Sonic Booms from Supersonic Transport

The operation of supersonic transport is considered in the light of the effects of sonic booms on people.

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When the British-French Concorde and the Boeing supersonic transports (SST) are fully operational, sometime in the late 1970's according to present plans, it is expected that about 65 million people in the United States could be exposed to an average of about ten sonic booms per day (26 million receiving 10 to 50 booms, and 39 million receiving one to nine booms). In contrast to these expectations, some people claim that such exposures will not be tolerated, and that an SST will be usable only over water, or sparsely populated land, and only very occasionally over populated areas. Whether these restrictions make the building and operation of a commercial SST economically attractive is a critical question, but one not evaluated in this paper. This paper, except where specially noted, is directed solely to the question of the feasibility of full anticipated operation overland of presently planned SST and in no way is it concluded that operation of the SST essentially over water is not practical or desirable.

The opinion is sometimes expressed that the existence of air and noise pollution in our country is *prima facie* evidence that sonic boom pollution will be allowed to develop. But the proposed advent of the SST and its sonic boom is unique in that (i) the available knowledge from research and experience about the effects of noise and sonic booms on people permit forecasting with probable accuracy the reactions of people and society to sonic booms from the SST; (ii) the federal government is underwriting much of the cost of the SST; and (iii) the sonic boom from presently planned SST's would represent an increase of orders of magnitude in the amount of noise present in the United States and in the numbers of people to be exposed to intense noise.

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In view of the costs and commitments of aviation facilities involved in producing and operating the SST, it would seem prudent for various governmental and scientific bodies, if not the general public itself, to examine closely the pertinent data from psychological and sociological research and their relation to arguments for and against the overland operation of the SST. The general unavailability of an integrated interpretation of the implications of the psychological, sociological, and acoustical research related to the acceptability of sonic booms to people has prompted the publication of this paper. In the last analysis the sonic boom is a psychological-sociological problem, and it would perhaps be regrettable if all relevant information, such as it is, from these scientific disciplines were not available and discussed in the practical context of the problem.

Before presenting a detailed analysis of relevant data, I will first briefly review, by way of further introduction, some of the arguments for and some of the arguments against deprecating the severity of the problems to be created by sonic booms from planned Boeing and Concorde SST's.

Argument 1. Information from research on the effects of noise on people is too vague to permit one to predict how people will behave toward the sonic boom in the 1970's or 1980's. Related to the latter point of the argument is the notion that an estimated $15 billion or so investment in an SST fleet and other financial considerations would more or less oblige the public and government to behave favorably toward the SST. Also, it is presumed that, inasmuch as the number of sonic booms will be relatively few for the first few years of operation (until inventory of the aircraft is enlarged), people will gradually become accustomed to the boom.

Counter arguments.

1) Sonic booms from the SST will be subjectively so unacceptable, both initially and after adaptation, people will not permit the boom to become part of their environment. A boom will initially be equivalent in acceptability to the noise from a present-day four-engined turbofan jet at an altitude of about 200 feet (60 meters) during approach to landing, or at 500 feet with takeoff power, or the noise from a truck at maximum highway speed at a distance of about 30 feet. (The effect of number of noise incidents versus intensity level and other data are presented in detail below.)

2) The number of people using the SST will be exceedingly small as compared to the number of people exposed to sonic booms (unlike the case of intense noise from trains, automobiles, or subsonic aircraft).

3) The sonic boom will have, from the start, in populated areas a very high equivalent level of noise unlike, in general, the train, automobile, and subsonic aircraft from which the initial levels of noise in populated areas were much lower than they later became.

4) With respect to predicting the behavior of people in the 1970's, it would seem highly questionable to presume that the attitudes of our society toward noise, or that the legal and political mechanism now available as a means of exercising attitudes and behavior against noise, will be changed in the direction of preventing society from effectively stopping operations of the SST if the sonic booms become sufficiently oboxious.

Argument 2. The SST represents progress that benefits all concerned and therefore will be accepted. For example, the noise from the automobile did not stop its development.

Counter arguments.

1) The SST is not a new form of transportation, but only a somewhat faster version of an existing and apparently reasonably satisfactory form. It is to be questioned that the overland use of the SST would significantly increase the amount of air travel within the United States or within Europe, or improve the economy because of increased production of aircraft. Proportionally

more subsonic planes will have to be manufactured if the SST is not made for overland use. It is probable, however, that the SST would significantly increase travel for long-range overwater air routes, and would also, therefore, increase the total number of aircraft required for that purpose.

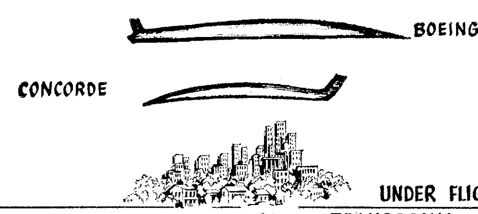
2) The use of transportation vehicles has, in fact, been tempered with consideration of and, to some extent, controlled by noise; the noise from railroads, trucks, cars, and aircraft has been and will, probably even more in the future (as measurement techniques and understanding of the control of noise are further developed), be the subject of lawsuits and government codes, laws, and regulations. Legal and semilegal codes in some cities and states of the United States, as well as of some other countries, set limits on road vehicular noise that are more reflections of the noise existing vehicles make than what are "acceptable" noise levels; even so, these levels are well below the equivalent noise level of a sonic boom from an SST. Adjustments have taken place in property values (in some cases compensation has been paid for noise easements), and in the selection of people living within a few hundred feet of certain railroads, highways, and near some airports where the noise environments are equivalent in objectionableness to that anticipated for the sonic boom from the SST. These more or less natural adjustments that can take place over time, unfortunately, are probably not practical for the sonic boom because it will fall over such large areas of the country and cannot be escaped by very large numbers of people regardless of their socioeconomic status or other abilities.

3) It is well established in the United States that a nuisance required for the general "well-being" of society can be declared as legal and, therefore, as a nuisance, unassailable by court action. Aircraft and other noises can often qualify as a legal nuisance; however, if a legal nuisance makes a given piece of property less desirable for its intended use and therefore less valuable, the owner of the property must be compensated for the loss or partial loss in value. The sonic boom, if a continuous, persistent condition over certain areas of the country, could be viewed by the courts as a compensable taking of property, but undoubtedly would not be so viewed for practical reasons (the fact that millions of pieces of property would be involved). This possible compensation is more or less independent of, or at least in addition to, the payment for repairs of broken windows or other structural damages caused by the booms; the homeowner would presumably be compensated for such damages as a matter of course.

4) Another basis for legal suit to enjoin someone from making undue noise could be damage to health. There is no threat of damage to hearing from exposure to sonic booms, and it is my personal conviction that there are no conclusive data that show that general environmental noise as we know it, or sonic booms as projected for the future, can cause significant problems of physiological or mental health. However, this latter assertion is debatable; when a sufficiently large population is exposed to sonic booms, there may be found valid damage to the physiological or mental well-being of some presumably small number of people.

5) When a noise nuisance is created that engages millions of people, in contrast to the thousands or even hundreds of thousands now exposed to environ-

POSSIBLE OVERLAND SST OPERATIONS



1. MEDIAN BOOM INTENSITIES	UNDER FLIGHT PATH TRANSSONIC	UNDER FLIGHT PATH CRUISE	12.5 MILES TO SIDE OF FLIGHT PATH TRANSSONIC	12.5 MILES TO SIDE OF FLIGHT PATH CRUISE
BOEING	2.1 psf (est)	1.8 psf (est)	1.6 psf (est)	1.3 psf (est)
CONCORDE	2.0 psf (est)	1.9 psf (est)	1.5 psf (est)	1.4 psf (est)

2. 50% OF LONG HAUL U.S. AIR TRAVEL ON SST WOULD PRESENT 10-20 BOOMS PER DAY TO;
   a. GREAT CIRCLE ROUTES
      65.5 MILLION PEOPLE (WITHIN 25 MILE BOOM PATH)
   b. CIRCUITOUS ROUTES
      35 MILLION PEOPLE (WITHIN 25 MILE BOOM PATH)

GENERAL CONCLUSIONS

1. WIDE SPREAD POLITICAL AND LEGAL ACTION AGAINST BOOM FROM SST SEEMS CERTAIN WHEN RESULTS OF BOOM-NOISE JUDGEMENT TESTS ARE RELATED TO REACTION OF PEOPLE NOW LIVING NEAR AIRPORTS AND IN VIEW OF OBSERVED COMMUNITY ATTITUDES TO ACTUAL SS OVERFLT
2. "BEST ESTIMATES" OF ANNUAL PAID DAMAGES (BASED ON 50% OF ACTUAL-PAID DAMAGE RATE EXPERIENCED TO DATE)
   a. GREAT CIRCLE ROUTE – $86,000,000
   b. CIRCUITOUS ROUTE $37,000,000

NOTE: COST OF PROCESSING CLAIMS NOT INCLUDED

STRONG POINT OF RESEARCH DATA

DATA FROM LABORATORY, FIELD, AND COMMUNITY RESPONSE STUDIES CONSISTENT WITH EACH OTHER

WEAK POINTS IN DATA

1. LABORATORY AND FIELD SUBJECTS NOT IN OWN HOMES OR ENGAGED IN TYPICAL ACTIVITIES
2. REACTIONS OF PEOPLE IN COMMUNITIES TO SUBSONIC JET NOISE AND BOOMS POSSIBLY NOT SUFFICIENTLY MEASURED.

Fig. 1. Sonic boom problem from the supersonic transport and research conclusions. Sonic boom intensity is given in pounds per square foot (psf).

ments of equivalent noise, it seems likely that the courts will act against the noise on the basis of present laws or that new legislation against the nuisance will be enacted.

Argument 3. It is argued that as a matter of economics the United States cannot afford to purchase SST's from another country or to lose such a large share of the international market for aircraft to another country. This argument has perhaps had the most influence and has been used to override questions concerning the sonic boom.

Counter argument.

The SST being developed by other countries, as near as can be determined, will have as great, if not greater, sonic boom than the SST now being developed in the United States. These aircraft cannot be expected to be any more successful in this regard than the Boeing SST, and therefore would also not be in demand as an overland aircraft.

Argument 3 is, however, a legitimate and powerful argument in favor of having the United States develop an SST, provided that there would be sufficient demand for an aircraft that operates supersonically essentially solely over water or very sparsely populated areas to make such an aircraft economically successful. The number of people exposed to sonic booms from the overwater operation of the SST, primarily those on decks of ships, would probably be too few to provide a significant social-political force against the overwater operation of an SST. In addition, the acoustic environment, as it affects people, aboard ships incident to ship motion through heavy seas is at its maximum probably equal to or greater than that which would be caused by a sonic boom from an SST; however, I know of no direct physical measurements made on this latter point. Also, calculations show that the acoustic disturbance, as would be perceived by marine life, that would be caused a few feet under water from sonic booms from the SST can be expected to be appreciably less than the acoustic disturbance present in the oceans because of normal wave action and from some ships moving through the water (*1*).

Argument 4. Finally it is argued that scientists will soon develop solutions to the sonic boom. In fact, however, the following points hold true.

1) The Boeing aircraft now being developed and built will have as large if not somewhat larger a boom than now expected because the weight of the aircraft has been increased from its original planned weight.

2) A fundamental factor in creating the sonic boom is that of gravity (that is, the weight of the aircraft and its contents must be lifted and moved through the air). Research on antigravity to date has resulted, to my knowledge, in but one partial solution to this problem—that of the ballistic vehicle in which the gravitational forces are overcome by making the speed of the vehicle such that it becomes essentially weightless. Ballistic transports are, of course, a possibility for the future, but they will probably not evolve from SST's.

3) A possible solution is to ionize the atmosphere in front of and surrounding the aircraft. This possible approach is one not concerned with the effects of gravity directly, but with changing the apparent geometry of the aircraft during flight. This ionization would, it is believed, have the effect of reducing the boom for a given size aircraft. However, it remains to be seen, if one assumes that there would be an economical and practical reduction to practice, whether or not the increase in size and weight of the aircraft as required to carry the power source for the ionizer do not cause an increase in intensity of the boom that offsets or more than offsets this "gain."

4) Conceivably a practical structure could be built that would not create a boom when passing through the air at supersonic speeds; examples are hollow cylinders or two-plane surfaces arranged so that the shock wave from one part of the structure is out of phase, at some point in space away from the craft, with the shock wave of the opposite part of the structure, so that the two shock waves cancel each other. Unfortunately, such a structure would not fly through

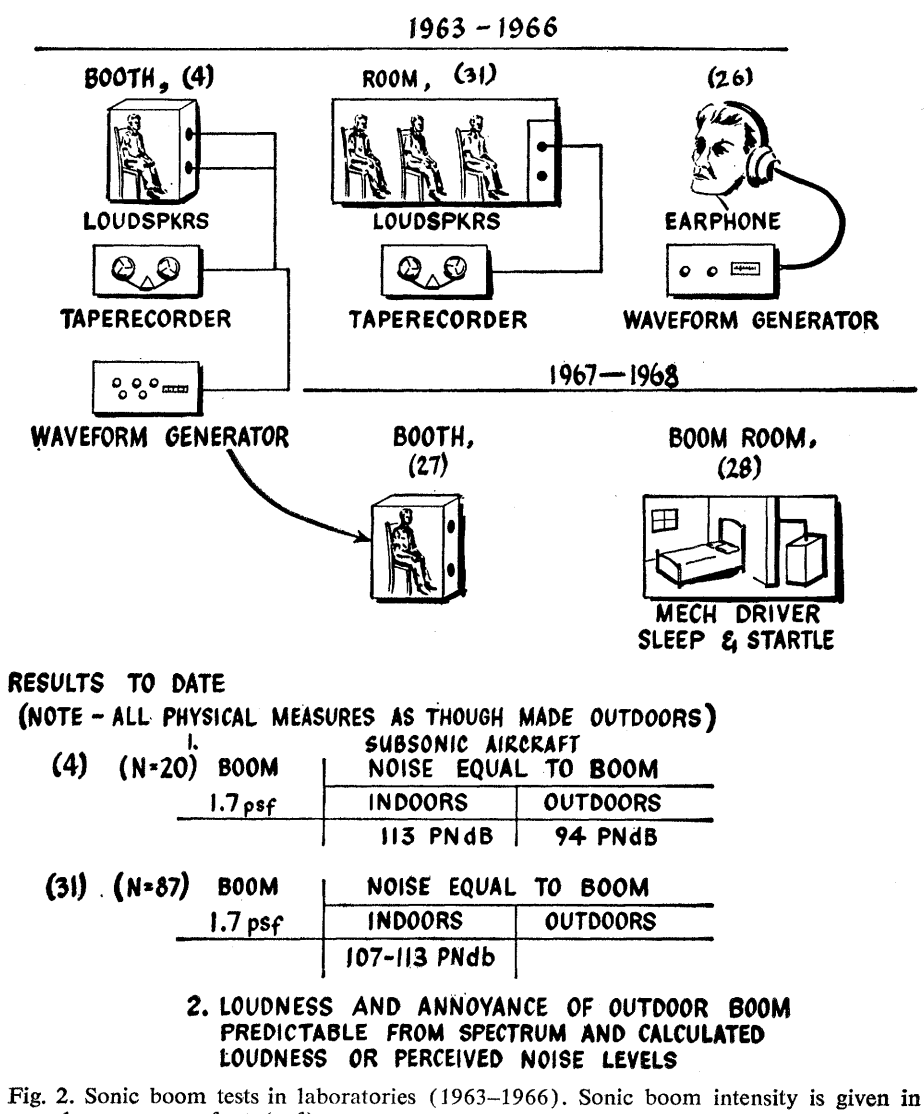


Fig. 2. Sonic boom tests in laboratories (1963–1966). Sonic boom intensity is given in pounds per square foot (psf).

the air because it would lack lift; it could, however, be propelled through the air ballistically.

5) While designing an SST with a much reduced boom seems very unlikely, at present, it is probable that future research will provide methods of designing an aircraft which creates a boom whose temporal waveform and spectral content on the ground is more acceptable to people and structures than the typical *N* wave.

Overland Supersonic Transport and Political Pressure

The fundamental difficulty the SST will face is that the political pressures brought by citizens and government officials against the operation of SST over land can be expected to be much more powerful than the insignificant, in a comparative sense, complaint and legal activity now brought against noise from aircraft. For example, the 150 homeowners at Skylandia, another 200 or so in the area of Millbrae, and another 200 or so in Foster City who complain about the rather intense noise (subjectively less, per occurrence, than sonic booms) from aircraft using the San Francisco airport, can probably not hope to bring sufficient political and legal pressure to stop the noise, particularly in view of the positive values of the airport to the entire San Francisco area. (All or nearly all that can be practically done at the present time to reduce noise in these localized areas has been accomplished by the Federal Aviation Administration and the airlines.)

Most people do not learn to accept noise from aircraft that is subjectively equivalent in annoyance value to a sonic boom, although they may learn that little can, or even should, be done about it because of the common good. But because there is not a sufficient number of people exposed to such intense noise from aircraft as to cause serious problems to the operation of most, but not all, airports, should not lead one to underpredict what the political and legal persuasiveness will be of 50 million or so people, at least 30 percent of whom feel they cannot live with the sonic booms, and 70 percent or so of whom either dislike or at the best are neutral to it. The question then is, How many people can be exposed to how many booms before the situation becomes unmanageable in a manner that is socially, politically, and legally acceptable? Data are presented below to show how the people will behave as a function of number of exposures to sonic booms; but how many people can be exposed without serious social-political-legal consequences is not quantifiable at present.

With respect to the latter, it can be noted that the U.S. Air Force sees fit to restrict, over any given populated areas of the country, regular flights of supersonic aircraft creating sonic booms of lower intensity and lower frequency than would be the booms from the SST. These restrictions come about because of complaints and damage caused by the sonic booms and in spite of the fact that the military supersonic flights are deemed by the government to be necessary to the defense of the country.

Some of the fundamental questions and answers involved can be succinctly stated as follows.

1) Can people "pay" physiologically and mentally the price of being exposed to the from one to 50 booms per day anticipated from regular operation of planned SST's? The answer is probably "yes," and there is not sufficient relevant data to prove otherwise.

2) Should, assuming the answer to question 1 is yes, people "pay" the price of the annoyance and discomfort of being exposed to the booms from regular operation of planned SST's? The answer is moot and can only be a compromise among the relative values held by the people making the decision.

3) Will the population of the United States "pay" the price of the annoyance and discomfort of being exposed to the booms from the regular operation of planned SST's? This is the most, if not the only, necessary question, and the answer, as is discussed below, appears to be a definite "no."

Clearly, these deductions emphasize the need for further research on ways

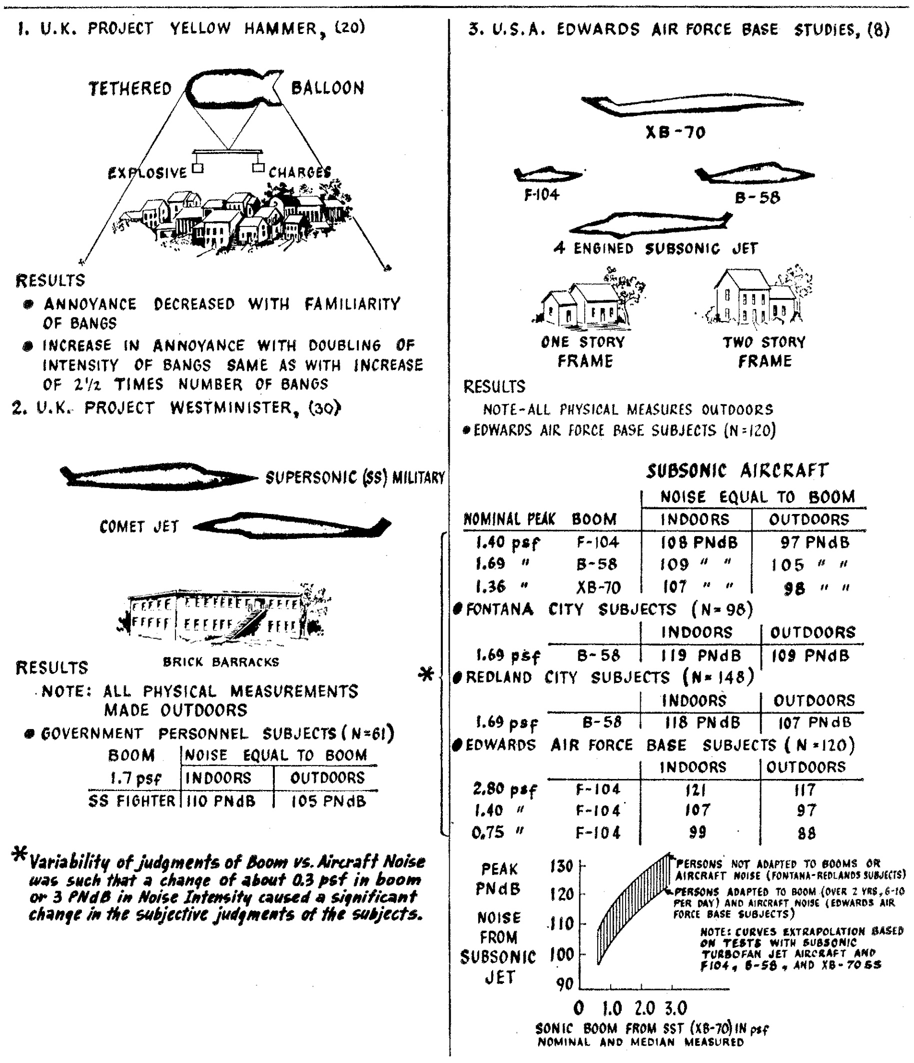


Fig. 3. Sonic boom field tests conducted in the United Kingdom (U.K.) and the United States (U.S.A.). Sonic intensities are given in pounds per square foot (psf).

of reducing or appropriately modifying the sonic boom, and for further studies of human response to the sonic boom that would be aimed at verifying, sharpening, or disproving conclusions made on the basis of research conducted to date on the problem.

Because of the nature of the question and material to be analyzed, it appears appropriate to present first the conclusions and directly related data on the acceptability of sonic booms, with a somewhat more detailed discussion section following thereafter. The conclusion reached is based on published research results and not upon the subjective opinion of the author. Also, the conclusion does not lean in any way upon humanitarian conjectures (*2*), with which we largely disagree (*3*, *4*), regarding mental and physiological health of people exposed to sonic booms.

Conclusion

It is concluded that the sonic booms from the Concorde and Boeing SST's operating during the daytime sometime after 1975, at frequencies presently projected for long-distance supersonic transport of passengers over the United States, will result in extensive social, political, and legal reactions against such flights at the beginning of, during, and after years of exposure to sonic booms from the flights. No data can be found to suggest that any other conclusion is possible. This conclusion is derived from the following data.

Intensity of Sonic Boom

The sonic booms from the Concorde and Boeing SST when flying at normal cruising altitude (somewhere in the vicinity of 70,000 feet) will have nominal peak overpressures on the ground directly under the flight path of about 1.9 pounds per square foot. At greater distances from the aircraft the nominal intensity of the boom becomes less. By nominal peak overpressure is meant the overpressure signature expected on the basis of theories regarding components regulating the volume and lift of the aircraft, and pressure and temperature changes in the atmosphere which have some influence on propagation of the boom along its path. The theories are the ones used by the United States National Aeronautics and Space Administration in calculating sonic booms subsequent to July 1966 and have been found to agree well with the average of actual measurements. Deviations from the nominal values at any point in space are usually attributable to both large-scale and small-scale turbulence of the air or movements of the air encountered by the sonic boom as it moves from the aircraft to the earth.

In the United States persons within a path 12.5 miles on either side of the flight track of the proposed SST [approximately 35 million people, with certain circuitous routing (*5*) of the SST to avoid populated areas, and 65 million people, with Great Circle routing of the aircraft] would be exposed daily to an average of about ten sonic booms (*5*) that have the following peak overpressures: 98 percent of the booms will vary from 1.5 to 2.0 pounds per square foot, with 1 percent of the booms reaching or exceeding 4.0 pounds per square foot and 1 percent of the booms being at or less than 1.0 pound per square foot. In addition, persons living as far as 25 miles to each side of the flight track will be exposed to booms having peak overpressures that vary on the average from near zero to 1.0 pound per square foot (*6*).

For 150 miles or so (starting about 100 miles beyond takeoff, when the aircraft is in transonic region), the booms will have nominal peak overpressures of 0.2 to 0.3 pound per square foot greater than the various values given above; also for a very small and variable segment of but a few miles in this transonic region the overpressure of the boom normally will be about twice the pressures cited above because of a boom "focusing" phenomenon related to aircraft accelerations, the so-called "super-boom."

Acceptability of Sonic Booms

Sonic booms from the B-58 aircraft of 1.7 pounds per square foot nominal peak overpressure were judged by residents of Edwards Air Force Base to be equal in acceptability to flyover noise of about 109 PNdB from subsonic jet aircraft. [The PNdB is the name of a unit that indicates physical intensity of a noise on a scale that approximates the

PROBABLE MEDIAN NOMINAL BOOM–1.2 psf to 1.7 psf IN U.S., 1.3 psf IN FRANCE

	FELT 8-10 BOOMS PER DAY UNACCEPTABLE DUE TO HOUSE SHAKING & STARTLE	PAID CLAIMS PER BOOM PER MILLION PEOPLE (BASED ON REF. 12)
1. OKLAHOMA CITY (10) (LEGAL & POLITICAL REACTIONS)	27% 1.2 psf	0.5
2. ST. LOUIS (23) 1 BOOM, 3 DAYS ANNOYING	35% 1.7 psf	5.8
3. EDWARDS (8) RESIDENTS 14% 1.1 psf	26% 1.7 psf	2.9
4. FRENCH TOWNS & COUNTRY (11)	34% 1.3 psf	–
5. PITTSBURGH	1.7 psf	6.8
6. CHICAGO	1.7 psf	6.1
7. MILWAUKEE	1.7 psf	5.8

Fig. 4. Supersonic overflights of civilian communities in France and the United States (1964–1966). Sonic boom intensities are given in pounds per square foot (psf).

response of the human auditory system to the noise (*7*).] The residents of Edwards Air Force Base were somewhat adapted to booms as a result of an average of 2 year's exposure to five to ten booms per day (*8*). "Unadapted" residents from quiet civilian communities judged the sonic boom from the B-58 at 1.7 pounds per square foot to be equal in acceptability to the noise from the subsonic jet at about 119 PNdB (*8*). Aircraft noise that equals or exceeds 100 to 110 PNdB or so is generally rated as unacceptable in communities adjacent to busy metropolitan airports and may be the cause of lawsuits against noise (*9*). Sonic booms from the XB-70 and presently planned SST's will probably, for equal nominal overpressure and relative to the noise from subsonic jet aircraft, be equal to or slightly less acceptable than sonic booms from the B-58 aircraft.

Sonic booms of estimated nominal median peak overpressures of about 1.1 to 1.3 pounds per square foot and a frequency of eight to ten times per day were rated as being "unacceptable" by 14 percent of the residents at Edwards Air Force Base (*8*), "can't live with" by 27 percent of the residents at Oklahoma City (*10*), and "intolerable" by 34 percent of the residents in two rural and urban areas in France (*11*). Exposure to eight to ten sonic booms per day of nominal median peak overpressures of about 1.7 pounds per square foot were rated as "unacceptable" by 26 percent of the residents at Edwards Air Force Base (*8*).

Damage from Sonic Boom

The continuing annual cost of the repair of damages (not counting the cost of processing paid and unpaid claims or inspection of damages) to houses as the result of exposures to a distribution of sonic booms having a nominal median peak overpressure of no more than about 1.7 pounds per square foot, and at frequencies anticipated for United States long-haul, overland SST flights (after 1978) would be about $37 million with certain circuitous routing of the aircraft to avoid populated areas, or an estimated $85 million for Great Circle routing of the aircraft (*5*, *12*). Supersonic transports under development could cause, if flown as anticipated, somewhat more damage than predicted because the intensities of their booms would be somewhat greater than the estimated 1.7-pound-per-square-foot nominal levels (from B-58 aircraft) that caused the damages used to predict possible damages from future SST operations. These estimates may be incorrect, in either direction, by a factor of 2 or so because of uncertainties in information about the strengths and weaknesses of structures and their distribution and locations throughout all parts of the United States, and possible improvements in circuitous routings or reductions in length of flight path during which the aircraft is supersonic to avoid booming populated areas.

The general nature of the anticipated problem with the sonic boom and conclusions are summarized in Fig. 1. In Figs. 2–4 and Table 1 there are summaries of the basic data that are available about the effects of sonic booms on people, damage to structures in communities, and numbers of people likely to be affected by the booms.

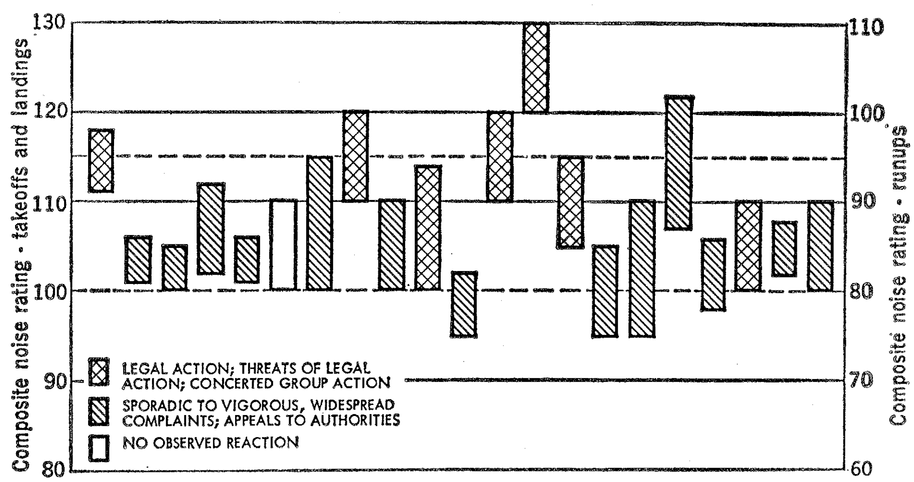


Fig. 5. Reactions of people in communities exposed to aircraft noise environments of different composite noise rating (CNR) values. The height of the bars represent the range of CNR values taken over a given neighborhood (*9*). Twenty-four additional cases are available.

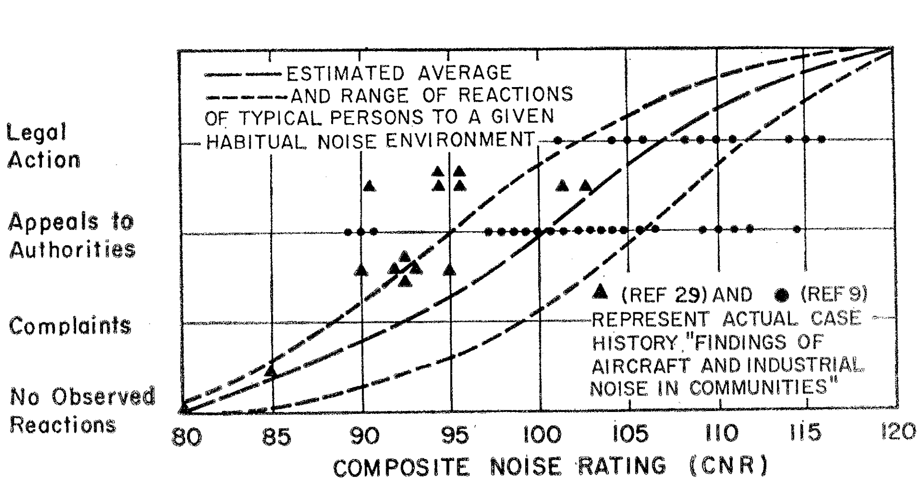


Fig. 6. General relation between community response to aircraft or other noises and composite noise rating (see references *7*, *9*, *18*, *21*, *22*, and *29*).

Analysis of Relevant Research Studies

Figures 2–4 and Table 1 are self-explanatory, and a detailed discussion of much of the data on which they are based is presented in the references cited. Nevertheless, the following comments are pertinent.

The general similarity of the results of the laboratory and field tests (except for the subjects from Fontana and Redlands, California) in which subjects judged the subjective acceptability of simulated, recorded, or actual sonic booms as compared with the noise from a subsonic jet aircraft is worthy of note. It appears probable, however, that the sonic booms created in the laboratory were somewhat more acceptable than supposedly comparable "actual" sonic booms because they lacked some of the high-frequency components present in actual sonic booms and because the vibrational aspects of the house response to the actual boom, which could be felt and seen, were lacking in the laboratory. Typical instructions to the subjects for these tests are as follows.

You will hear a series of sounds from aircraft. Some of the sounds will be sonic booms and some will be the sound made by a subsonic jet aircraft. The sounds will occur in "pairs" and your task is to judge which sound in each pair you think would be more acceptable to you if heard in or near your home during the day and/or evening when you are engaged in typical, awake activities.

After you have heard each pair of sounds please quickly decide which of the two you feel would be more acceptable to you. If you think the second sound of a pair would be more acceptable, circle B for that particular pair. If you think the first sound in the pair would be more acceptable to you than the second, circle A.

The rate (0.5 paid claims per 1,000,000 people per boom) of damage claims paid in Oklahoma City probably should not be used as a basis for projecting the rate of damage claims that will be paid from sonic booms from SST. This comment is based primarily on the fact that the peak overpressure of the sonic booms from F-104 fighter-type aircraft was less (about 1.2 versus 1.7 pounds per square foot) and of shorter duration (0.075 second versus 0.17 second) in Oklahoma City than the booms in cities other than Oklahoma City. The other cities where the major number of paid damages occurred (Chicago, Milwaukee, St. Louis, and Pittsburgh) were exposed to booms mostly from the B-58 bomber type of aircraft at median nominal peak overpressures of about 1.7 pounds per square foot. In addition, a study (*13*) of the minor repairs made to homes in Oklahoma City and in Tulsa in the 6-month period for the year before the tests of sonic boom in Oklahoma City, and during the 6-month period of the tests revealed that the number and costs of minor repairs on houses (although not paid for by the government) increased by about 60 percent between the two periods in Oklahoma City but remained the same in Tulsa.

The claims paid by the government were for damages that could be ascribed by government inspectors as being most probably caused or induced by a sonic boom. In order to qualify as a payable claim, the damage in question (i) had to have occurred by actual observation or near observation at the time a sonic boom occurred; (ii) must have been a type of damage that could reasonably have been caused by a sonic boom; and (iii) the recipient had to sign an affidavit of criminal liability that the claim was not fraudulent. About one-half of complaints of damage resulted in the filing of actual claim, and about one-half of the claims filed were ultimately paid. Except for certain minor glass damage claims of less than about $10, all alleged sonic boom damages were inspected by trained government investigators.

Table 1. Estimated 1975 population under each sonic boom category for Great Circle routing of medium- (1200 to 1800 miles) and long-range (2000 to 2400 miles) SST routes in the United States. Because of overlapping boom paths across the country some relatively small regions of the country will receive many more booms per 24-hour period than will other regions. About one-half of the total numbers of people given in the table would receive ten or more booms per day, and the remainder would receive less than ten booms per day.

Booms expected (No. per 24 hr)	Boom path			
	50 miles wide		25 miles wide	
	No. of people (millions)	CNR*	No. of people (millions)	CNR*
1–4	52.4	(92–103)	26.2	(95–103)
5–9	25.2	(98–106)	12.6	(101–106)
10–19	19.5	(101–109)	9.75	(104–109)
20–34	29.4	(104–112)	14.7	(107–112)
35–51	2.9	(107–114)	1.45	(110–115)

* The composite noise rating (CNR) for exposures to noise during the daytime is calculated as follows: CNR, average peak PNdB $- 12 + 10 \log_{10}N$, where N is the number of occurrences of the noise.

It has been demonstrated that sonic booms having peak overpressures of 10 pounds per square foot or less will not cause damage in structural elements of normal strength (*14*), but can apparently trigger damages in a few structural elements under unusual stress (*12*). It is tentatively assumed that the damage rate would decline with continued exposure to sonic booms. This is because the unusually weak elements in houses would be damaged early, leaving only the normal, stronger elements. This could be true even though the vibrations repeatedly induced in structures from continued exposure to sonic booms could conceivably result in some greater-than-normal increase, with age, in the fragility of structural components. It is practically impossible to relate, or hope to relate, a specific measure of a particular sonic boom from normal flights of supersonic aircraft with specific occurrences of boom-induced damage; this difficulty arises from the very low incidence of damage (about one every 100 square miles in heavily populated areas) per boom (*12*) and because of variations of as much as 50 percent or so in overpressures for a given boom between points on the ground as close as 200 feet from each other, due to low-altitude air turbulence and other atmospheric conditions.

Based on information in (*5*) and (*12*), the estimates of about $85 million in annual paid damages for Great Circle SST routes for the United States, and $37 million for circuitous SST routes to avoid, as practical, populous areas in the United States are derived as follows. The number of people in 25-mile-wide paths per SST route is multiplied by the number of daily booms per route (1185 million for Great Circle routes, and 512 million for circuitous routes), which is multiplied by 5.5 (the average paid damage claims rate found in St. Louis, Pittsburgh, Chicago, and Milwaukee per million people per boom), which is multiplied by $72 (the average money paid per damage), which is multiplied by 365 (the number of days per year), and the result is divided by 2 (the assumption that rate of damages will decline by 50 percent with continued SST operations because of improvements in structure strength and repairs).

It is surmised that the damage to be expected from proposed SST would actually be, if they were flown as anticipated, somewhat greater than the cost of damage as estimated on the basis of paid damages due to sonic booms from B-58 aircraft because the proposed SST would create sonic booms that average 5 to 25 percent higher in intensity and have about twice the duration as booms from B-58 aircraft.

Behavior in Real Life and Results of Relative Judgment Tests

Essentially two groups of experiments have been conducted that purport to demonstrate what the effects of sonic booms from the SST might be upon people: (i) attitude surveys and

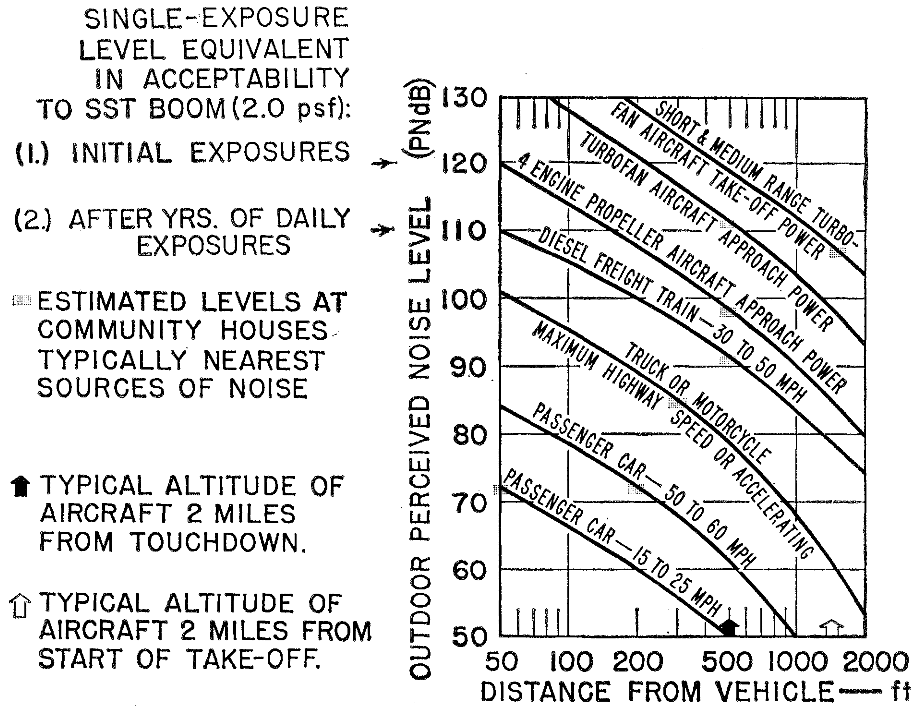


Fig. 7. Typical levels of intermittent outdoor noise produced by vehicles (PNdB). An increase of 10 PNdB is usually equivalent to a 100 percent increase in subjectively judged noisiness. Sonic boom intensity is given in pounds per square foot (psf) (*21, 25*).

observations of behavior of residents in Oklahoma City, Edwards Air Force Base, and France, when these residents were subjected to sonic booms generated by military aircraft; and (ii) so-called paired-comparison tests conducted in laboratories and under field conditions in Great Britain and the United States in which subjects estimated the relative acceptability, as though heard under real-life conditions, of two sounds presented in rather rapid succession (a boom as compared to fly-over noise from a subsonic aircraft, and one boom versus another, different boom).

One virtue of the relative judgment tests is that the listeners are able to make direct, immediate comparisons between the two sounds without concern as to the absolute acceptability of either one. However, the main argument in support of the relative judgment tests is that they allow the results to be related to the real-life behavior of people as influenced and shaped by the positive psychological, social, and economic values placed upon the benefits of commercial aviation and the negative values placed upon the neighborhood noise created by commercial aviation by the same people. If one accepts the notion that booms and subsonic aircraft noise, though widely different physically, can be validly judged with respect to their relative acceptability for everyday living even though heard under laboratory or field listening conditions, then it follows that we can indirectly relate these judgments to the likely effects of sonic booms upon people in the general context of everyday living. It is, of course, not possible to say that the paired-comparison judgment test can be extrapolated and used with complete validity in this fashion; however, there is no apparent reason why the judgments do not have considerable validity, and as many arguments can be put forth that the subjects underestimated as overestimated the subjective noisiness of the booms compared to the noise from a subsonic aircraft. The following points can be made in this regard.

Inasmuch as the durations and nature of the boom and subsonic aircraft noise are so different, perhaps subjects cannot reliably decide which of the two is the more acceptable to them. This criticism is not too persuasive inasmuch as the data obtained in the three experiments in which this method was used are in agreement with each other, and subjects in all the experiments apparently experienced little difficulty in making the judgments even though they undoubtedly equated different effects, such as being startled by the boom as compared to the masking of speech by the aircraft noise, to arrive at an overall opinion on the two sounds.

The subjects, who were given a 1- to 2-minute warning before the occurrence of each boom and each noise from the subsonic aircraft, were perhaps more startled by the boom than if they had not been expecting the boom to occur; or conversely, the subjects were perhaps less startled by the boom because of the warning signal than they would have been without it. Which of these possible biases, if either, operated during these comparison tests cannot be determined. Whatever biases of this sort were present, they probably applied equally to both the sonic booms and the noise from the subsonic aircraft; further, we believe that reasonably intelligent and conscientious subjects can judge the stimuli in question not only in terms of their relative acceptability or unacceptability, but also in terms of how they would react on the average if the sounds had occurred in their homes when they were engaged in typical awake activities.

The behavior of people exposed to what they consider intense and obnoxious noises have been studied (*9, 10, 15–20*) to some extent. Two major variables related to sound that control the behavior of people are (i) the intensity, often measured in terms of perceived noise level in PNdB, and (ii) the frequency of occurrences and duration of occurrences of the noises. The methods of relating these two aspects of noise in the environment to the behavior of people are discussed in detail elsewhere (*7, 9, 21, 22*); for present purposes the reader is referred to Figs. 5 and 6. In these figures we see that an environment with a composite noise rating of 100 or greater can lead to a considerable amount of complaint and organized group and legal activity against the noise environment. (The method of calculating composite noise rating is given in the legend of Table 1.) Figure 7 shows typical peak levels in PNdB of the noise produced by various transportation vehicles.

If one accepts the equation that a sonic boom of 1.9 pounds per square foot from an SST will be subjectively equal, after adaptation resulting from several years of exposure to the booms, to the noise from a subsonic aircraft of 110 PNdB, it turns out that one sonic boom per day from an SST would provide a composite noise rating of 98. Therefore, presumably it would cause after habitual daily exposures, about the same behavior expressed by small communities (groups of several thousands each) habitually exposed for many months to composite noise ratings of 98 due to commercial aircraft operations (Fig. 5).

Without a drastic reduction in number or length of anticipated supersonic flights, it is estimated that, in the United States after 1978 or so, tens of millions of people would be in a noise environment equivalent to a composite noise rating of 98 to 115 because of one to 51 daily occurrences of sonic booms from an SST (Table 1). It is to be expected that 25 to 50 percent of these people, presuming a buildup over several years in frequency of exposures to provide for some adaptation to sonic booms, would express behavior ranging from extreme annoyance, complaints to authorities, to legal actions, or stronger, against the sonic booms (Figs. 4–6).

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