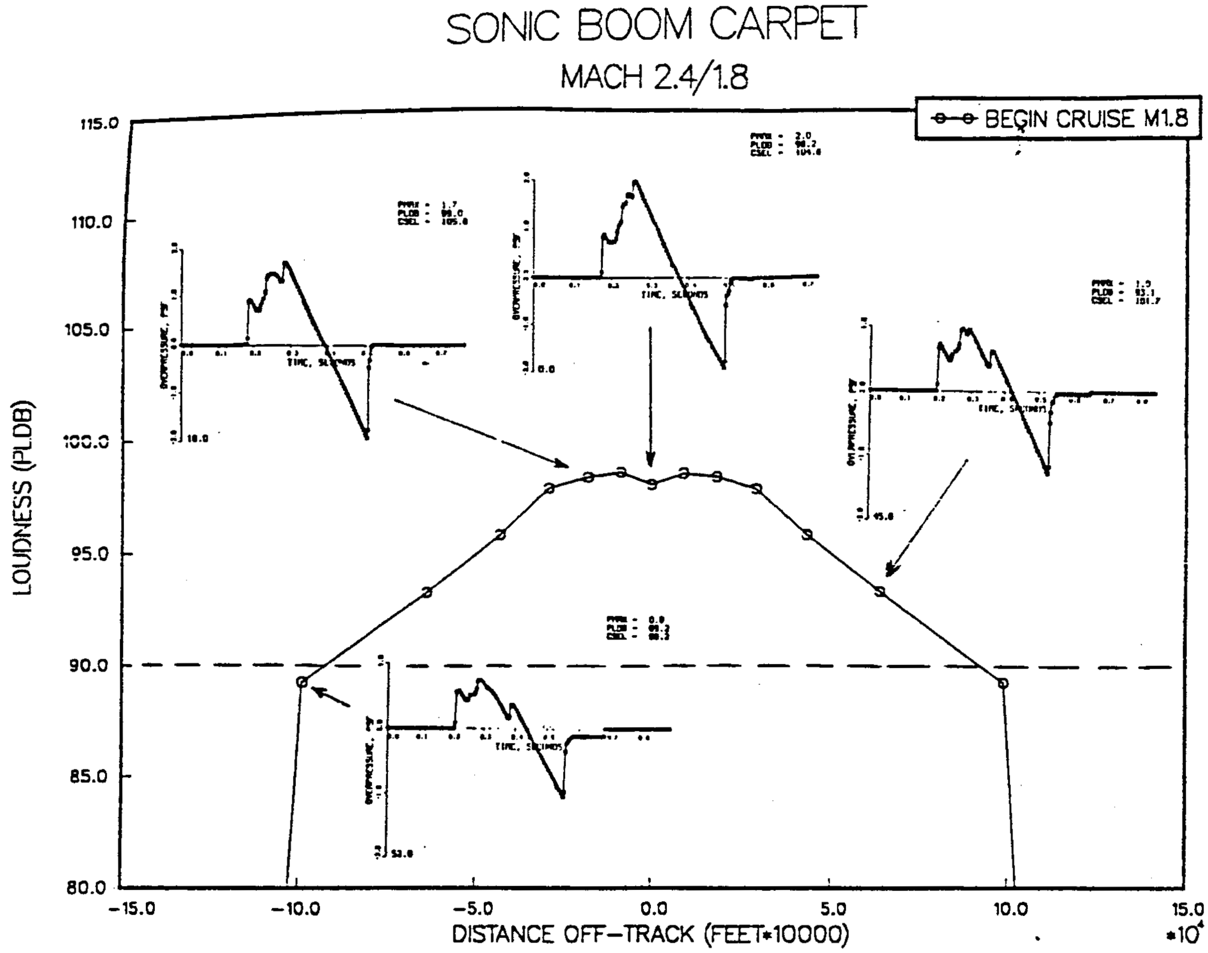

Figure 8

(original figure unavailable)

One solution to both problems would be to add an aft horizontal tail in addition to the front canard. In an optimum supersonic trim condition, it is generally beneficial to carry some aft tail lift. The size of the canard could also be reduced. The problem in using this approach is that the available methods are not currently capable of handling three surface configurations.

In spite of the large aft shock, it is important to hightlight how far the design has progressed toward an acceptable low boom signature. Significant attention was paid to minimizing off-track loudness during the design process. Figure 8 shows the total sonic boom carpet loudness for the beginning of cruise condition, along with waveforms at several points along the carpet. Note that a shaped waveform is retained throughout the carpet. The effect of the nacelle pressure spike is controlled at all roll angles.

In addition to looking at off-track loudness, sonic boom carpets at other than the beginning of cruise must be considered. Figure 9 compares the Mach 1.8 beginning of cruise sonic boom carpet with the Mach 1.2 climb carpet (without acceleration effects) and the Mach 1.8 end of cruise carpet. The Mach 1.2 climb values are held to roughly the same loudness level, but the carpet is consider-

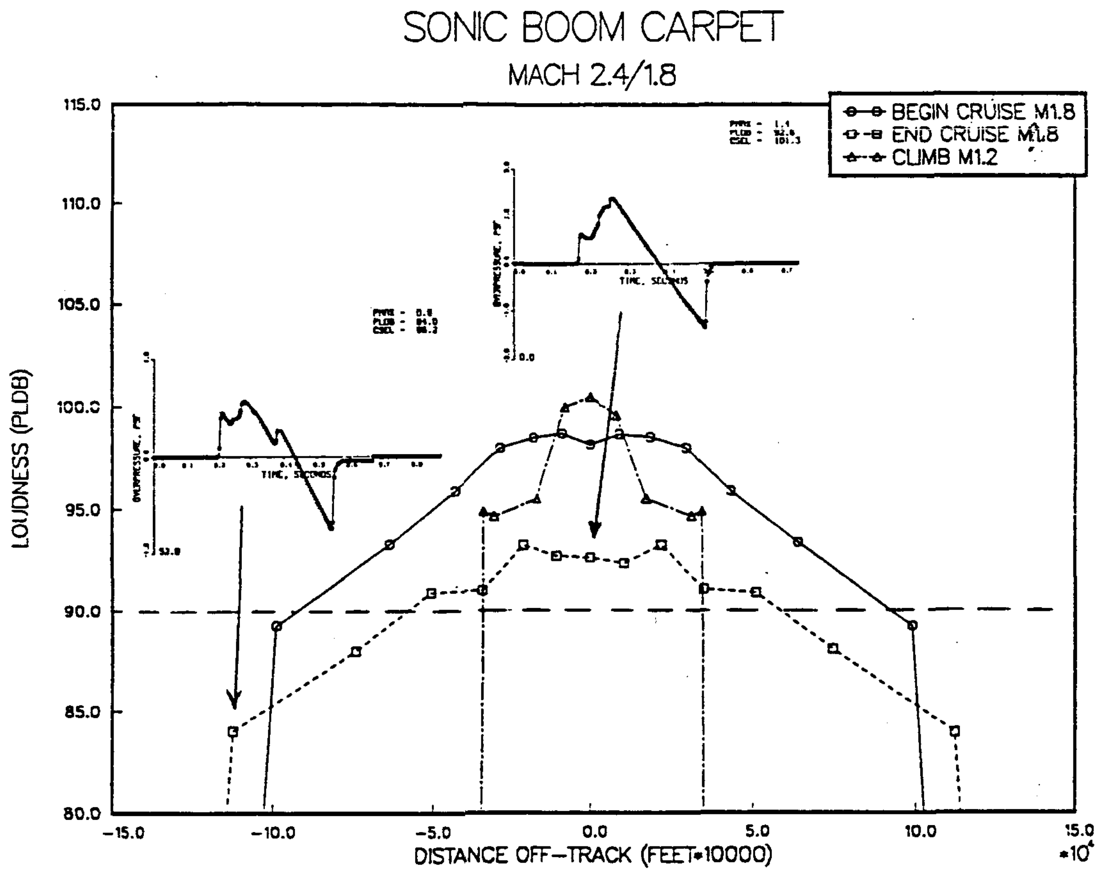

Figure 9

ably more narrow. A low noise, mid-field (non N-wave) waveform at the ground is achieved by climbing in a low q (dynamic pressure) ascent tragectory similar to those shown in reference 3. The fuel burn penalty for the lower q climb is 1.5 to 2 percent. It is possible that this penalty could be reduced by tailoring the canard lift distribution for Mach 1.2 boom minimization in future studies.

Of paticular interest is that the Mach 1.8 end of cruise waveforms are almost identical in shape to the beginning of cruise waveforms, except they are about 6 PLdB quieter. The ground waveform from the end of cruise has the same "aged" shape as the beginning of cruise waveform, because the airplane is flying at a constant lift coefficient which means that the same p_{local}/p_{∞} ratio exists all along the vehicle throughout cruise. The implication is that throughout climb, cruise, and descent the "aging" of a low boom ramp waveform will be held at or below its design target, and thereby, maintain a shaped waveform (in a non-turbulent atmosphere.) In summary, altitude changes at the same Mach number do not cause low boom waveform shapes to "age" differently when using typical constant lift coefficient climb, cruise, and descent tragectories. Conversely, Mach number directly affects waveform "aging", so that at Mach 2.4 beginning of cruise the low boom 2.4/1.8 configuration produces a typical N-wave of 104.5 PLdB loudness, undertrack.

Since Mach 2.4 cruise over water is more productive and 70% of the earth is covered with water, the 2.4/1.8 low boom airplane is likely to spend most of its time cruising at Mach 2.4. Therefore, Mach 2.4 cruise efficiency is of paramount importance. Wing leading edge sweeps were chosen with this speed in mind and the planform twist and camber distribution are optimized for it. The area distribution is smoothed for Mach 2.4 cruise and simultaneously shaped for low boom at Mach 1.8. The Mach 2.4 roll averaged area distribution is shown in figure 10.

MACH 2.4/1.8 ROLL AVERAGED AREA DISTRIBUTION AT MACH 2.4

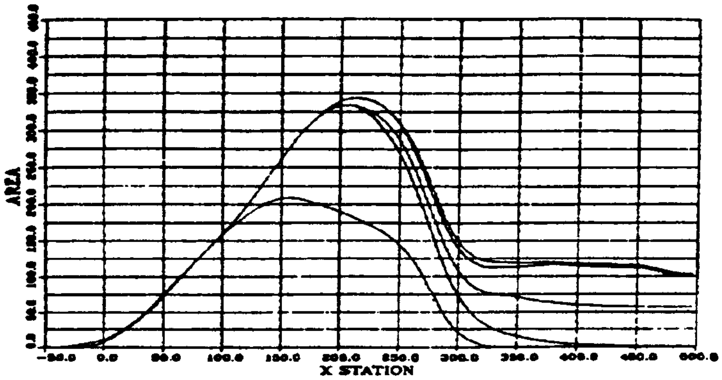

Figure 10

Table 1 below gives a comparison between the 2.4/1.8 low boom airplane and a 2.4/0.95 baseline, both sized at the same MTOGW and flying 25% over land at reduced speed. The Mach 2.4 cruise performance of the two configurations is about equal; however, the 2.4/1.8 configuration is significantly more efficient at Mach 1.8 over land than the 2.4/0.95 baseline is at Mach 0.95 over land. The main penalty of the 2.4/1.8 configuration is the weight of the large wing, which contributes most of the 18 percent increase in operator's empty weight (OEW) relative to the Baseline. This performance assessment analysis is preliminary and no changes of the Low Boom geometry were allowed during sizing.

Table 1

	LOW BOOM 2.4/1.8	BASELINE 2.4/0.95
MTOGW (lb)	830 000	830 000
OEW (lb)	358 000	304 000
W/S (lb/ft²)	66	89
FN (lb)	62 900	57 900
RANGE (nm) @ 25% OVERLAND	5 000	5 660

WIND TUNNEL TEST AND FURTHER PLANS

At this point, it is desirable to fabricate and test a wind tunnel model of the 2.4/1.8 low boom geometry. It represents many new features that have yet to be validated. Predictions indicate that a ramp front waveform should be achieved undertrack and shaped waveforms are achieved at all roll angles with ground intercepts. The strong aft shock would not make a difference with the proposed wind tunnel test methods, because the signature behind the nacelles cannot be modelled accurately due to sting interference and the lack of engine power effects (engine exhaust). Further revisions of the 2.4/1.8 configuration will be undertaken to reduce the aft shock and improve performance. In the meantime, the CFD predictions of the nacelle effects need to be verified along with the off-track prediction methodology. Further, a newly developed method that links full configuration CFD solutions to sonic boom predictions[4] will be used on the 2.4/1.8 Low Boom design. The CFD is better able to account for three dimensional effects, but more complex, low boom wind tunnel test data are needed to develop experience and thereby accuracy with the method.

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