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Status of Sonic Boom Methodology and Understanding

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Preface

The purposes of the 2-day Sonic Boom Workshop were to assess the state of the art in sonic boom physics, methodology, and understanding, to determine areas in which additional sonic boom research is needed, and to establish strategies and priorities in this research. Attendees included approximately 60 representatives of industry, academia, government, and the military. Many of these participants were internationally recognized sonic boom experts who had been active in the Supersonic Transport (SST) and Supersonic Cruise Aircraft Research Programs of the 1960's and 1970's.

Summaries of the assessed state of the art and the research needs in theory, minimization, atmospheric effects during propagation, and human response are given.

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ABSTRACT

In January 1988, approximately 60 representatives of industry, academia, government, and the military gathered at NASA Langley Research Center for a 2-day workshop on the state of the art of sonic boom physics, methodology, and understanding. The purposes of the workshop were to assess the state of the art in the sonic boom area, to determine areas where additional sonic boom research is needed, and to establish some strategies and priorities in this sonic boom research. Attendees included many internationally recognized sonic boom experts who had been very active in the Supersonic Transport (SST) and Supersonic Cruise Aircraft Research Programs of the 1960's and 1970's. Summaries of the assessed state of the art and the research needs in theory, minimization, atmospheric effects during propagation, and human response are given.

INTRODUCTION

Significant shifts in the United States' balance of trade in recent years have caused many national leaders to reassess the international economic situation. Since 1980, the United States has steadily lost its place in the high technology export market. In 1986, for the first time, high technology imports into the U.S. exceeded exports. The situation has caused great concern among the leaders of this country.

The aeronautics industry in the U.S. has for many years been a world leader and a symbol of technological pride. Even in this area, however, competition from European and Far Eastern companies and governments has caused great concern in both U.S. industry and our government.

In 1985, the Office of Science and Technology Policy of the Office of the President formed the Aeronautical Policy Review Committee, whose purpose was to assess this situation. In their report, "National Aeronautical R & D Goals: Technology for America's Future," presented in March 1985, the committee recommended that all sectors of the American aeronautics community direct their skills and energies toward the highest-payoff technology areas. Specific goals in the subsonic, supersonic, and transatmospheric flight regimes were established.

A second report, "Agenda for Achievement," was issued in 1987 as a sequel to the 1985 document. Included in the second report was an eight-point plan presented as a strategy to achieve the national goal of remaining a viable competitor in the world of aviation. In addition to several points on increasing the R & D effort in this country, specific points in this plan addressed the Aerospace Plane, supersonic transport technology, and vertical takeoff and landing/short takeoff and landing (VTOL/STOL) programs. National programs on the Aerospace Plane and on rotorcraft systems are already in place, and an effort on supersonic transport technology is under way.

As a first step in assessing the market and technology needs for a viable supersonic transport, contracts were awarded to Boeing Commercial Airplanes and Douglas Aircraft Company in October 1986. Areas emphasized in these feasibility studies included market, economics, range, Mach number, fuels, payload, and technology needs. Results of the contractual studies indicate that environmental concerns should be top priority in the development of technologies for a future high-speed civil transport (HSCT). Results also show that the economic viability of a supersonic transport would be tremendously reduced by current environmental constraints which would significantly limit overland supersonic flight. Therefore, research that would develop technologies which permit supersonic overland flight would be extremely important to the viability of a future HSCT. To help in the organization of this sonic boom research program, a workshop was held at Langley Research Center on January 19-20, 1988, to assess the state of the art in sonic boom knowledge and to give direction and priorities to areas of technology need.

Sixty persons who currently or previously worked in the area of sonic boom, representing industry, government, and academia, attended. Several representatives of the Air Force Noise and Sonic Boom Impact Technology (NSBIT) Program also attended. The 2-day workshop began with an overview of the reasons for renewed interest in sonic boom technology, and was followed by brief status papers on sonic boom research and current activities in the Air Force NSBIT program. The attendees were divided into working groups on theory, minimization, atmospheric effects during propagation, and human response. A panel of experts in each of these areas led discussions on what had been done in each area, what needed to be done, and the prioritized research needed to meet the ultimate goal--supersonic overland flight. On the second day of the workshop, each working group reported its findings to the entire workshop and open discussions of the findings were held.

The following is a discussion of the areas covered in the overview paper, a description of the work being done by the Air Force, and a summary of each of the panel discussions held at the workshop. Significant recommendations or conclusions from the general discussions are also included.

SONIC BOOM PHYSICS AND MODELING

Pressure disturbances created by an airplane in flight travel in all directions at the local speed of sound. When the aircraft itself is flying faster than the speed of sound, it will advance faster than the disturbances it has generated and create a conical region which extends behind the aircraft nose and defines the entire region of disturbance at any given time. This conical region is shown schematically in figure 1. The intersection of this region with the ground defines a "footprint" of the pressure disturbances. Pressure signals felt within the footprint region normally display the characteristics illustrated in the pressure signature diagram shown in the left upper corner of figure 1.

Initially, there is an instantaneous rise in pressure caused by the shock from the aircraft nose. After the initial shock, the pressure declines linearly to a below-normal level. Then another shock occurs from the rear of the aircraft which restores the pressure to its normal value. These are the shocks heard by the ground observer. The level of Δp in the pressure signature indicates the loudness of the boom that will be heard. If the time between these two shocks is very short, the observer will hear only one boom, but as the time between the shocks increases, the observer is more likely to hear two booms in rapid succession. On the other hand, the degree of indoor disturbance or structural damage attributed to the pressure signature is believed to be more dependent on the impulse (the integral of the positive portion) and the length of the signature.

Referring again to the region of ground disturbance, notice that the loudest boom occurs on the ground track, and the signature gets longer and the boom gets weaker as the distance from the ground track of the aircraft increases. This region of pressure disturbance can be 60 miles to 70 miles wide, depending on the altitude and Mach number of the aircraft.

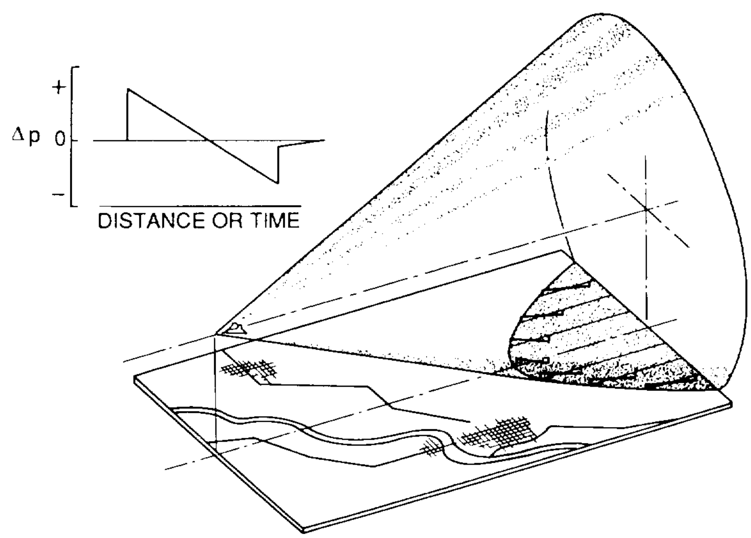

Figure 1.- Mach cone of pressure disturbances.

Predictions of the sonic boom levels caused by complex supersonic aircraft configurations are based on work done by Whitham (ref. 1), for axisymmetric supersonic projectiles, and by Walkden (ref. 2), who extended the theory to wing-body lifting configurations by representing these as bodies of revolution. The most widely used prediction methods today make use of the linearized theory and the supersonic area rule developed by Hayes (ref. 3). At large distances, the Mach fore cone can be treated as a plane in which all disturbances arrive at an observer simultaneously. Thus one can determine a linear distribution of singularities that produce the same pressure disturbances at large distances as those produced by the aircraft. This linear source-sink distribution can be related to an equivalent body area distribution made up of volume and lift contributions. The normal projections of area intercepted by the Mach-cutting planes define the equivalent body area due to volume as shown in figure 2, and the area due to lift is determined by integrating the lifting forces up to the Mach cut. The equivalent area distribution then defines the Whitham "F function" through the following relations:

$$F(x) = \frac{1}{2\pi} \int_0^x \frac{Ae''}{(x - t)} \, dt$$

This function represents the source and influence distribution which causes the same disturbances as the aircraft at large distances from the aircraft. A typical equivalent area distribution and F-function are shown in figure 2.

Because the pressure signal propagates at the local speed of sound, and each point of the signal advances according to its amplitude, the signal is

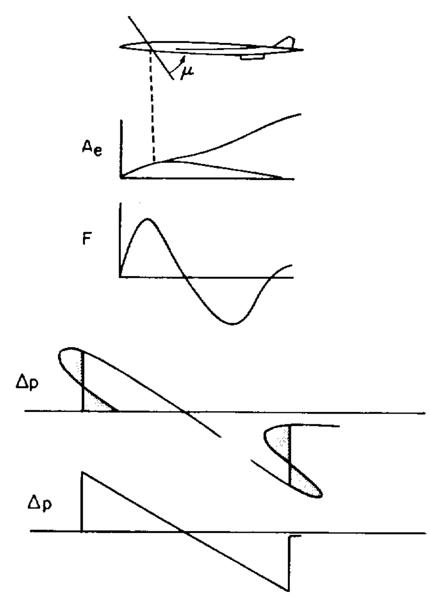

Figure 2.- Prediction methods.

distorted at the ground and theoretically could be multivalued. The physically unrealistic multiple values of pressure in the ground signal are eliminated by the introduction of shocks. Shock location is determined by a balance of the signature areas within loops on either side of the shocks, based on the observation that for weak disturbances the shock bisects the angle between two merging characteristic lines. This procedure is demonstrated by the shaded areas of the distorted signal in figure 2. For present-day supersonic aircraft, the distance of propagation and the pattern of shock coalescence has been such that only two shocks remain in the signature at ground level with a linear variation of pressure between them as seen in figure 3--thus the name "far-field N-wave" (ref. 4).

For the far-field N-wave, the shape of the generating aircraft has an effect on the magnitude but no effect on the shape of the resulting signature. Based on

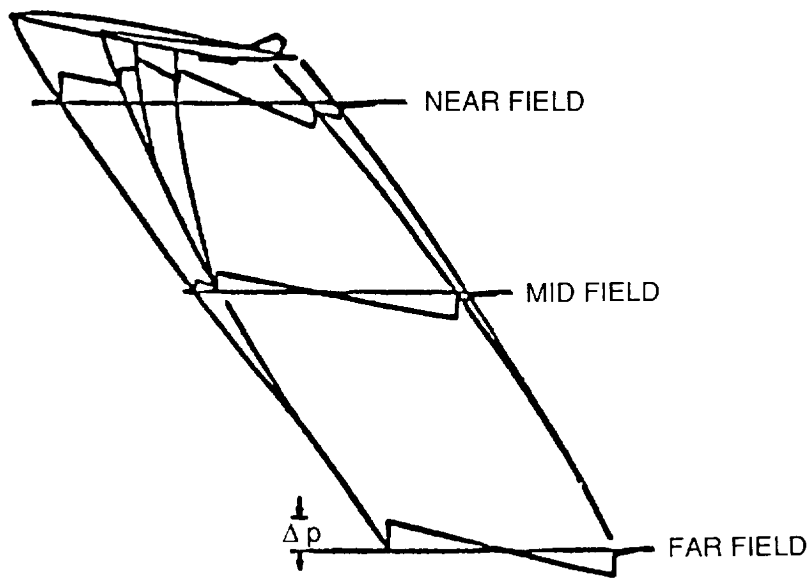

Figure 3.- Pressure signature propagation.

the assumption that all pressure signatures reaching the ground would have the characteristic N-wave form, Jones showed that the lower bound for the shocks occurred when the defining area distribution was extremely blunt and the corresponding F function was characterized by a Dirac delta function (an infinite impulse) at x = 0 (refs. 5 and 6). Shape changes required in current aircraft to produce such equivalent areas were found to result in great efficiency losses due to drag penalties (ref. 7).

It was observed by McLean (ref. 8) that attention should not be confined solely to the far-field signature, because during transonic acceleration the signature created by large and slender SST's might not necessarily attain their far-field N-wave form. During the mid-1960's, as more researchers began to look at ways of reducing boom levels, it was observed that even in cruise conditions a sufficiently long airplane could produce a signature which has not attained its N-wave form. Further along this avenue of thought, Hayes (ref. 9) pointed out that in the real atmosphere characteristics coalesce more slowly than in a uniform atmosphere, on which previous estimates of near-field characteristics were based, and the shape of the signature "freezes," thus increasing the possibility that midfield signature shapes may intersect the ground.

Because the shape of a midfield wave depends on the shape of the aircraft, such shaping was recognized as a much more powerful means of reducing the sonic boom than was previously believed. Seebass (ref. 10) and George (ref. 11), on extending the work of McLean and Jones, showed that the lower bounds for the bow shock of these midfield signatures also required the F-function to be characterized by a delta function at x = 0.

The form of the F-function for minimizing the bow shock strength in midfield signatures and the observation that the effective length available for bow shock minimization is reduced when the rear shock also is constrained led to the F-function deduced by George and Seebass in their minimization of the entire signature (refs. 12 and 13). That the F-function deduced by George and Seebass was the minimizing F-function was shown by Lung (ref. 14) using bang-bang control theory. The George and Seebass scheme, which placed constraints on both the bow and rear shocks and produced either the minimum shock or the minimum overpressure signature, was applied to propagation through an isothermal or real atmosphere. As with other minimization techniques, these minimum booms were found to be produced by F-functions characterized by a delta function or by effective area distributions having an infinite gradient at the nose. The design of aircraft to match exactly these area distributions generally results in nose shapes so blunt as to create substantial penalties. This result, seemingly paradoxical, can be explained by the created shock-attenuation pattern in which the shock strengths, and therefore the drag, are found to be greatest near the aircraft with no further shocks forming during the propagation of the wave, as illustrated in figure 4. The net result of this process is weaker shocks at large distances because of attenuation, but an overall increase in drag. In contrast, notice that the shocks are weaker and the drag is lower at the sharp-nosed aircraft, but the coalescence of shocks causes a much stronger shock at mid- and far-field distances.

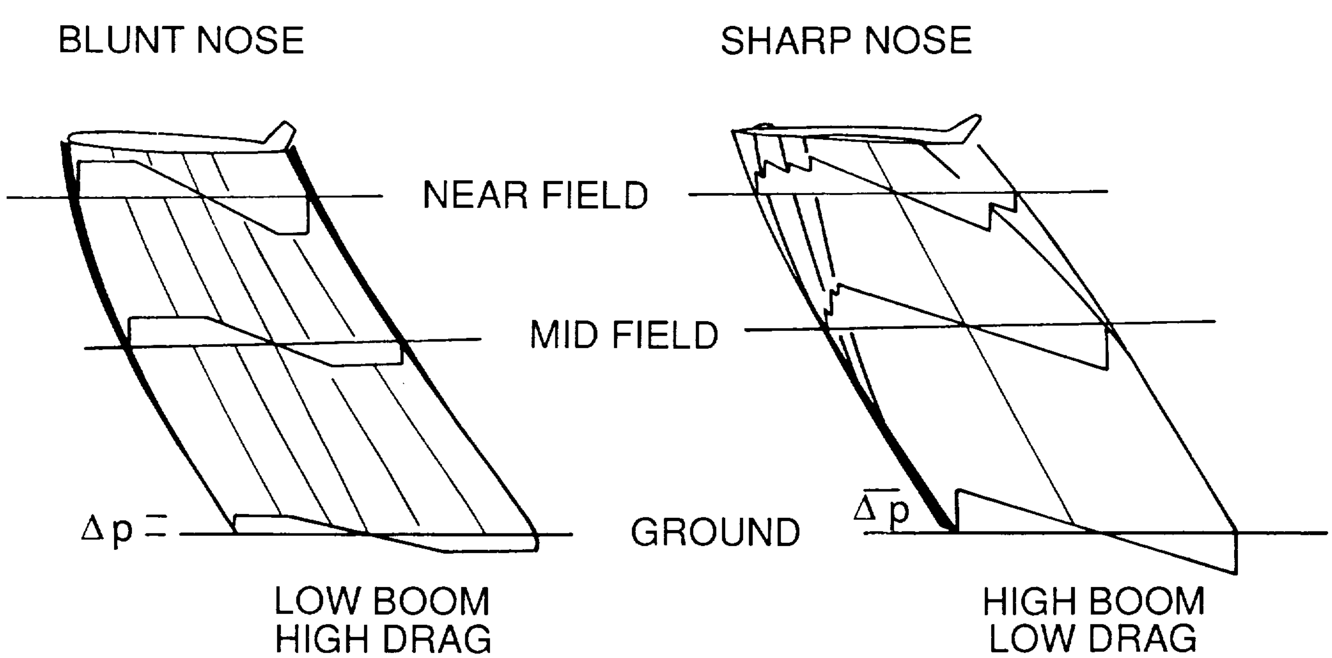

Figure 4. - The low boom - high drag paradox.

Current minimization capabilities are such that if the flight conditions of altitude and Mach number and the airplane parameters of weight and length are given, then the equivalent area distribution needed to create either a minimimum overpressure signature or a minimum shock signature can be defined as shown in figure 5. The question as to whether either of these signatures is the minimum, or "acceptable" in terms of human response, has yet to be answered.

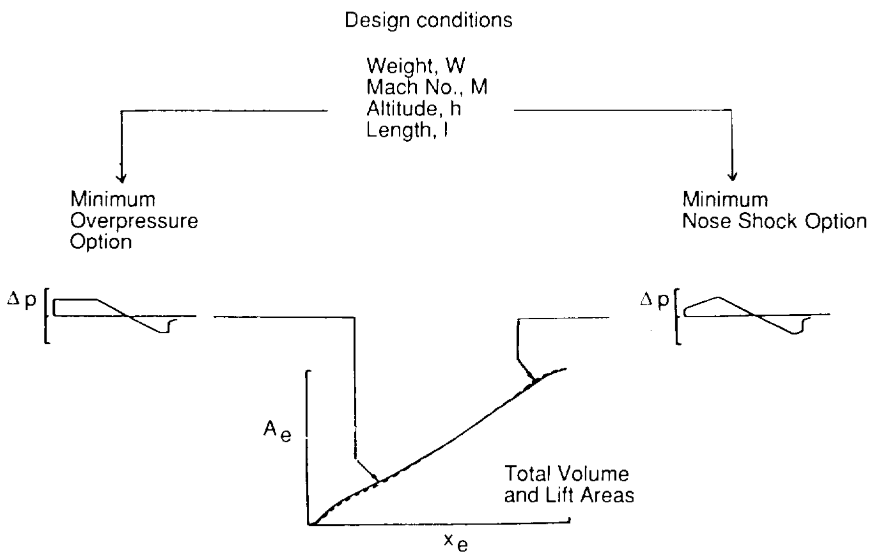

Figure 5.- Schematic of minimization process.

Other ideas for boomless supersonic flight have been pursued. One of these includes flight at Mach number and altitude combinations for which no sonic boom is observed on the ground--flight below the Mach cutoff. Typical Mach number and altitude pairs for Mach cutoff flight are seen in figure 6. Though no boom

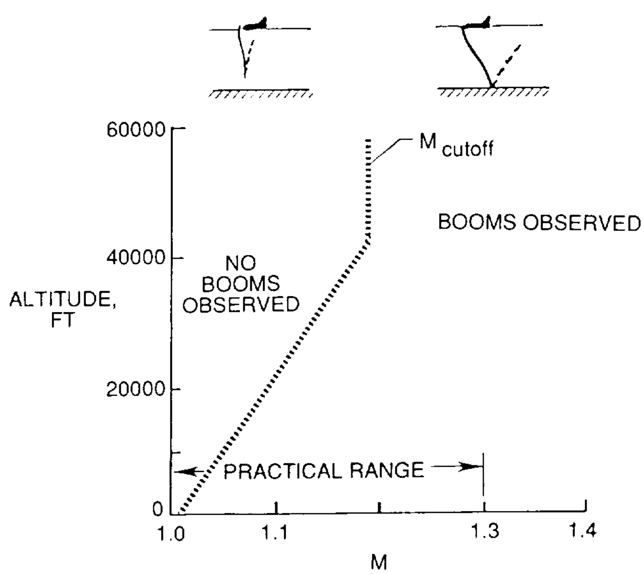

Figure 6.- Conditions for boomless flight.

intersects the ground when proper conditions are met, extreme sensitivity to turbulence and temperature variations can cause the proper conditions to change rather quickly. At Mach cutoff, rays from the sonic boom wavefront are reflected back into the atmosphere at some altitude above ground level. This point of reflection is a focused area of the sonic boom known as a caustic. Overpressure values are intensified by several orders of magnitude at a caustic. Failure to

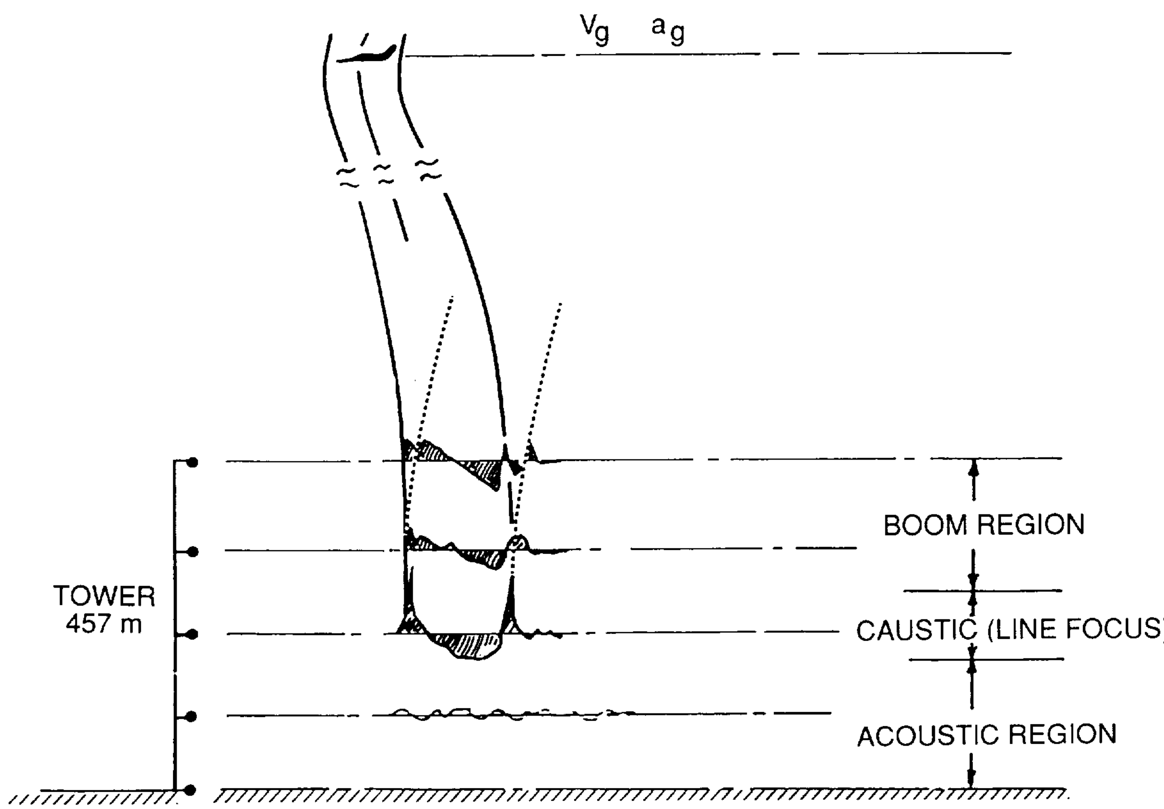

Figure 7.- Experimental measurements of Mach cutoff flight.

adjust flight conditions to atmospheric conditions could cause this caustic to intersect the ground. Figure 7 illustrates the caustic which occurs when an aircraft is flying supersonically, but below Mach cutoff.

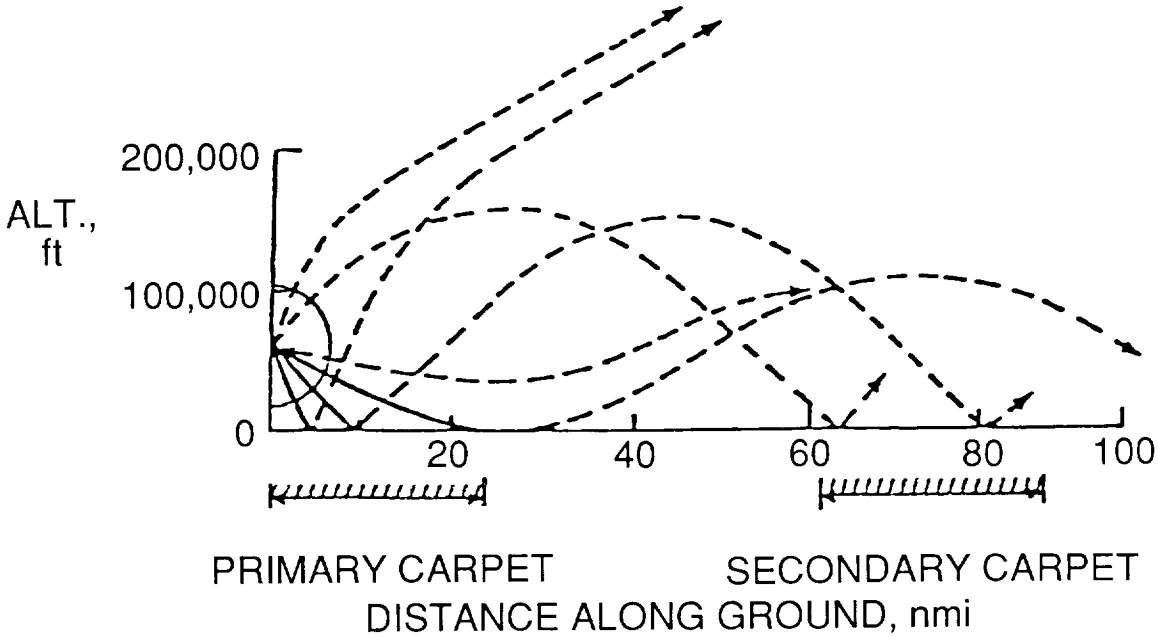

Figure 8.- Sonic boom ray paths.

Rays or pressure waves which travel directly from the aircraft to the ground without reflection determine the primary carpet of the sonic boom. Some rays intersect the ground after having been reflected either by the upper atmosphere, the ground, or both. The area in which these rays intersect the ground is known as the secondary sonic boom carpet. An illustration of the rays and the secondary carpet are shown in figures 8 and 9.

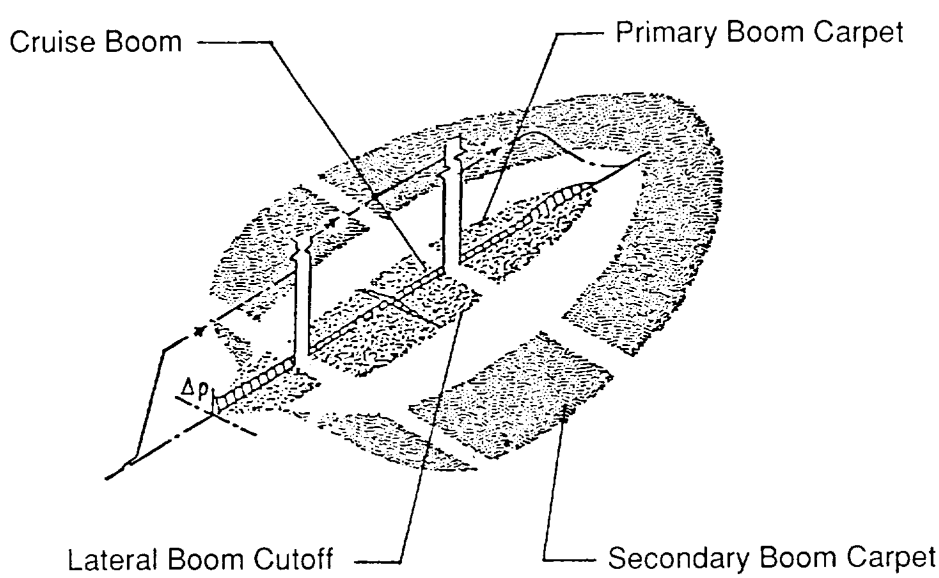

Figure 9.- Schematic of ground exposure carpets.

Extensive flight test measurements in the 1960's and 1970's have indicated that the atmosphere itself can have an effect on the shape of the resulting boom. Winds, temperature variations, and humidity cause turbulence and absorption effects which either round the leading shock of the pressure signature or cause the shock to become even more peaked. A statistical representation of the variations caused by atmospheric effects is shown in figure 10 for a number of flight tests. Note that most of these flight tests were at Mach numbers below 3.

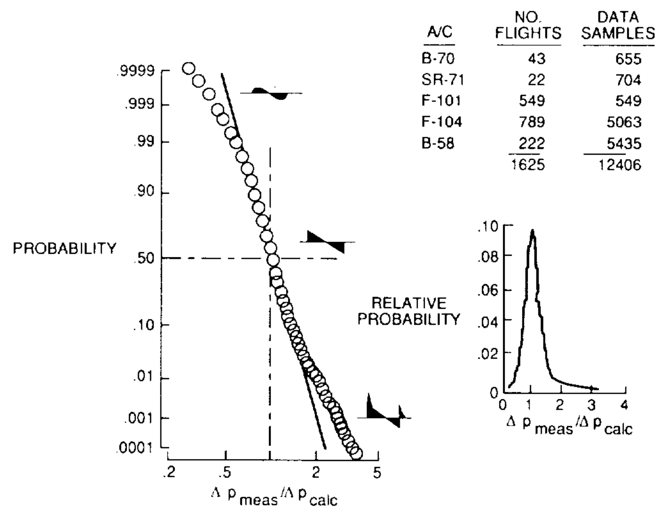

Figure 10.- Statistical representation of bow shock amplitude variability.

Most of the sonic boom flight tests made during the 1960's and 1970's were for airplanes which produced N-wave signatures with a bow shock in the range of 2 to 2.5 lb/ft^2 on the flight track. The off-track booms decreased from this level as the lateral distance increased. Most of the responses from people in the flight track indicated that levels of 2 to 2.5 lb/ft^2 were unacceptable. Limited responses from persons off of the flight track indicated that N-waves with a shock level of 1 lb/ft^2 may be acceptable. To develop Environmental Impact Statements for their aircraft test ranges, the Air Force has been involved for several years in a Noise and Sonic Boom Impact Technology (NSBIT) Program. This program has developed a new and improved sonic boom measurement instrument called the Boom Analyzer and Recorder (the BARE unit). Measurements with this unit compare favorably with measurement methods which were previously used and verified. Further, this unit is able to capture up to 50 complete sonic boom signatures over a period of about 10 days while unattended. The recorded data, which are in digital form, are then transferred directly to a personal computer.

Flight tests of current Air Force aircraft also were conducted as a part of the NSBIT Program in August 1987. These tests sought to verify existing prediction methods. These prediction methods are also being expanded to provide the capabilities of developing a contour map of ground sonic boom exposure. In addition, the Air Force is studying the effects of sonic booms on human morbidity and mortality rates.

SECTION I - THEORY

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In discussing the theory of sonic boom, the areas first considered were those for which it was felt that the theoretical methods were doing a satisfactory job. In the Mach number range from 1.2 to 3.0, the consensus was that linear theory methods are generally applicable. For a uniform atmosphere with level, unaccelerated flight, formulas may be used to transfer the signal to the ground. For a stratified atmosphere with the possibility of maneuvers, the ARAP code (ref. 15), its derivative, the TRAPS code (ref. 16), and the Thomas Extrapolation Code (ref. 17) all provide satisfactory predictions. In the 1.2 to 3.0 Mach number range, the limitations on the theory come from the limits on linearity.

Linear theory methods do not apply to regions where the flow is highly nonlinear. Such a region is the flow around the aircraft itself. For this region of the flow field, computational methods are needed for near-field calculations. These calculations must be matched with a ray-tracing calculation. References 18 through 21 provide ray-tracing methods which include nonlinear effects. Quantitative estimates are needed to determine when these nonlinear improvements are necessary and under what conditions they are not necessary.

At the higher Mach numbers, between 3 and 5, a strongly nonlinear solution for the aerodynamics of the airplane itself may be needed. This nonlinearity is a problem which may require specialized solutions to hyperbolic equations. These methods involve the three-dimensional method of characteristics with shock waves for higher Mach number ranges. Methods which are capable of calculating strongly nonlinear local flow about an aircraft to relatively high Mach numbers are being developed or are currently available. Computations made by nonlinear methods should be verified with an experimental program. These strongly nonlinear local calculation methods must extend into the acoustic field. In principle, it is also possible to use the three-dimensional method of characteristics to calculate throughout the atmosphere down to the ground. This effort is probably very inefficient; we should take advantage of the simplicities that most of the flow field offers, where acoustic approximations are appropriate. Matching the local nonlinear solution near the aircraft with a ray-tracing program may be a severe problem since the ray-tracing program could have some nonlinearity.

The third area where nonlinearity is important is that of caustics; this is especially true at the lower Mach numbers. The mathematical formulation for the behavior of the pressure signal at a caustic is given by Guiraud (ref. 22) and Hayes (ref. 23). Seebass developed the theory for describing the nonlinear acoustic behavior at a caustic in terms of a linearized equation (ref. 24). Further work on this procedure was done by Seebass and Gill (ref. 25). The solution based on this approach satisfies one of the two necessary boundary conditions, but not both at once. This analytical solution, which includes nonlinear and diffraction effects, was further developed by Plotkin and Cantril (ref. 26). The method was incorporated into the Thomas sonic boom extrapolation code by Plotkin and is called FOBOOM (ref. 27). This prediction method is included in the Air Force prediction program called BOOMAP2. While results of the FOBOOM method are in good agreement with experimental data taken at "Operation Jericho" (refs. 28 and 29), the exact solution of the governing equations for caustics does not exist and much work remains to be done in the area.

The fourth area where nonlinear theory is needed is less important than the caustic, but is still an area which needs to be considered--that of a cusped caustic, a super focus. Again, the linear theory for this problem is straightforward, but nonlinear theories do not yet exist. Cramer (ref. 30) produced the state-of-the-art analysis in this area, but it has not been applied numerically.

When sonic booms are calculated at an azimuthal angle other than at -90 degrees under the flight path, a rough approximation of cosine of the azimuthal angle often is used as a factor to correct the volume and lift contributions. For accuracy, the actual cuts for volume and lift at that azimuthal angle should be determined and the canonical procedure for predicting the sonic boom should be followed. Predictions and minimization calculations are most often done at an azimuthal angle of zero since boom levels are most often a maximum there. The lateral distribution of the boom should be accurately calculated, especially in minimization procedures when the flight track boom has been minimized and those off track may be larger.

If a signature maintains near-field effects and multiple shocks into a caustic, then the caustic solution must be able to handle these multiple shocks. The Seebass results apply to the single shock wave and in principle may be applicable independently to each shock wave in the signature. This assumption should be checked.

As previously stated, one computational method which is a nonlinear correction to ray theory currently exists. This method begins with the Whitham solution as the zeroth-order solution (refs. 19-21). The full nonlinear equations are rewritten as characteristic equations with the leading terms on the right side of the equation reproducing the Whitham theory in each step by integrating numerically. The right side then represents the correction to the Whitham theory. By taking this approach, 40 000 to 50 000 ft can be calculated in about 200 steps. The method requires matching input data from experimental measurements or from numerical flow field calculations. This computational method, called modified method of characteristics (MMOC), operates only in the plane of symmetry; it must be expanded to other planes for footprint-type calculations.

Ray-tracing or linear theory methods are only valid where the flow can be assumed to be locally axisymmetric, therefore the nonlinear codes like MMOC must be modified to calculate in all azimuthal directions. Flow field codes would have to calculate further radially than they do currently so they could match the ray-tracing codes. Otherwise, experimental data for extrapolating from the near field to the midfield would have to be obtained from tests of wind tunnel models in large tunnels.

It should be noted that where MMOC results have been compared with ARAP results for Mach numbers up to 5, the differences in the bow shock overpressure were found to be less than 10 percent. The major differences in the results of the two methods occur in the length of the signature and in the strength of the rear shock. If it becomes known that the bow shock of the signature was the most disturbing portion, then a ray-tracing program like ARAP or the Thomas Code could be used quite successfully in developing footprints. However, if some other parameter of the signature which depends on the length of the signature is found to be more disturbing, then more accurate methods like MMOC must be used. These more accurate methods must be modified to calculate in all azimuthal directions.

It was the general consensus of the group that the blunt body sonic boom prediction method, developed by Tiegermann (ref. 31) for hypersonic speeds, was probably not applicable to supersonic transport-type configurations.

Thus, in the area of theory, the group felt that two big questions need to be addressed: exactly what are the limits of the linear methods, and what parameter of the pressure signature best measures its disturbance level?

SECTION II - MINIMIZATION

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In the area of minimization, various speed regimes were considered. Within each speed regime, applicable sonic boom theory was evaluated since minimization is necessarily connected with the theory. The maturity and adequacy of the theory for far-field calculations, near-field calculations, and the nonlinear aerodynamics methods was assessed. A major consensus was that much more information was needed in terms of desirable signatures and criteria, including sensitivity to changes, before a definitive evaluation of minimization theory could be achieved. However, since signature and criteria were not available, an assessment was made with the available information.

At Mach 0.9 to Mach 1.15, in the transonic regime, there has been essentially no work on minimization. In this regime, calculations of the far field are satisfactory, but the near field is highly nonlinear with mixed flow regimes. This is the flight range of the cutoff Mach number--the speed at which no boom may hit the ground because the speed of sound on the ground is faster than the speed of sound at the flight altitude. The temperature gradient in the atmosphere which causes this difference, however, causes a refraction of the waves and thus a caustic is created at that refraction level. Turbulence, different local temperatures, and other factors cause the cutoff Mach number to vary. Extreme care must be used so the caustic surface does not inadvertently intersect the ground.

Most of the minimization work to date has been carried out in the Mach 1.15 to Mach 3.0 speed range. Linear theory methods for the near field and the far field are mature and accurate within this range. The problem areas for minimization in this speed regime include the modeling of the trailing edge of the body, the wakes, and the propulsion plumes. Within this speed regime, procedures exist for minimizing the impulse of a signature or for providing a finite-rise time signature based on work done by Hayes, et al (ref. 32) and Jones (ref. 5). George and Seebass (ref. 12 and 13) developed procedures which minimize the initial shock of the signature, both the front and the rear shocks, or the maximum overpressure. All of these methods are based on the same general idea even though scaling laws vary. Based on the flight conditions of weight, length, Mach number, and altitude and on the parameter which is to be minimized (initial shock or overpressure), the equivalent area distribution which provides that minimizing signature is produced.

The final Mach number range considered in the minimization discussions was that of Mach 3 to Mach 5. The assumptions utilized here were that in the far field the flow field remains primarily linear and that the theories in hand are sufficient. In the near field and in describing the aerodynamics, the flow field contains nonlinearities to the extent that numerical methods are required for solutions. These numerical methods should describe the flow field to a radial distance that is greater than those of current methods. Because of these nonlinearities, inverse methods which calculate from a ground signature in the far field to the responsible equivalent area distribution do not exist, are not unique, and would have to be accomplished by iteration.

As stated previously, all of the current minimization theories define the equivalent area distribution, which is made up of the Mach-sliced distribution of the defining aircraft volume and lift distributions. The process of going from the equivalent area distribution to an aircraft design is not unique and considerable latitude for the designer exists, but this is a very critical step in the design process. Some configurations will suffer such severe performance penalties that they will not be viable, while others may offer both acceptable sonic boom characteristics and efficient operation. More possibilities lie within the lower Mach range and at lower altitudes since characteristic signals from the aircraft have not coalesced into shocks and aircraft shaping has a stronger effect on the resultant signal.

To date, only one set of experiments has been performed on wing-body configurations designed to match a given equivalent area distribution for a minimum overpressure or "flat top" signature. Though the theory was essentially verified, no iterations on the design were performed. Some automation of the process of going from Mach-sliced area to an airplane component is needed since this process has been at best hit-and-miss and very cumbersome and time-consuming. The slope of the final area distribution needs to be matched because the results show great sensitivity to slight deviations in the slope.

To summarize, for a given airplane weight and length, at a given cruise Mach number somewhere between 1.15 and 3, and at a given altitude, current theories can predict the minimum shocks attainable if a minimum overpressure signature is the goal. Theories can also predict the minimum shock, minimum impulse, or other variations. The equivalent areas necessary to achieve these minimums are defined. Whether any of the above signatures are "acceptable" to the public is a question that minimization specialists cannot answer. Also, current theories do not allow a 250-ft, 700 000-lb airplane to be shaped to achieve a pressure signature with an initial shock of 0.7 lb/ft^2 at reasonable flight altitudes. Fundamental questions remain to be answered: what is the criteria for measuring the disturbance of a sonic boom, and what is an acceptable level of that metric? If and when those questions can be answered, then minimization theorists will attempt to define equivalent areas which produce those boom shapes.

SECTION III - ATMOSPHERIC EFFECTS

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Based on extensive flight tests and other research in the 1960's and 1970's, it is generally agreed that the atmosphere can have significant effects on the sonic boom signature. The atmosphere can alter a waveform shape by causing a more spiked pressure distribution, by causing a more rounded pressure distribution, by increasing the initial pressure rise time, or by adding precursors or extra cycles to the pressure distribution. Additionally, the atmosphere can redistribute boom signatures to various regions of the ground, such as the primary carpet of the signature, the secondary carpet, or the shadow zones between the carpets. The atmosphere can cause the formation of caustics, or as is sometimes believed, mitigate superbooms caused by acceleration. The atmosphere also can alter the frequency spectrum through frequency-dependent diffraction out of ray tubes and through nonlinear effects.

Speculations existed in the early 1970's that the sonic boom also could have a negative effect on the atmosphere and cause adverse environmental effects. A tentative theory suggested that the overpressure levels of a nominal sonic boom became extremely large at high altitudes because of the reduced density of air, and that the acoustic velocity was quite large. Researchers at the Naval Research Laboratory addressed the problem and determined that a mistake had been made in the previous calculations and that the effect of the factor specific heat times density on the amplitude had been neglected. When the error was corrected, the consensus of the scientific community was that sonic boom signatures had very little effect on the atmosphere.

Several concerns in the general area of atmospheric effects need additional research. For computer predictions to more accurately simulate actual occurrences, the atmosphere must be characterized fairly accurately for typical temperature, wind, and humidity profiles, and for turbulence models and scales. Advances in meteorology in recent years have improved some of these models, and the atmospheric measurements taken to very high altitudes near launch sights should be useful in improving the humidity models.

Many questions in regard to several critical regions of the ground sonic boom carpet remain unanswered, and additional research is needed. These critical regions include the edge of the primary carpet, the edge of the secondary carpet, the shadow zone between the carpets, and the secondary carpet itself. A limited number of experimental measurements have been made in the secondary carpet area, but a more systematic investigation of this region is needed. Knowledge of secondary sonic boom phenomena is important for overwater flights because of the need to determine how far offshore deceleration must begin. Although boom levels in the secondary carpet are usually much smaller than those in the primary carpet, they also should be considered in environmental impact assessments of tentative overland flight routes because they might cause adverse reactions in regions distant from the flight path. Ray-tracing programs must be used to comprehensively map the secondary carpet so the size and shape of the region can be better determined. Flight tests could be used to fill in areas with a paucity of information. Questions that need to be answered include: are secondary carpets located on all sides, and are they seasonal?

Existing theories suggest that the arriving low-frequency sound may have relatively high amplitudes near the inner edge of the secondary carpet. The amplitudes are very sensitive to atmospheric structure, and the possibility exists that the field at the edge is associated with a caustic. Computer predictions differ substantially when the atmospheric profiles of temperature and wind velocity are assumed to consist of piecewise straight lines with discontinuities in the height derivatives, as compared to predictions that use profiles described by continuously differentiable cubic splines. Some disagreement exists as to which approach more accurately models the atmosphere. This dissension is a further indication that more precise measurements are needed to determine atmospheric models.

In the real world, the shadow zone between carpet areas has been found to have sound where all theories predict that no sound is present. The unanswered questions are: how much sound is there, and exactly how does it get there?

A third area of research needing attention is the area of ground effects. Normally in sonic boom studies, researchers assume that the ground is perfectly rigid. In many cases this is a good approximation. If, however, the ground has finite impedance and the ray comes close to grazing, then the ground looks like it is perfectly soft--the acoustic pressure goes to zero instead of the normal velocity. When rays are curved and the grazing incidence is discussed, the ratio of the curvature of the wavelength to the curvature of the rays is important and the result is a frequency dependence and a possibility of ground effects. This outcome particularly affects waves at the edge of the primary carpet and in the shadow zone between the carpets. Another aspect of ground effects is that waves get carried into the shadow zone along the ground by two mechanisms - ground waves and surface waves (creeping waves). These additional ground effects also need more investigation.

A fourth area which needs investigation is the manner in which sonic boom waveforms are measured. A precise and relevant single parameter which describes a waveform is needed. Earlier measurements focused on factors such as positive phase duration, the time from onset of wave to peak, or possibly the highest value of overpressure. With current measurement techniques able to store entire waveforms in digital form, enough detail is available to make a more systematic study of waveforms possible. Some sort of descriptor, perhaps related to the physics and to the consequences of the sonic boom, may be possible. One example of a problem with past waveform description methods is the inability to distinguish between a waveform of high amplitude which has a very narrow spike and a waveform of high amplitude which has no spike but has a long-term pulse. In other instances, ambiguity exists in the definition of the rise time of a signature.

The relative importance of certain atmospheric effects on single parameter descriptors of the sonic boom signature needs to be studied. For example, what is the relative importance of turbulence, molecular relaxation or absorption, nonlinear steepening, and diffraction on the rise time and on the duration or the frequency content of the boom? All of these actions are occurring simultaneously. The effect of each needs to be studied so more accurate models may be developed.

Although knowledge of atmospheric absorption is more than 50 years old, knowledge about the exact mechanism of absorption continues to increase. There are two primary relaxation effects--one is associated with the O_2 vibrational relaxation and the other is the N_2 vibrational relaxation. For the sound that we normally hear from airplanes, the O_2 vibrational relaxation is most important. The N_2 vibrational relaxation can be important at the lower frequencies. The problem concerned with trying to predict relaxation time is its sensitivity to water vapor. Water vapor acts as a catalyst for transitions of atmospheric molecules from one vibrational state to another, thus the humidity of the atmosphere must be known very accurately. Studies done on cruise noise from an advanced turboprop found that, depending on the frequency, the peak absorption occurs at about 20 000 ft to 30 000 ft. Peak absorption is substantially greater at that altitude than on the ground or at higher altitudes. With recent measurements by meteorologists, especially around launch sites, enough data should exist to get fairly good models of the humidity trends in the atmosphere. At very high altitudes, humidity is less important because air becomes extremely dry.

Atmospheric absorption affects the rise time of the shock. The length and low frequency of the N-waves are such that they are not much affected except at the shock itself. As the shock weakens, atmospheric absorption becomes very important. Shock thickening which is attributed to absorption is associated with rise time increases of 1 ms to 10 ms. This increase corresponds to frequency ranges which are very important if response to boom is frequency dependent. Thus, the importance of accounting for the details of atmospheric absorption depends very much on the determination of the correct noise metric.

Some of the thickening and most of the variability occurring in signatures is thought to be caused by atmospheric turbulence. This effect reaches its maximum in the lower 3000 ft of the atmosphere. A more thorough investigation of turbulence models and of the correct turbulence scale is needed to improve the prediction methods. This investigation is especially important since most experimental data for sonic booms are waveforms which have already attained their N-wave shape, and the effect of turbulence on shapes of "minimized" waveforms is unknown and could be very different.

Another issue in the area of atmospheric effects is the degree to which high Mach number flight affects the variability of the waveforms. A large data base exists on turbulence-related variability, but this data base may not be applicable at the higher Mach numbers where path lengths are shorter. Is the use of models that assume the waveform to have reached an asymptotic form with certain invariant properties justifiable when the distance of propagation through the atmospheric boundary layer is comparatively short? How does turbulence affect magnification or focusing that occurs during maneuvers? What probabilities are associated with the occurrence of extremely large booms? These are all questions which need additional research.

Finally, new ways of conducting experiments on atmospheric effects should be developed. Flight testing is prohibitively expensive, therefore more ways of using laboratory facilities should be explored. Even if an experiment does not exactly simulate the real situation, it may provide information that would be helpful in understanding that situation. Very little is known about turbulence and shadow zones. Stratified-flow wind tunnels or turbulent low-speed tunnels could be used for experimental studies. Laser doppler anemometry has progressed significantly since sonic boom studies of 20 years ago, and its possible use in current experiments should be explored. Collimated sound beams could be used to study ray paths. Additional innovative designs for tests of transient sound may allow more control than was possible with previously used methods.

SECTION IV - HUMAN RESPONSE

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In the area of human response, a critical need is to identify the research required to quantify the pressure characteristics of a sonic boom signature that would be acceptable to the general population. The perception of sonic boom signatures is usually characterized in terms of loudness, annoyance effects and startle. Researchers believe that a high correlation between each of these parameters results primarily from sound energy in the audible frequency range. The perception of sonic boom signature also can result from vibration and vibration induced rattles caused by sound energy in the subaudible (infrasound) frequency range. Effects may accumulate where multiple booms occur. Temporal effects which depend on the time of day or night also may exist.

For the outdoor situation, the loudness of a boom can be predicted and, in general, the response in terms of annoyance and noisiness also can be predicted. Two different aspects of startle should be considered--the effect of startle on annoyance and the possibility that startle can cause accidents.

Past experimental results generally conclude that the shock levels or the high-frequency components of the pressure signature correlate best with outdoor disturbances and that the impulse of the signature and the low-frequency components correlate best with indoor disturbances. For given airplane configurations and flight conditions, minimization processes which reduce the shock level of the signature and outdoor disturbances tend to increase the impulse of the signature. Therefore, efforts to minimize both situations may be extremely difficult.

Previous experimental flight test studies of response to sonic boom have considered only the typical N-wave pressure signatures. In these studies, when the same sonic boom occurrence was measured both indoors and outdoors, the indoor loudness levels were much reduced as compared to the outdoor loudness levels, although the annoyance was about the same. This indoor level meant that about 20 dB in loudness was not explained by the loudness of the event for the indoor situation. Some researchers have called this special indoor disturbance factor the "rattle factor." The fact that the disturbance level was about the same both indoors and outdoors in the studies indicated that researchers could work with outdoor acceptance levels and the indoor levels would be acceptable. This trend would have to be reevaluated for minimized signatures since they could be very different from the typical N-wave.

Permissible levels of sonic booms may be established by some commission or agency of the government. Questions remain as to how these criteria will be set and what parameter of the signature will be used as a measure. It is generally felt that peak overpressure probably is not a sufficiently accurate indicator of human response and that some other noise metric which accounts for a number of characteristics of the pressure signature is necessary to accurately predict human response. In an attempt to get a measure of the signature which includes effects of rise time, shock level, impulse, maximum overpressure, and spikiness of signature, Johnson and Robinson (ref. 33) devised a response prediction method in which a Fourier transform is applied to the sonic boom signal. The resulting spectrum can then be converted into a noise level expressed in any of several metrics. Some uncertainty remains, however, as to which metric (loudness, perceived noise level, A-weighted sound pressure level, etc.) correlates best with human annoyance response. In using this method, the question of which theory of human response is most reliable still remains.

Researchers who have looked at the effects of the sonic boom on health report that the increased noise increases stress but results have not indicated adverse effects to the health or life expectancy of exposed individuals, especially for the levels which we would expect from overland high-speed civil transports.

The response of buildings to sonic booms also can be predicted well. Sonic booms which are acceptable to people will probably not damage buildings. Rare instances of damage in older, historic, or damaged buildings may occur. Buildings in good condition, newer buildings, and modern buildings which are constructed largely of glass have been designed to withstand loads which far exceed those caused by a typical sonic boom.

Most domestic animals do not appear to be bothered by sonic booms that are acceptable to humans. Studies have indicated that at moderate levels sonic booms most probably will have no adverse effects on wild animals.

The possibility of sonic boom-related avalanches or mudslides should be addressed when giving a full environmental impact statement; however, it is believed that this possibility is so unlikely that research in this area should not have the highest initial priority.

The primary research needs in the area of response are listed in figure 11. Sonic boom signatures, especially those which have been shaped for minimization, should be looked at in terms of loudness, annoyance and startle effects. Booms which are not symmetric should be examined. Responses to booms with and without infrasound and the effects of frequency or time-of-day should be studied. Long term epidemiological studies should address the effects on health, and some quantification should be given to damage to historic structures which may be expected.

- HUMAN RESPONSE
  - — LOUDNESS, ANNOYANCE, AND STARTLE
  - — INFRASOUND, CUMULATIVE, AND TEMPORAL EFFECTS
  - — INDOOR/OUTDOOR EFFECTS ON IMPACT MINIMIZED BOOMS
  - — HEALTH—EPIDEMIOLOGICAL STUDIES, SLEEP DISTURBANCE
- STRUCTURAL RESPONSE
  - — DAMAGE TO UNCONVENTIONAL/HISTORIC STRUCTURES
- DEVELOPMENT OF ACCEPTABILITY CRITERIA
  - — HUMAN RESPONSE
  - — STRUCTURAL DAMAGE
  - — POLITICS AND ECONOMICS

Figure 11. - Research needs.

The highest priority should be given to quantifying the outdoor/indoor response to shaped sonic boom signatures and to quantifying the annoyance of sonic booms. The suggested approach for quantifying these areas of human response are outlined in figure 12.

* LOUDNESS/NOISINESS — LABORATORY COMPARISON OF N-WAVE AND SHAPED BOOMS
* INFRASOUND EFFECTS — LABORATORY COMPARISON OF BOOMS WITH AND WITHOUT SUBAUDIBLE FREQUENCY COMPONENTS
* VIBROACOUSTIC EFFECTS — IN-HOME ACOUSTIC AND VIBRATION REPRODUCTION AND RESPONSE QUESTIONNAIRE

Figure 12. - Research approach.

Laboratory studies using sonic boom simulator booths can be conducted to examine the relative loudness and noisiness of the signatures of N-wave and shaped sonic booms. A comparison of study results using similar acoustic signals, with and without the subaudible frequency components, and of studies with and without the frequency-induced vibration and rattle can provide insight into infrasound effects. The relationship of loudness as noisiness to true annoyance can be examined in studies which simulate sonic boom acoustic and vibration signatures in people's homes. These in-house studies can also be useful in determining other noise exposure effects, such as number of sonic booms per day and time-of-day of sonic booms.

Although not included in the research approach outlined in figure 12, a preliminary study should be conducted to determine the benefits and feasibility of a social survey of responses to the relatively infrequent sonic booms which occur in some parts of the country. Such a survey would require extensive preparation and noise measurements to insure any statistical validity of results correlating annoyance or acceptability to sonic boom exposure. The benefits and feasibility preliminary study may well contraindicate the desirability to conduct a new sonic boom community survey.

RESEARCH NEEDS

In summary, at Mach numbers above 3, a great deal of work must be done in all areas of sonic boom research. Nonlinear effects become very important and therefore methods for predicting the cruise boom which are based on modified linear theory may not be adequate. Existing minimization methods are based on the prediction theories and also are not directly applicable at the higher Mach numbers.

Caustics are generally formed during the acceleration/climb portion of a flight at low supersonic Mach numbers. Approximate solutions to the caustic problem do exist and are being used as research tools, however work to solve the caustic exactly must continue.

Questions remain about atmospheric effects, the secondary boom and aerodynamic tailoring for minimization at all Mach numbers. A large body of experimental sonic boom measurements exist at moderate Mach numbers and statistical tables on the variability to an N-wave caused by the atmosphere exist. Even at these Mach numbers a better understanding of the "cause and effect" relationship between individual atmospheric phenomena and their effect on the parameters of the sonic boom signature is needed. Whether atmospheric effects on shaped sonic boom signatures result in variabilities similar to those for N-waves is a question that needs to be answered. At higher Mach numbers, where ray paths through the atmosphere are shorter, virtually no experimental data exists.

A more careful mapping of the secondary carpet of a sonic boom is needed as is a better understanding of exactly what happens at the edges of both the primary and secondary carpets.

Initial tests on wing-body models indicate that current minimization theories are valid at moderate Mach numbers. Whether these theories can be used as a fundamental constraint in the design process and a viable configuration can be developed are fundamental questions that need to be addressed at all Mach numbers.

Finally, the need to address the area of human response is most important. The process of defining the metric of the sonic boom and the approach to setting criteria for acceptability are questions that must be answered and answered soon.

RESEARCH PRIORITIES

Participants in the workshop agreed that the following research priorities should be addressed concurrently and as soon as possible. Efforts should begin immediately in three areas: (1) establishing the criteria for an acceptable waveform; (2) designing a viable aircraft to an existing shaped waveform; and (3) quantifying the atmospheric effects on "shaped waveforms". Answers to whether an acceptable waveform exists, whether an aircraft can be designed to that waveform, and whether the atmosphere will destroy the benefits of that waveform will be needed very early in any studies to develop overland high-speed civil transports.

CONCLUDING REMARKS

This report summarizes the results of a sonic boom workshop held at Langley Research Center on January 19-20, 1988. The purpose of the workshop was to assess the state of the art in sonic boom knowledge and prediction capability and to prioritize research efforts needed in the immediate future. The consensus of the 60 national sonic boom experts who attended was that concurrent efforts in the areas of establishing human acceptability criteria, minimizing sonic boom through design tailoring and operations, and quantifying the effect of the atmosphere on shaped booms should begin immediately.

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16. Abstract

In January 1988, approximately 60 representatives of industry, academia, government, and the military gathered at NASA Langley Research Center for a 2-day Sonic Boom Workshop on the state of the art of sonic boom physics, methodology, and understanding. The purposes of the workshop were to determine areas where additional sonic boom research is needed and to establish some strategies and priorities in this sonic boom research. Attendees included many internationally recognized sonic boom experts who had been very active in the Supersonic Transport (SST) and Supersonic Cruise Aircraft Research Programs of the 1960's and 1970's. Summaries of the assessed needs in theory, minimization, atmospheric effects during propagation, and human response are given.

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