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STATUS REPORT

COMMITTEE ON SST-SONIC BOOM

NATIONAL ACADEMY OF SCIENCES

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INTRODUCTION

In May 1964, acting on the advice of the President's Advisory Committee on the Supersonic Transport, President Johnson requested the National Academy of Sciences to provide guidance on an expanded program for studying the sonic boom and the effects that would result from operation of a supersonic transport. Accordingly, Dr. Frederick Seitz, President of the Academy, established the Committee on SST-Sonic Boom under the chairmanship of Dean John R. Dunning, School of Engineering and Applied Science, Columbia University.

The Committee itself has formed special panels in several areas in order to provide expert knowledge in all the areas that are involved. Thus, a panel of architects, engineers, those with experience in the use of explosives and those with knowledge of major structural materials has examined the area of structural response. Similarly, an insurance panel, composed of the major airline underwriters, has examined the projected effect on airline insurance costs from operation of supersonic aircraft, and a small group of behavioral scientists have looked at problems of public response.

The National Academy of Sciences has also utilized established units within the Academy in problem areas important to sonic boom considerations. Arrangements have been made with the Building Research Advisory Board and the Committee on Hearing and Bio-Acoustics to provide advisory services on the structural and material effects and the physiological effects, respectively. Each of these groups has examined the sonic boom question and has submitted the results of their examinations to the Committee on SST-Sonic Boom for inclusion in this report.

The Committee on SST-Sonic Boom has three immediate goals (1) the development of advice on the planning and analysis of sonic boom tests, (2) examination and analysis of available data on the sonic boom for the purpose of assisting in determining the feasibility of SST operations, and (3) the preparation of recommendations covering the direction and emphasis on research pertaining to the sonic boom problem.

The Committee first met in July 1964 and has been meeting at approximately four week intervals since then. It has been briefed on sonic boom tests, such as at Oklahoma City, and on Air Force and NASA research on the mathematics involved in calculating sonic boom characteristics and their relation to aircraft design and performance. The Boeing, Lockheed,

General Electric, and Pratt and Whitney companies have made presentations to the Committee, and the work conducted by the Department of Commerce on the economics of the supersonic transport was described and discussed at a Committee meeting.

The Committee has recognized four major problem areas which it is using as the major sub-divisions of this report:

1. Generation and propagation of shock waves - the aeronautical aspects of the problem.

2. Effects of the sonic boom on structures and structural material.

3. Physiological effects of the sonic boom.

4. Behavioral response to the sonic boom.

Supporting this report are the following:

1. THE GENERATION AND PROPAGATION OF SONIC BOOM SHOCK WAVES prepared by Herbert A. Hutchinson, Wright-Patterson Air Force Base.

2. ANATOMICAL AND PHYSIOLOGICAL EFFECTS OF IMPULSIVE PRESSURES IN AIR AND THEIR PROBABLE RELATIONS TO SONIC BOOMS prepared by D. H. Eldredge, Central Institute for the Deaf, and Henning E. von Gierke, Wright-Patterson Air Force Base; and the members of an ad hoc Committee of the Committee on Hearing, Bio-Acoustics, and Biomechanics.

3. LONG-RANGE STRUCTURAL RESPONSE RESEARCH AND TESTING PROGRAM, Interim Reports 1, 2, and 3, prepared by an ad hoc Committee on Structural Response to SST-Sonic Boom of the Building Research Advisory Board, National Academy of Sciences. The members of this ad hoc Committee are as follows: John A. Robertson (Chairman), United States Gypsum Company; Russell B. Akin, E. I. DuPont de Nemours & Company, Inc.; F. J. Crandell, Liberty Mutual Insurance Company; Ben H. Evans, American Institute of Architects; John P. Gnaedinger, Soil Testing Services, Inc.; J. D. Gwyn, Libby Owens Ford Glass Company; James R. Simpson, Federal Housing Administration;

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STATUS REPORT

COMMITTEE ON SST-SONIC BOOM

SUMMARY CONCLUSIONS

1. It can be stated with confidence that at the sonic boom intensities anticipated for the SST, there will be no signficant direct physiological effects on people.

2. The structural response to sonic booms from aircraft the size of the SST is not yet known. Moreover there is evidence that overpressure alone is not a reliable criterion and that the total impulse under the positive portion of the pressure-time signature (pounds per square foot times seconds) may be more meaningful. Research to identify fully the significant parameters and to relate them to effects is required. If the impulse, rather than overpressure, is the critical parameter, then, depending on the dynamic response of structures, the best current knowledge indicates that sonic booms with total impulses as high as 1.5 pound seconds/ft^2 will not cause damage or failure of framing members of structures. Impulses as low as 0.06 pound seconds/ft^2 may cause some damage to brittle materials such as glass, plaster, gypsum board, paint, and bric-a-brac. The frequency and severity of damage may increase as the impulse increases, until damage becomes pronounced at impulses of the order of 0.6 pound seconds/ft^2 as generated by F-104 and B-58 aircraft.

3. The introduction of a supersonic transport of currently assumed characteristics will involve significant risk of adverse public reaction. This can be expected to increase as exposure to the boom increases and particularly if it disturbs sleep. Public reaction and the basic question of acceptability of the sonic boom can only be settled with certainty by subjecting the population to the actual operation of supersonic overflights.

4. The extent of minor claims for real or imagined damage is very difficult to predict and it is probable that no research or test program can provide adequate data for

estimating the amounts involved. There is urgent need for the government to establish uniform policies and procedures for the handling of damage claims.

5. Research on effects of booms on animate and inanimate objects must continue, with special effort on obtaining information that will bridge the gap in knowledge between booms generated by the relatively small aircraft that have been tested and those from the SST. SST design decisions are needed and can only be obtained by placing more emphasis on B-70 test flights accompanied by adequate measurement of sonic boom signatures.

6. Any construction of an SST within the competitive future implies commitment to the state of the art, i.e., direct extension of existing experience which offer hope of only slight lessening of the boom. Recent encouraging evidence of progress by NASA in research on the generation and propagation of sonic booms emphasizes the need for intensive, continued effort in that area and on principles of aircraft design for reducing or making more acceptable the effects of sonic booms.

7. Much more vigorous long range research effort needs to be directed toward the development of principles by which appreciable alleviation of the boom can be achieved. Such research is within the capability of present day science and technology and should be carried out both in-house and through outside contracts. Research directed to the development of highly imaginative future means of supersonic transport should be encouraged and financially supported.

8. Moving into the next phase of SST development is clearly warranted by the evidence from research, tests, and studies of sonic boom phenomena. While no difficulties sufficiently cogent to stop the program have been disclosed, and while many aspects of the sonic boom are reasonably well understood, there are some aspects where much more information is needed.

GENERATION AND PROPAGATION OF SONIC BOOMS
THE AERONAUTICAL ASPECTS OF THE SONIC BOOM PROBLEM

The aeronautical aspects of the sonic boom problem is understood to mean the influence of the airplane parameter on the boom phenomenon and, conversely, the influence of boom requirements or limitations on the airplane design and its economic potentialities. With this in mind, answers have been formulated to the following specific questions:

1. Is the present state of the knowledge such that the essential characteristics of the sonic-boom phenomenon can be reliably predicted for a certain airplane configuration?

2. Is the state of the art of supersonic airplane design such that the economic consequences of limitation in intensity of the sonic boom can be reliably assessed?

Since the initiation of the work of the Committee, the large amount of background material which is available for formulating the answers to these questions has been reviewed. Needless to say, this work has been helped effectively by the presentations to the Committee and by the review work of the staff. Needless to say, also, that final and exhaustive answers to these questions cannot yet be made.

State of Knowledge

The gas-dynamic equations of motion, even for idealized conditions of a still atmosphere and simplified properties of air, are complicated and do not generally permit surveyable solutions except for certain restricted circumstances. That, in spite of these difficulties, the phenomena of the sonic boom and the more complicated theory of design of supersonic airplanes have reached a satisfactory agreement between theory and experiment is a tribute to the imagination and resourcefulness of the leaders of this field over the last decades. Certain specific developments may be mentioned to illustrate these advances. The perturbation theory in which the velocity field, besides a uniform velocity in the direction of flight, has superposed upon it another field of small velocity components, is one of the important devices whereby the equations may be rendered linear. This, in turn, depends on the

fortunate circumstance that the change of entropy across a shock can be neglected to a high order of accuracy for weak shocks. The presence of shock waves, even waves of the strength encountered in a sonic-boom phenomenon, may thus be taken into account with the aid of relatively simple theory of isentropic changes.

Over the years since the 1930's, this had led to a theory of lift and drag for airplane structures which has provided a rational basis for the design of airplanes, reaching from subsonic to the hypersonic speed regimes.

In the present context the influence upon this theory of the understanding of the sonic-boom phenomenon is most relevant. In the gross picture the discontinuities and changes in sections of the airplane, together with its lifting surfaces as it moves through the still air, generate a system of shock waves (resembling the bow and stern waves of ships) which reaches out as a conical sheet with the airplane at its apex. The intersection of this sheet with the surface of the earth as it moves with the flight velocity produces the sonic-boom phenomenon. At some distance from the airplane the phenomenon generally takes the form of the characteristic N wave. The forward portion of the disturbance is a rapid compression - a shock wave; this is followed by a more gradual expansion, and then there is a second shock wave. The wave length, the distance between the two shocks, is related (as in surface ships) to the length of the airplane; but since the waves are not exactly parallel, the wave length is greater than the length of the airplane.

The shapes, positions, and strengths of the two shock waves at the ground, even in still air, actually depend on the detailed geometry of the airplane, for the waves are modified by every detail of the pattern of velocities around the body and wings. In principle, this detailed field could be computed for any given configuration, but the computation would be tedious, and fortunately it is not usually needed. In the hands of G. B. Whitham a practical solution became possible by virtue of his intuitive insight; following M. J. Lighthill he postulated that the disturbances calculated for an idealized Mach line will hold to a close approximation when transferred to the actual Mach line, whose position can also be established by an approximate method. It is this theory, rationalized through the extensive work by many specialists in NASA and in several of the airplane companies, that now forms the basis for prediction of the wave form and intensity of the sonic boom. It accounts for the shock waves

produced by both the lifting elements (wings) of the aircraft and its volume elements (body, nacelles, etc.). For aircraft at higher altitude, the part due to lift becomes the more important.

An important feature of this theory has recently been pointed out by engineers of NASA's Langley Laboratories; namely, that the rate of approach of the disturbance pattern to this "far-field" configuration is remarkably slow for large airplanes like the SST, especially at climb speeds. Thus the Whitham-Lighthill theory in its far-field approximation, which predicts a rather simple N-wave at the ground and is insensitive to details of the airplane's geometry, is not always applicable for the SST in the climb condition. The significance of this discovery is that the sonic-boom signature in this case can be favorably affected by details of airplane geometry. NASA personnel believe that, in some cases, alleviation of ground overpressures by as much as 50% in the climb might be accomplished with little or no increase of drag and overpressure at cruising speed. Unfortunately, there does not appear to be an analogous possibility of alleviation at higher speeds, since ground level is definitely in the far-field in this case. Moreover, as explained elsewhere in this report, there is evidence that overpressure alone is not a reliable criterion for the structural-damage potential of the sonic boom and that the total impulse under the positive portion of the pressure-time signature may be more meaningful. It must be recognized that these modifications of the near-field signature can probably not reduce the integrated impulse appreciably. Thus if our conjecture about the importance of impulse is confirmed, the alleviation in the near field is likely to be illusory.

It is no reflection on the great achievements of this theory to emphasize its limitations. As described above it pertains to an aircraft in steady flight in an idealized atmosphere, at rest with respect to the earth, and having known pressure and temperature variations with altitude only. The effects of headwinds and tailwinds and their gradients can also be calculated to a good approximation. This theory has been confirmed by a number of experiments, both in wind tunnels and in flight. Needless to say, flight tests are not carried out under the idealized conditions envisioned by the theory, for the atmosphere and its winds are typically nonuniform. Quite apart from this complication, it is necessary to keep in mind the great difficulties of experimentation. Meaningful results can only be obtained if the observer or the instrumentation is accurately located with respect to the

flight path. Fully reliable experimental results require that not only the pressure amplitude but also the shape of the impulse be recorded by sensitive and rapidly responding transducers.

In spite of these difficulties it is generally believed that the present theory essentially accounts for the sonic-boom phenomenon due to aircraft in steady flight in still air and in somewhat more realistic, but still idealized, models of the atmosphere. This contention cannot be proven with absolute certainty, because, as already mentioned, there are no such idealized atmospheric circumstances. When an attempt is made to make full allowance for all the variables of atmospheric influences, the theory becomes very complicated, although solutions may still be possible by means of extensive computer programs if necessary. We are doubtful that extensive calculations of this kind would be meaningful. They could hardly be useful as verifications of the theory, for the detailed, transient structure of the atmosphere in which flight tests are carried out is never recorded. And as soon as we depart from standardized, non-turbulent models of the atmosphere (such as the ICAO standard atmosphere and the corresponding warm- and cold-day models) we are confronted with the absence of either accepted standards or statistical data of general significance.

This situation requires that experiments of sonic-boom phenomenon be interpreted statistically. The experimental series now available indicate that sonic-boom results appear as distribution curves of probabilities, the spread from predicted values apparently depending upon the degree of departure from the ideal atmosphere during the period of the test. Hence, if a sonic-boom overpressure of 2 lb/ft^2 is predicted by the available theory, the experimental results will indicate a spread, so that there will be a few observations up to 3 or 4 lb/ft^2. There will probably be statistical spread of overpressures in actual operations because of the focusing effects of accelerations and flight-path curvatures.

This conclusion makes it evident that the operation of a future SST will subject structures and people in the path of its shock waves to disturbances which can only be predicted by a combination of the gas-dynamic theory described above and statistical corrections. The most probable intensities can be predicted with accuracy, but the form of the distribution curve is still open to conjecture and can only be established by extensive experiments and measurements with supersonic airplanes. The analysis of existing test programs

and the results of future test series will do much to firm up the estimate of the form of this distribution curve. It is thus necessary to recognize that limitations in the sonic boom can never be absolute; there will always be a small probability of more intensive shocks. As long as this must be the case, it is important that all estimates of public reaction to sonic booms be made with full appreciation of this situation.

It may also be important to point out that we do not know just what aspects of the sonic-boom phenomenon, e.g., what properties of the pressure-time signature, are in fact most important in determining annoyance to humans (or other animals), so that it may be rash to say that any gas-dynamic theory is adequate in this area. It seems possible that details of the signature (such as, perhaps, its oscillatory content in a certain frequency range) that are almost wholly outside the scope of the still-air theory are signficant in determining what people and animals "hear" as a boom passes. It is important that this be kept in mind in the planning of future experiments.

Influence Upon Airplane Design

Limitations of sonic-boom intensity have presented the designers of the supersonic transport with a variety of problems that require insight into the entire array of components of the whole airplane system. The influence upon the requirements of the propulsion system turns out to be the most important.

Practically speaking, reductions in the overpressure on the ground during cruising can only be effected by increases in the flight altitude. Roughly, each $\frac{1}{4}$ lb/ft^2 involves an increase in altitude of about 10,000 ft. At the higher altitudes the airplane must fly with a higher angle of attack or at higher speeds; the resulting increase in drag requires more thrust from the engines.

The greatest overpressure usually occurs during the period of acceleration into the supersonic speed. The flight path must be such as to produce this maximum of boom intensity at sufficiently high altitude. But this period of acceleration through sonic speed is typically critical for the aircraft because of the great magnitude of transonic drag. The requirement for transonic acceleration at higher altitude clashes head-on with the fact that

turbojet-engine thrust diminishes with increasing altitude; thus sonic-boom limitations demand over-dimensioning of the engines, with attendant increases of aircraft size and weight. At this point abnormal circumstances of the atmosphere enter the problem in their most severe form. If the temperature of the atmosphere is higher than normal, the propulsion system may not be adequate for this acceleration, and under these conditions the limits in overpressure may be exceeded. The only safeguard against such a contingency is to over-dimension the engine still further.

One of the important consequences of the sonic-boom limitation, therefore, is in its effect on the sizing of the engines. The relationships are exceedingly sensitive and present a typical example of a critical design problem, where an injudicious choice may lead to absurd consequences. The situation is best described by a curve submitted to us by Boeing Aircraft Company which is reproduced from the paper by Kane and Sigalla (Figure 1). This shows that if a base point is established for an overpressure of 3 lb/ft^2 during climb, the engine size for an overpressure of 2 lb/ft^2 would have to be increased by about 10%. The gross weight of the plane would then be increased by about 5%. However, if the limit in overpressure were to be set at 1-3/4 lb/ft^2, engine size and gross weight would increase many-fold, and the economic characteristics of the airplane would be badly, perhaps catastrophically, compromised. A related study made by Lockheed California Company has led to the curves of Figure 2. Here the ordinate is annual earnings (before taxes and interest) per aircraft; the study was made for a series of Mach 3.0 supersonic transports of 213 seats. The results are typical and are much the same as those presented to the Committee by spokesmen of the Boeing Company. They show that limitations imposed on permissible sonic-boom overpressure in the climb (calculated for steady flight in still air) can seriously reduce the earning capacity of the aircraft in domestic operation. Moreover, in international operation, where trip lengths are longer, the deleterious effect of sonic-boom limitations is more striking and occurs at larger values of the calculated overpressure. It should be emphasized that these effects on earning capacity were calculated by a simulation scheme for transport operations involving flights of various lengths, i.e., they have been averaged over a variety of trip lengths typical of domestic and international airline operations, respectively. In actual fact the effect of severe sonic-boom limitations can be more drastic in some operations. For example, limitation of calculated climb sonic boom overpressure to less than 2.0 pounds per square foot can make it

FIGURE 1

DESIGN PENALTIES

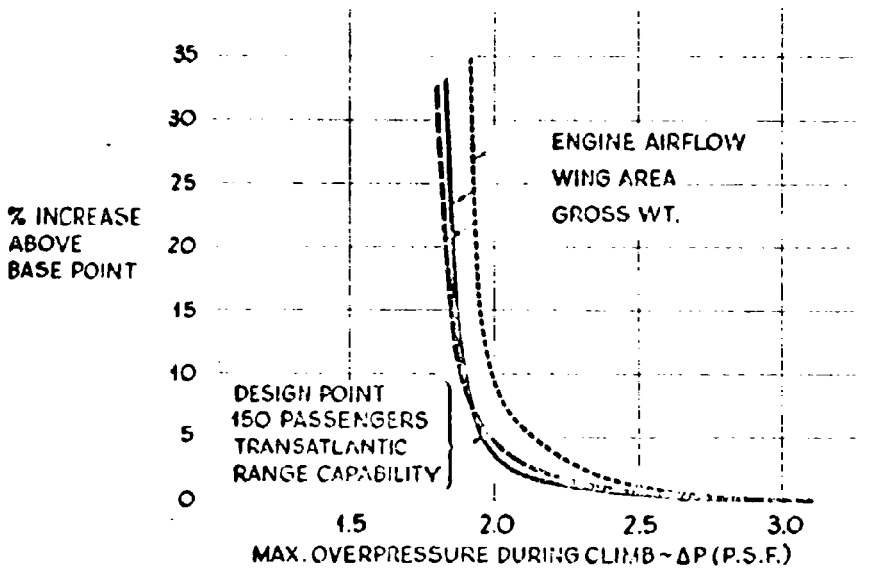
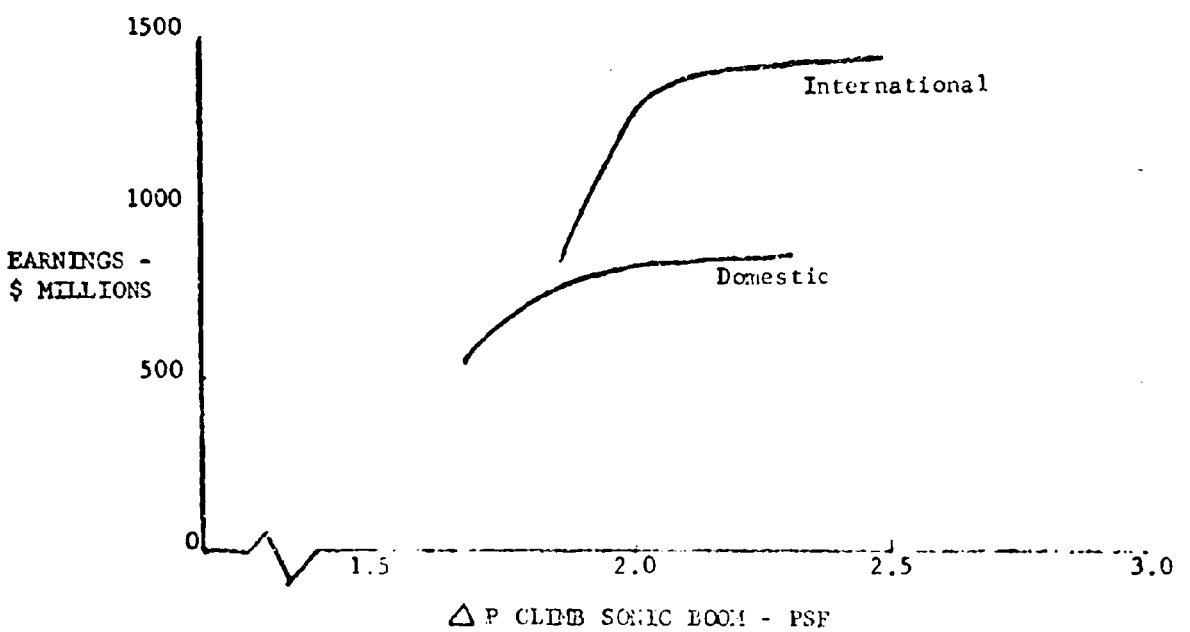


FIGURE 2

EARNINGS AND RETURN ON INVESTMENT
VS SONIC BOOM OVERPRESSURE



impossible for certain aircraft to carry out the New York-to-Paris operation; this might render the aircraft totally unacceptable for transatlantic use, effectively reducing its earning power to zero, as far as some airlines are concerned.

This sensitivity of airplane efficiency and economy to sonic-boom limitations is the outstanding aspect of the whole problem. When these conclusions are viewed against the uncertainties introduced through turbulence and wind and velocity gradients and our uncertainties as to exactly what features of the phenomenon are responsible for damage to structures and for annoyance and discomfort to people and animals, the need for additional information becomes apparent.

Research Needs

It has been emphasized in the preceding paragraphs that the sonic boom phenomenon arises from well-understood behavior of a compressible fluid under the influence of any projectile or conventional airplane moving through it at a supersonic speed. Thus, at the present writing, there appears little hope of eliminating this phenomenon, or even alleviating its effects drastically, within the scope of present concepts of supersonic airplanes propelled by turbojet engines. This does not mean that drastic improvements cannot be achieved in the future by means that are presently unknown, but rather that they will probably be achieved by some far-reaching new concepts of propulsion and/or sustentation of supersonic flight. But such future developments will require research; imaginative minds must be brought to bear on the underlying physical phenomena, and basic studies must be followed by ingenious inventions.

In the meantime, there are more immediate possibilities of alleviation of sonic booms if supersonic flight can be carried out at higher altitudes. This has been pointed out above, and the great difficulties involved have been mentioned. Still, it appears to be the only solution within sight at present. It therefore seems desirable to ask the aeronautical industry (and NASA) to give immediate consideration to methods of achieving higher altitudes; as has been stated above, this is primarily a propulsion problem. To date, studies of thrust augmentation by use of rockets or other devices have not appeared economically attractive. Recent developments on ramjets, however, should be seriously considered; it is not clear to the committee that the economic possibilities of all possible composite-powered aircraft have been studied.

Conclusions

1. The state of knowledge appears sufficient to predict with considerable accuracy the sonic-boom phenomena for steady flight in still air or in various idealized atmosphere models involving head- and tail-wind gradients as well as temperature variations.

2. The state of the art of airplane design is therefore capable of developing the consequences of sonic-boom limitations that are specified in terms of the pressure-time signature on the ground under these conditions.

3. Sonic-boom limitations must be made with expectation of a certain statistical spread and will eventually have to cover a predictable probability of a range of intensities.

4. The principal sources of statistical spread in intensity are believed to be deviations of the aircraft from straight, steady flight and atmospheric phenomena, particularly turbulence, but including also other complex departures of the real atmosphere from the idealized models mentioned above.

5. It is imperative that further information be obtained concerning the significance of various features of pressure-time signatures in determining structural damage and annoyance to people and animals. Until such information is available, neither theoretical predictions of boom intensities nor statistical empirical information can be intelligently evaluated.

STRUCTURAL RESPONSE

Since publication of the Committee's status report dated 27 January 1965, preliminary summary reports on the FAA Oklahoma City and White Sands test programs have been made available to the Committee. These reports tend to confirm the Committee's previously stated position that there is not sufficient correlated information to constitute a barrier to a decision to proceed with SST development, although this lack of information prevents firm answers to the structural response question. These reports, together with other pertinent sources of information, have been studied in depth by a committee of the Building Research Advisory Board which was established at the request of the Committee. The Third Interim Report of that committee is attached.

State of Knowledge

The full-scale investigations of structural response in Oklahoma City and White Sands, as well as data from both earlier and more recent tests, have produced results of value to a long-term effort to resolve the structural response issue. Agreement achieved in these tests between predicted and free-field recorded sonic boom pressure/time signatures has substantiated the theoretical method of predicting the far-field signature resulting from constant velocity, level flight of fighter-type aircraft and of aircraft as large as the B-58. The more recent efforts by NASA to record the signatures from flights of the B-70 have been partly successful, and the Committee is informed that recordings thus far obtained tend to substantiate further the method of signature prediction for steady speed, level flights of larger aircraft. Thus, it is felt that the nominal pressure/time signature that will be generated in the far-field by a given configuration of SST in high altitude cruise can be predicted with confidence. Moreover, based on recent NASA testimony, it is felt that the nominal pressure/time signature that will be generated in the near-field by an SST in steady speed, level flight can also be predicted with fair accuracy. Still to be substantiated, however, is the prediction of variations in normal signatures that may result from various aircraft altitude-, speed-, and maneuver-changes.

The foregoing synopsis indicates confidence in predicting the generation and propogation of the nominal sonic boom shock

wave. From a structural response viewpoint wherein the shock wave constitutes a dynamic loading on the building or structure and its elements, however, the level of confidence in predicting the actual loading on the structure is appreciably lower because there can be statistically significant variations in both the form and amplitude of recorded sonic boom signatures. If these variations are, as suspected, attributable principally to micrometerorological variations in the atmosphere, topographical differences at the recording site, and reflections from nearby buildings, or to faulty instrumentation, it still remains to be ascertained statistically the acutal maximum loading to be expected for predicted nominal pressure/time signatures.

Prior to delivery of the report of the BRAB special committee, an extended discussion of the nature of building response to the sonic boom would be gratuitous. It appears, however, that both the Oklahoma City and White Sands test programs have clearly identified those structural elements that could possibly sustain damage from the sonic boom shock wave generated from supersonic flights of present day aircraft. Both of these programs have demonstrated that building or structural failure -- i.e., impairment of the integrity of the structural system -- can be eliminated as a possibility in any discussion of the response of buildings to the sonic boom.

In the main, the building items found to be susceptible to damage are glass, the cracking and crack-extending of plaster, and nail-popping in gypsum board. There was, however, a disparity between the results reported in the two programs regarding thresholds of damage for these materials which may be significant enough to mention. For example, at Oklahoma City damage in the form of plaster cracking and nail popping in existing structures at the 1.5 to 2.5 psf overpressure level was reported, whereas at White Sands, no boom damage was reported below 5 psf except for paint flecking at 2 psf.

Both the Oklahoma City and the White Sands tests related the effects of sonic booms to overpressure levels. The Committee believes, however, that it maybe the impulse rather than the overpressure that is the critical factor in the response of structural materials and is concerned that a satisfactory correlation between damage and impulse level has not been established. If the critical factor in causing damage to structural elements is the impulse characteristic, then there is a serious question about the effect of sonic booms from aircraft of the size contemplated for the SST, e.g., one with

a time signature about 5 times as long as that of a fighter -- since the peak overpressure from the large aircraft would have to be correspondingly reduced.

Conclusions

In the interim since this Committee's January 1965 report, no new information has been furnished this Committee which requires modification of its previously stated position that the structural response question poses no barrier to a decision to proceed with step-wise development of the SST.

The difference that might be expected in the response by structural material to booms from fighter type aircraft and the SST, the need for positively establishing that another parameter rather than peak overpressure is the critical and limiting factor, and the effect on SST design criteria that is thereby implied, make it urgent that research and test programs give maximum emphasis to providing essential data on booms from aircraft more nearly SST size.

By repeating some of the thoughts expressed in the Committee's January report, we seek to emphasize the fact that some boom damage to structures can and will be caused and some will be claimed, at least as long as the audible sound of the boom resembles that of an explosion. Whether the claims will be justifiable will have to be determined by courts. If boom-pressure or impulse levels are as large as those which struck Oklahoma City, poorly-installed or marginal-thickness glass windows, even in new construction, may break when booms strike. Poorly supported bric-a-brac will tumble from vibrating shelves as buildings shake. Prestressed, brittle construction materials such as plaster, tile, concrete, and glass will sometimes crack or break when subjected to the additional loading of a sonic boom.

Recommendations

It is to be noted that many of the structural response/dynamic loading unknowns are not peculiar to the resolution of the sonic boom structural response question. For example, the development of dynamic loading-response theory, the definition of urban environmental conditions, and the estimate of future building inventories all have an importance that goes beyond the SST problem. Accordingly, investigation of such items should not be undertaken by a single agency, but should be

undertaken by as broad a base of government agency - private industry - academic institution as can be brought to bear on these problems.

Pending receipt of the forthcoming report from the Building Research Advisory Board, which will contain specific recommendations for future research, this Committee currently makes but two structure-related recommendations. Others will follow, after study of the BRAB report.

(1) Development of one or more techniques for simulating low-intensity, sonic-boom-like pulse loadings of building components should be undertaken;

(2) Whenever opportunities are available for obtaining more sonic-boom pressure-versus-time signatures, particularly from large aircraft, these data should be taken to improve the statistical information now in hand, to learn more about reflectances in urban areas, and to confirm theory regarding booms from aircraft involved in altitude- and speed-change maneuvers.

PHYSIOLOGICAL EFFECTS

Sonic booms of intensities of 5 lb/ft^2 may be anticipated as the maximum that might be produced by SST planes in normal operation. Such booms will not cause direct injury to the normal human body. This conclusion is based on experience with explosions, including atomic bomb tests, with artillery fire, and with very powerful sonic booms produced in low-level flights. The margin of safety is very wide indeed. Dozens of individuals have been exposed to sonic boom overpressures from 35 up to 120 lb/ft^2 with no worse effect than momentary discomfort and slight temporary ringing and a sense of "fullness" in the ears.

The ear is the body structure most sensitive to and most easily injured by sudden changes in air pressure, whether produced by explosions, sonic booms or sustained noise. Possible injuries are rupture of the drum membrane and partial impairment of hearing. The margin of safety is so great, however, in regard to overpressure, that direct injuries from a single sonic boom must be considered incredible. The sonic boom is in a different class from sustained noise because of its extreme brevity. Its frequency of occurrence would be so low that cumulative effects on hearing can also be dismissed as negligible. There remains only the marginal possibility of an ill effect in an ear in which an artificial stapes has been placed surgically to restore hearing in otosclerosis. Such an artificial stapes might possibly be dislodged. The hazard should be no greater, however, than from minor blows or from jerks of the head.

Indirect or "Trigger" Effects

Sonic booms come without warning and are therefore more startling than most other varieties of intruding noises. Familiarity with sonic booms and the knowledge that they are to be expected more or less regularly greatly reduce the startle effect but do not eliminate it entirely. Startle reactions can certainly precipitate accidents and injuries. Plausible types of such accidents would include slipping on a ladder, an automobile collision due to distraction of a driver's attention, a surgeon's knife slipping, and so on. Rather less plausible would be the precipitation of a heart attack, a stroke or other sudden medical misfortune. Such events will sometimes occur at the very moment of a sonic boom and the claim will be made that the boom was the cause, although the probability of an actual causal relation is extremely small.

Disturbance of Sleep

Disturbance of sleep, particularly the sleep of invalids, must be reckoned as a significant medical problem. The effects of repeated disturbance of sleep may be cumulative, particularly when emotional factors become involved. The "normal threshold" for disturbance of sleep by such sounds has not been determined, but certainly the intrusion of sonic booms into quiet hospital areas where patients are being deliberately sheltered from the stresses of daily living would not be desirable.

The arousal effect in sleep can be evaluated in physiological experiments which simulate booms. Such experiments would usefully supplement but not replace the exposure of a community to night booms.

PSYCHOLOGICAL RESPONSE

It is generally accepted that the psychological response area is the most difficult of all sonic boom problems and contains the most elusive questions. There is little doubt that the more we can learn from tests and studies about the effects of the boom on people and animals, the better we can define and meet the problems. This is true in spite of the difficulty of devising tests that can measure psychological response in a meaningful manner, and that will reflect the chronic characteristics of booms which the population would actually face with operational SST's. It should, however, be recognized that the only way to obtain answers to many of the questions is through continuing, actual, full-scale experience with the SST or comparable airplanes.

There have been determined efforts to obtain data on psychological response through such tests as those at St. Louis in 1962, and at Oklahoma City in 1964, but the test of the effect on a population of continuing night booms is still in the planning stage, and no conclusive evidence on the effects of sonic booms on animals. This section of the Committee's interim report is given under four headings (1) Public Acceptability; (2) Psychoacoustic Effects; (3) Legal and Insurance Aspects; and (4) Public Relations.

Public Acceptability of the Sonic Boom

Public reaction to a new experience will be determined by the properties of the new stimulus, the situation into which it is introduced, and the characteristics of the public.

Present Status of Knowledge. The principal available information on the acceptability of the sonic boom by the public comes from the Oklahoma City tests of 1964, and, to a much smaller degree, from the 1962 tests in St. Louis. Reports on both were prepared by the National Opinion Research Center, University of Chicago. The Oklahoma City test report was much more complete and detailed and therefore constitutes the primary source of information today on public reaction.

It is the consensus that the NORC study "Community Reaction to Sonic Booms", based on the Oklahoma City tests of 1964, is professionally competent and free of bias, even with its

major, though temporary, exclusion from the analysis of the 29% of the sample who indicated a belief that it was improper to complain. The full report, to be available this summer, will include the views of this group.

The studies of the Public Reaction to Sonic Boom appear to have been satisfactorily conducted as far as they have gone. They do not show overwhelming and aggressive negative reactions nor do they show clear cut or adequate acceptance of the annoyance. It is clearly unwise for the authorities concerned to overlook or neglect the possibly troublesome problems that could arise from supersonic overflights of commercial airlines.

It is probably impossible to designate a specific overpressure level which leads to adverse public reaction which could be called "serious" or "intolerable". However, there is a range of overpressures below which the boom is tolerable, and above which the boom is intolerable. Even at the relatively low level of intensities and frequency of exposure and at the limited times of day of the Oklahoma City tests, the extent of public annoyance was large enough to provide the basis of a significant level of protest if some important organization or public body undertook to mobilize it. This is not only suggested by the findings of the study but also by the actual course of events in Oklahoma City, where organized attempts to call off the boom tests were made.

It is clear from the study results that even though the average intensity of the booms did not exceed 1.6 psf, the Oklahoma City population was very much aware of them. The evidence demonstrates that the intensity of public reaction varies with the intensity of the boom, at least within the limits of this test. It also suggests, as does the earlier St. Louis experience, that public annoyance tends to cumulate over time, even among those people whose basic attitudes toward the SST are favorable. The findings of the St. Louis study also indicate that the public would find it much harder to accept night booms than those in the daytime. This dimension was not explored in the Oklahoma City study.

It cannot be said that the findings of the Oklahoma City study are especially surprising. They conform generally to the results of the earlier St. Louis study although the reaction in Oklahoma City based on a much greater public exposure, seems some what stronger than that in St. Louis. One cannot be surprised to find that the introduction of frequent sonic booms in the life of a community produces a

certain amount of complaint. Since, as yet, the sonic boom has not been shown to have effects much more damaging or annoying than other nuisances to which people in our society normally submit, it represents no absolute barrier to a program of developing the SST. On the other hand, the boom may be a sufficient barrier, if other considerations (mainly economic, prestige, and military) are not overriding. We are in no position to say what the significance of the boom annoyance phenomenon as studied to date is, because its significance depends on its relative importance.

A slight increase in overpressure or in the number of booms per day does not simply cause a slight increase in public aversion and in the number of complaints. More signficantly, it increases the risk of an effective public protest, perhaps of a political character. The trigger for such a protest might well be some irrelevant accident or coincidence or the emergence of an aroused leader of hostile public opinion.

Regardless of any studies made, or contemplated, in advance of introducing the SST, thought must be given to the possible need for a large-scale program of public education and the development of favorable public relations.

The NORC study indicates that public inconvenience would be both wide-spread and real; there is little basis for confidence in the ability of a public relations campaign to banish this inconvenience. The house rattling, involuntary startle, interruption of conversation, and loud sound are not mere matters of opinion; they are not due to ignorance or misinformation. They will not be dispelled by propaganda or education. An "education" campaign might induce people to accept the inconveniences in behalf of overriding national interest, but propaganda claiming commercial SST to be in the national interest might boomerang, because it could not be supported by evidence convincing to the public. The extent of the annoyance observed, particularly since it is concentrated in the higher income and educational levels of the community and tends to increase over extended periods of exposure, is disturbing. It leads us to the conclusion that the introduction of a supersonic transport of currently assumed characteristics involves significant hazards in the realm of public reaction.*

Future Testing. In examining the need for and type of sonic boom testing that should next be undertaken to investigate public reaction, it should be clearly understood that, although important information on why and how people react can be

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* It should be emphasized that this conclusion applies only to the super-sonic portion of the flights of the SST over land. For instance, use of SST's on the North Atlantic runs would be quite free from public acceptance problems caused by sonic booms.

obtained, no test can produce a usable, single standard for determining with certainty whether the US public will accept, for an indefinite number of years, the sonic booms from scheduled airlines. Regardless of how much study and research is carried out, the question "is the sonic boom acceptable?" can only be finally settled by subjecting the US to the actual full scale, permanent experience of supersonic overflights on a continuing basis. However, tests, when properly done, can undoubtedly give us a probable prediction of whether the boom will be acceptable and, if unacceptable, the ways in which the public will react. Such information seems essential in launching anything so grand in scale as the development of the SST.

Questions on public reaction that can probably be answered, and where answers will be useful, are on such subjects as:

(1) the relative acceptability of booms from military and booms from commercial aircraft;

(2) how AF procedures concerning payment of damage claims can be reconciled with test results regarding the effect of booms on glass, fresh plaster, etc.;

(3) how to avoid the exorbitant costs of investigation; and

(4) the need for and feasibility of educating the public on relationship of sonic boom intensities to the probability of physical and psysiological damage and of educating people to the difference between direct and indirect damage.

The next test should be predominantly a test of public reaction, with tests of structural damage, etc., considered secondary and conducted only to meet the needs for information related to that problem. The major purpose of any new test should be to obtain information on sleep disturbance, with such secondary objectives as:

(1) determining more about patterns or paths of protest; and

(2) obtaining information on the importance to the public of having a US SST, in terms of competition with Europe and USSR, balance of

payments, industry bolstering, need to move people faster, possibly military usefulness, and the like.

More specific views include:

(1) The next test should be of indefinite and undisclosed length, but long enough to get data on how well people adapt to sleep disturbance. It should take place during seasons when windows are closed, when they are usually open, and when the boom can be related to claps of thunder.

(2) Overflights should not be precisely scheduled and might come in groups (4-6) over a half hour period during the interval between midnight and 6 a.m.

(3) There is advantage in keeping to the Oklahoma City/NORC pattern of testing where possible in order to accentuate continuity of the over-all test program.

(4) The largest aircraft available should be used.

(5) Quite apart from tests of a community, the acoustic data from high fidelity recordings of the audible (100-10,000 cps) portion of the boom produced by a large aircraft are still urgently needed. These data will be used in certain immediate laboratory studies that can employ simulated booms.

Questions of what city to test are not yet answered, although there are advantages in having it a small to medium one.

The contractor is not being proposed; it should be emphaized, however, that NORC should not be excluded from consideration.

Psychoacoustic Effects

Psychological Acceptability. The psychological acceptability of sonic booms is difficult to assess. It is certainly increased by familiarity with booms, by the knowledge of their source and significance and by the knowledge that they are harmless. Booms are transient and do not interrupt conversations and radio programs like the noise of jet-plane flyovers. Frequency of occurence and the time of day at which they occur will undoubtedly be very important factors. Complaints of young children being awakened from sleep must be

anticipated. People will vary greatly in their psychological reactions. Some will certainly come to take booms for granted and accept the mild startle that they may feel. Others will become progressively more irritated by the booms, particularly if the booms are felt as well as heard or cause windows to rattle. People who dislike sonic booms may be more easily and profoundly disturbed than the average.

Some very scanty data suggest that booms with a nominal overpressure of about 2 lb/ft^2 are about equally annoying as the level of jet noise that is considered just allowable near airports. Further tests of this relation should be made. It should be possible to do this by simulation studies, but in preparation for effective simulation studies, whether on men or on structures, a considerable number of booms, produced by a large plane such as the B-70, must be recorded by proper techniques, both outdoors and also inside of a variety of typical buildings.

In order to make a rough estimate of the level of overpressure at which booms are likely to become unacceptable a series of psychoacoustic experiments is urged. A jury of observers would be asked to compare the "acceptability" or the "annoyance" of alternate sonic booms and subsonic jet-plane fly-overs. A broad guideline as to public reaction to sonic booms may be established in this way. Unfortunately, however, these comparisons cannot include the element of surprise which probably contributes greatly to the annoyance of the sonic boom. Also a systematic study of the disturbance of sleep is planned, and perhaps of the intensity of startle reactions. But even with these data the practical psychological effects will be hard to assess, and they become less easy to predict as we pass from the average individual to the unusual individual and finally to the group behavior of many individuals in a community.

Future Research

It is recommended that

1. Some experiments on psychoacoustics can and should be done in existing laboratories immediately. Adequate methods for simulating the sonic booms are available, and, although simulation may not be perfect, information obtained in the experiments will

be useful in planning future laboratory and field experiments. Investigations that can be started immediately include

a) The effects of simulated sonic booms on sleep as measured both by the EEG (electroencephalogram) and behavioral indices. Both the effects of the auditory stimulus and of structure-borne vibrations can be studied.

b) Laboratory experiments can also be done in which subjects judge the comparative annoyance of simulated sonic booms with other sounds such as noise produced by jet planes. In these experiments it will be possible, for example, to experimentally change the shape of the N-wave and note any obvious changes in the judgments of annoyance.

2. Consideration be given to Wright-Patterson AFB or NASA's Research Center for the conduct of this research. Both have good facilities and equipment but would need staff augmentation. In addition, Stanford Research Institute may acquire a capability for such research.

3. Additional recordings be made of the sonic boom. While it is agreed that the boom can be simulated well enough to start experiments immediately, there is a difference of opinion as to whether available recordings contain information that is necessary to reproduce effectively and accurately that part of the sonic boom in the frequency range that most affects the human auditory system.

Legal and Insurance Aspects

The problem of noise has always been present in the field of aviation -- principally noise at airports. The problem will be aggravated by the SST, not alone at the airports but throughout its line of supersonic flight, and particularly under its acceleration-climb path.

It may be expected that the inauguration of supersonic flights by commercial aircraft will give rise to claims for damage to property alleged to be due to sonic booms. In the light of the experience of the Department of Defense it also may be expected that many such claims will be for pre-existing

damage and will be prompted by irritation arising out of exposure to the unaccustomed sound of sonic booms. This is not to imply that there will be a great many claims deliberately falsified. Rather such cases occur most frequently where a person, annoyed by booms to which he is not (and may never become) injured, closely examines glass and plaster in his abode and for the first time observes cracks which had previously been ignored. Air Force experience with claims is illustrated by the following table.

FISCAL YEAR	CLAIMS MADE	AMOUNT CLAIMED	CLAIMS APPROVED	AMOUNT APPROVED
1956	36	$ 12,220.03	21	$ 1,913.71
1957	372	157,100.45	286	18,907.85
1958	522	196,215.66	235	39,519.06
1959*	632	285,182.30	243	21,355.98
1960	681	107,767.94	227	20,263.22
1961	1,146	703,174.65	527	57,274.44
1962	3,092**	990,483.35**	1,451	132,370.25
1963	7,200	4,022,718.00	2,268	239,450.00
1964***	5,102	3,544,754.99	1,664	182,543.71
	18,783	$10,019,617.37	6,922	$713,598.22

NOTE:

* B-58A FIRST FLIGHTS IN NOVEMBER 1958
** ONE CLAIM FOR $19,000,000.00 NOT INCLUDED
*** THROUGH 30 JUNE. DOES NOT INCLUDE OKLAHOMA CITY TEST CLAIMS.

Also a report of a USAF - NASA - FAA 1961-1962 flight test program states that, in the range of overpressures from 0.04 to 2.3 psf, a maximum of 0.87 damage incidents per flight per million population occurred, and that the settlement value was $71 per claim ($57.57 per flight per million population). The Committee notes that the majority of these claims apparently were without merit, and that, despite a too liberal attitude toward damage claims, less than 10% of the total amount claimed was actually paid out.

Especially in the early stages of supersonic flying it will be necessary to investigate carefully all claims for alleged damage even though the great majority of such claims presumably

will be for relatively small amounts and the costs of investigation probably will appear to be disproportionate to the losses actually incurred. Ultimately, when and if the general public has become used to the sound of supersonic flying, claims might be confined to an occasional extraordinary boom, perhaps arising out of abnormal maneuvering of the airplane.

It appears appropriate to call attention to a discrepency which may have significant influence on the number of future claims for structural damage caused by sonic booms. This is the difference in judicative procedures followed by two U.S. governmental groups relative to small claims for sonic-boom damage. As our Committee understands the situation, the FAA procedure, at least during and following tests, has been to have all claimed damage inspected by professional engineers prior to any agreement for settlement; whereas the Air Force pays minor claims without inspection. Thus while one government agency (FAA) is attempting to proclaim that low-overpressure booms do not cause damage, another (USAF) is indicating through its actions that they do. To continue these two opposing attitudes will certainly confuse the public, which does not distinguish between governmental agencies involved with aviation. Professional investigations of minor claims may initially be more costly than payments; but for the continuous operations anticipated for the SST, a policy of paying all minor claims could be ruinous.

The special problems the airlines must face with the operation of the SST emphasize the need for a technique or formula for the original setting of rates for insurance to protect airlines against damage and other claims. As experience is gained, the major problem may become one of reducing the cost of handling claims.

Public Response

If the SST were to be put into commercial use in the United States today, those affected directly might be expected to express highly vocal public protests against the "sonic boom nuisance". Some of those who disapprove on the basis of the boom might also cite, as arguments for their case, the extremely high development costs of the SST and its limited usefulness on short or medium-length flights.

However, it must be assumed that there will be strong pressures, not only against, but in favor of the SST. Proponents of the

supersonic transport will no doubt base their principal arguments on economic grounds. If West European or Soviet Union airlines put SST's into successful operation, those favoring the SST will urge the public to accustom itself to the sonic boom annoyance. Their arguments will be strengthened if foreign airlines and airframe manufacturers use the SST to take large segments of business away from United States companies, and will be further strengthened if the balance of payments situation is affected adversely.

The advantages and disadvantages of the SST may continue to be a matter of major public discussion for a considerable period of time. Eventual decisions will be based on realistic and intelligent appraisals by leaders of the unfavorable factors, especially public annoyance with the sonic boom, as against projected benefits for American transportation and the United States economy as a whole.

Those who believe the United States must use SST's to maintain its present important position in world commercial aviation will doubtless use every device to convince the public of the validity of their arguments. It is probable that the major emphasis will be to urge the public to avoid premature conclusions based on false ideas and unfounded fears, and that they will express whatever hopes are justified by the facts for improvements in the situation.

Since public opinion is now in the process of being crystallized, it is important that future tests be handled properly from the standpoint of the press. Tests present an opportunity to inform the public of the facts. The visit of newspapermen to White Sands during the sonic boom tests in December 1964, and the press conferences in Washington by FAA officials, are regarded as having promoted a much better public understanding of the problem. The general impression of the newsmen attending the White Sands tests was: "The sonic boom is not nearly as bad as we had expected". This type of background understanding on the part of the press is valuable, and tends to offset the influence of those who are inclined to dramatize individual cases, or to jump to conclusions that may later be proved unsound.

The next tests may provide an opportunity to undertake a pilot public information program to inform the public in advance what to expect, in somewhat the same manner as would be done in an actual situation in which SST's were to be put into service. At Oklahoma City there was not a great deal of public warning or preparation. Possibly if there had been, some

elements of the public might have been more understanding. The procedure in this type of public approach would be to explain the tests in advance to editors and other opinion leaders with the hope and expectation that if people knew the general experience in previous tests they are more likely to accept the boom annoyance without complaint.

Over the long range the public interest will be served if all concerned - including airlines and airframe builders - realize there is a need for public information, and that this information as it develops should be presented objectively and not in the form of "campaigns to sell the public on the SST". It is important to know, for instance, of engineering and design changes that may reduce sonic boom characteristics and increase the safety, efficiency and total acceptability of the SST. It is important to know what measures airlines and governmental agencies are considering to increase operational effectiveness and minimize sonic boom effects on the public through route changes and flying patterns.

The public relations approach by the military is somewhat different since there is a general public understanding of the necessity for the supersonic plane for national defense. However, military agencies can and should contribute to public information on the subject whenever they have the opportunity to do so.

Public understanding of the problems aviation leaders face in developing airplanes of the future will be facilitated greatly by a spirit of cooperation on the part of all of those concerned, including not only the aviation industry itself and government agencies, but also interested business and educational leaders. Such a cooperative attitude would provide an improved climate for considered and intelligent appraisals of developments and sound decisions as to industry and national policies. Under such circumstances, it might be reasonable to expect that some individuals and some groups might be influenced to forego public protests against the SST and its boom.

There are definite advantages in a continuing coordinating group in this general area, not only a subgroup in the field of psychological studies, but a subgroup in the field of public approaches. This latter group might keep in close touch with informational activities on the subject of the SST and the sonic boom by such interested agencies as the Federal Aviation Agency, the Civil Aeronautics Board, the military services, the Air Transport Association, individual airlines, airframe manufacturers and possibly airline insurance companies.

Recommendations

1. An effort should be made in advance of the next tests to explain the situation to the public in the selected city, and thus determining the effect of this type of public relations procedure on public understanding and acceptance of the boom.

2. All concerned with the SST program should present information objectively, not as propaganda or "selling", to show what they are doing or planning to do to minimize boom effects and annoyance.

3. Military agencies using supersonic equipment can and should continue to contribute to public information on the subject.

4. The aviation industry, government agencies, and other interested organizations should cooperate and coordinate informational activities, whenever practicable, with a continuing coordinating group in this area, including a subgroup in psychological studies and a subgroup in public approaches.