Sonic Booms

How are sonic booms created?
What do they do to people and buildings?
Will the future be dominated by the boom?

by Harvey H. Hubbard

Sonic booms are explosive sounds that occur without warning. Sometimes annoying because of their startle effects and their ability to shake buildings, these sounds pose a unique problem for the orderly development of high-speed air transport. Although booms from military aircraft are widely observed around the world, the real concern is for proposed commercial air-transport operations that will cause repeated booms over very large areas. What are the effects of sonic booms and what steps can be taken to minimize the exposure to a suitable level?

What are they?

Before we examine the particulars, it would be advisable to take a look at the general nature and history of sonic booms. As is generally known, sonic booms are associated with aircraft shock waves. They have been observed only since about the middle 1940's when they were first generated by high-performance fighter aircraft that dived and exceeded the speed of sound for short periods of time. Shock waves associated with such maneuvering flight conditions were oriented so that they propagated to the ground and caused sudden explosive sounds. The startling effects of such sounds or "booms" as they were labeled ("booms" is an important term psychologically) have led to a substantial research effort—particularly at the NASA Langley Research Center—directed at uncovering the secrets of their generation, propagation and effects. This work has involved special equipment and facilities, machine computers and wind tunnels as well as extensive flight-research work.

Our current understanding of sonic-boom phenomena can be traced to the shock-wave technology of bullets and projectiles. Sound ranging, used extensively in World War I to locate distant guns, drew on a knowledge of shock-wave patterns of projectiles in flight. The current sonic-boom problem in its physical aspects is very similar in nature to that of the projectile. The nature of the shock-wave patterns generated by a projectile is illustrated in figure 1. Shock-wave patterns are radially symmetrical, and this shadowgraph picture represents their projection on a plane through the axis of a bullet. Two relatively strong waves are associated with the bow and tail of the bullet and are labeled accordingly. Between these waves and close to the body surface one can detect other weaker waves. At relatively long distances from the bullet these weaker

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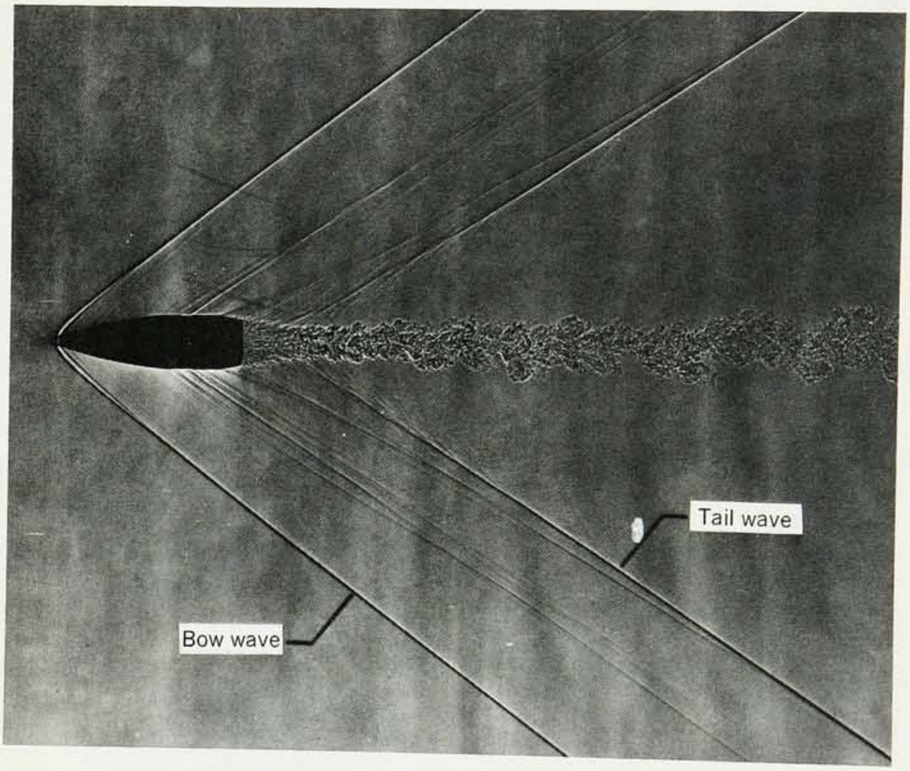
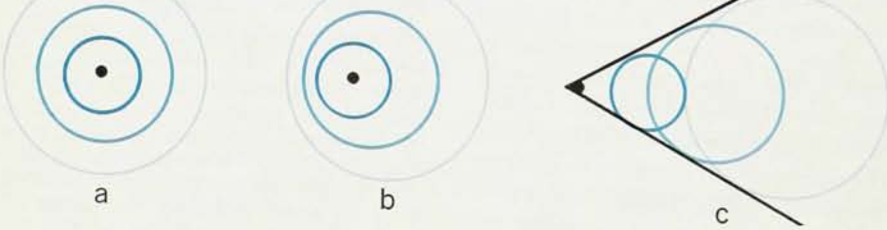
waves tend to coalesce with the stronger ones; thus, in the distant pressure field, one can identify only two main waves.

Prominent boom men

It is appropriate to mention some of the early contributors to sonic-boom information. Physicists and aerodynamicists such as Jesse DuMond, Jakob Ackeret, Wallace D. Hayes, Adolf Busemann, Kurt O. Friederichs and Gerald B. Whitham are prominent for adding to our greater understanding of the aerodynamics of the problem and the development of current concepts of generation. Their contributions, along with those of many others such as Joseph L. Randall, P. Sambasiua Rao, Manfred Friedman, Thomas Palmer and Edward Kane (mainly concerned with propagation of waves in an inhomogeneous atmosphere), form the basis for the more refined analyses developed recently by F. Walkden, Charles H. E. Warren, Harry Carlson and Francis McLean.



A BULLET generating shock-wave patterns (from reference 1). These patterns are similar to those which are generated by aircraft in supersonic flight. —FIG. 1



WAVE PROPAGATION from stationary and moving sources. (a) shows the waves when the source is stationary; (b) illustrates the waves when the source speed is subsonic; (c) represents formation of waves at supersonic source speeds. —FIG. 2

The NASA Langley team of scientists is credited with systematic, analytical and experimental studies that have resulted in improved understanding of the generation and propagation phenomena, a refinement of prediction procedures and an insight into the manner in which communities react to sonic booms. Carlson has developed precision wind-tunnel techniques for measuring shock-field characteristics and has collaborated with McLean in establishing firm calculation procedures for predicting sonic-boom exposures, particularly involving lift and volume interactions. Domenic Maglieri and his associates have conceived and executed precision flight-research programs to advance the understanding of the generation, propagation and effects of sonic booms and their relation to aircraft-flight operations.

Point-source disturbances

To explain the phenomena of shock-wave generation, I shall graphically review the concepts. The three elementary diagrams of figure 2 illustrate qualitatively the manner in which disturbances emanate from a point source. When the source has no forward motion, compressible waves travel outward equally in all directions. If the source of the disturbances is in motion but at a velocity lower than the speed of sound, the radiation pattern is distorted in the direction of flight as indicated in figure 2b. When the source moves at supersonic speeds, the velocity of propagation of the disturbances is less than the speed of the source; hence the waves tend to pile up (figure 2c). The coalescing of these waves results in formation of shock waves along the disturbance envelope as illustrated by the "Mach cone" lines.

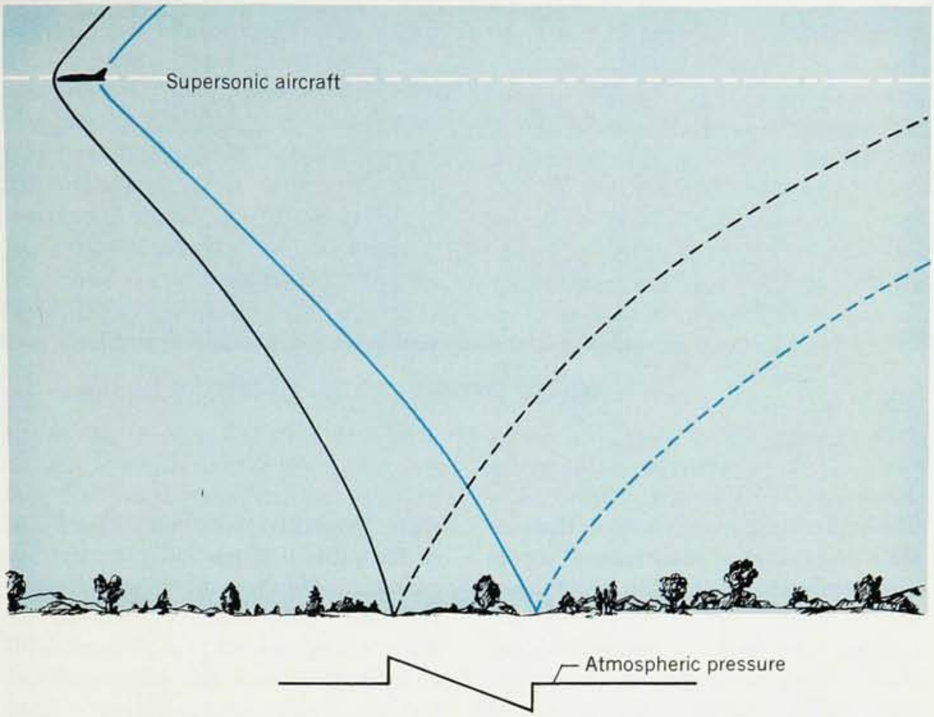
Aircraft disturbances

Figure 2 applies most directly to a point source and thus does not properly account for the more complex patterns developed in flight by a three-dimensional object such as the axisymmetrical bullet. For aircraft the presence of lifting surfaces adds an additional complication. This situation results in a body that is radially asymmetrical and is known to have marked variations in its shock-wave patterns in different directions radially from its longitudinal axis.

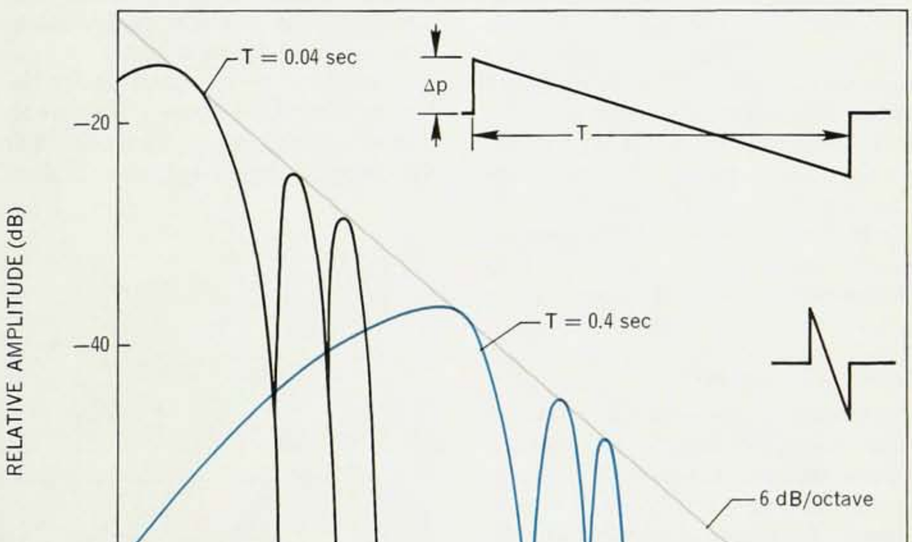
If sonic-boom waves generated by an airplane could be made visible, they might appear as shown during the cruise portion of supersonic flight (figure 3).[2] These shock waves extend outward from the airplane to the ground (solid lines) and are reflected (dashed lines). The whole shock-wave pattern moves at the speed of the airplane although the shock front moves at approximately the local sound speed. Sonic-boom disturbance is observed only after the aircraft is past the observer; for transport airplanes this distance may be 30 to 50 km. Shock-wave pressure-disturbance time history that is superposed on the ambient atmospheric pressure at the observer has the main features of an "N"-shaped wave (bottom of figure 3). This N-wave disturbance represents pressure changes of the order of a thousandth of an atmosphere and is characterized by a rapid compression, then a slow expansion and finally another rapid compression. The N-wave shape is idealized since the actual signature shape may vary because of atmospheric effects and aircraft design and operation.

The bow wave is associated with a higher-than-atmospheric pressure region; hence it propagates at slightly more than the ambient sound speed. On the other hand the tail wave travels at less than ambient sound speed. This nonlinear propagation, plus the effects of flow turning around the body, results in a spreading of the waves. Because of the three-dimensional character of the flow field, the overpressures decrease as the three-fourths power of distance.

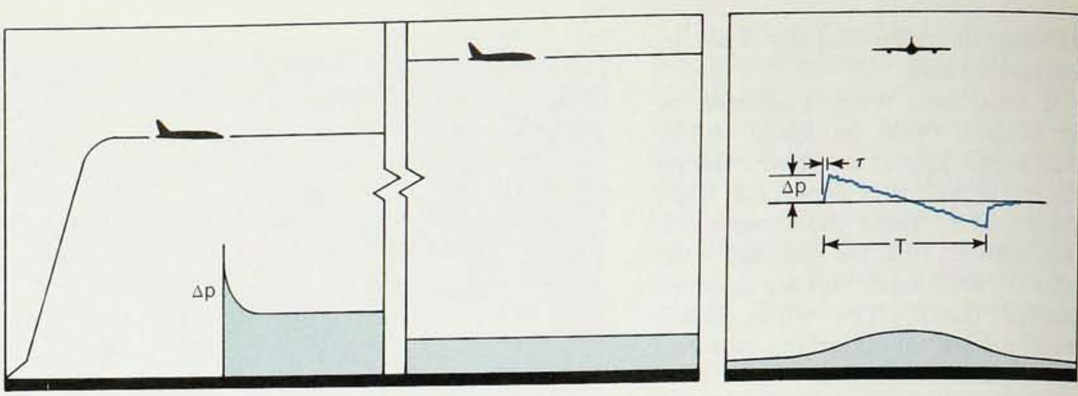
Sometimes it is helpful to study the spectral content of such waves when considering their effects on people, structures, etc. An example of such a spectrum for two waves of different durations—commonly referred to as the "energy spectrum"—is illustrated in figure 4. The spectrum for the short-duration wave, which is representative of a small airplane (colored curve), and that for a long duration wave, which is representative of a large airplane (solid curve), consist of several convolutions that are tangent to a 6-dB-per-octave line at higher frequencies. This fact suggests that



SONIC-BOOM wave pattern and overpressure signature from a supersonic aircraft. The shock waves (solid lines) extend outward from the aircraft and are reflected (dashed lines). At the bottom of the figure is an idealized representation of the pressure-disturbance time history that is superposed on the ambient atmospheric pressure. This time history has the general features of an "N"-shaped wave. —FIG. 3



ENERGY SPECTRA of N waves with equal overpressures but different time-duration values. Wave of longer duration (solid curve) has stronger low-frequency components than shorter-duration wave (colored curve). Although these components may not be important for outdoor audibility, they are for indoors perception. —FIG. 4



GROUND OVERPRESSURE PATTERNS for aircraft in accelerated and steady flight. —FIG. 5

the higher-frequency content that affects the audibility sensations of a person outdoors is roughly equivalent for the two different waves. One can see, however, that the wave of longer duration has stronger low-frequency components. Although these may not be important for outdoor audibility, they are important for the perception of sonic booms indoors.

Perhaps I should point out that the main feature of the airplane signature that differentiates it from the bullet signature is its longer time duration. This difference results in dissimilar subjective reactions. Because of its longer time interval, airplane exposure is recognized as two explosive sounds or booms. On the other hand bullet exposure is more like a single crack for two reasons. First, it has a predominantly high-frequency content. Second, the two compression phases of the N wave that normally produce the booms are so close in time that they cannot be separately identified by the human ear

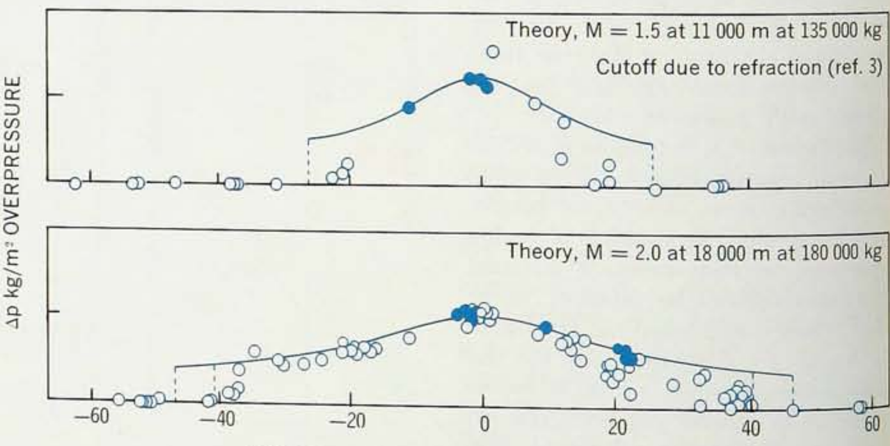
Sonic-boom exposures

To define the nature and extent of sonic-boom ground-exposure patterns I have included the data of figures 5 through 8 from references 2 and 3. Figure 5 shows schematically, by means of the colored area, the shape and extent of the exposure pattern for a proposed supersonic transport flight. The booms are first observed approximately 160 km from the point of take-off; the pattern is terminated at approximately the same distance from the destination. The pattern can be several thousand miles in length, but it does not encompass the airports or their immediate vicinities. The width of the pattern is generally greater for increased Mach number and aircraft altitude; for proposed supersonic-transport operations it will extend 50 to 65 km on each side of the ground track. Peak overpressures (Δp) are not uniform within the colored area. They are highest in the transonic acceleration region and are generally greater along the ground track than near the edges of the pattern.

In addition to peak overpressure other features of the sonic-boom signature, such as rise time (τ) and time duration (T) as defined in figure 5, are significant in loudness determination and aural identification.

The lateral spread patterns for the XB-70 aircraft at two different altitudes are defined in figure 6. For the flight conditions noted the highest pressures near the ground track are of the order of 1.2 grams/cm^2 (2.5 lb/ft^2); these gradually reduce to small values at the extremities of the pattern. Because of a decrease in size and weight, other military aircraft generally have smaller boom pressures than those of figure 6 for similar operating conditions. Proposed supersonic transports, because of optimized volume and lift distributions, will also have lower overpressures even though their gross weights may be greater than that of the XB-70.

Pressure variations of the magnitudes noted above are not large by comparison with others experienced in routine living. They are, for instance, smaller than that experienced in a 15-meter change in level on an elevator and markedly less than is associated with a dive into a swimming pool.



OVERPRESSURES for XB-70 aircraft as a function of lateral distance for two different Mach numbers, altitudes and gross weights. Open circles are averages of 3 to 6 microphones; solid circles are averages of 33 to 40 microphones. Because of smaller size and weight, other military aircraft generally have lower pressures. —FIG. 6

Although adverse physiological effects are thus remote, the more rapid onset of pressure in the boom signature produces sudden audible signals not associated with the other cases.

Another feature of the sonic-boom signature that is significant for both subjective reaction and building response is its time duration. Tracings of signatures measured for different aircraft are shown in figure 7. Those at the left of the figure are for the F-104 aircraft, for which the time duration is about 0.1 sec. Similar signature tracings shown on the right are for the B-58 and XB-70, for which the time durations are approximately 0.2 and 0.3 sec, respectively. One can see that variations in wave shape occur for all of these aircraft. For a given aircraft the main differences between waves occur during rapid compressions. The largest peak overpressure values are generally associated with sharply peaked waves.

Variations in wave shape are associated with effects of the atmosphere, particularly the lower few kilometers, as the shock waves propagate toward the ground. Two features of such variations are significant. When a large number of measurements have been made for a given aircraft flight, the ground-pressure signatures progress in shape in an orderly fashion: A wave-like pattern is defined on the ground such that measurements show a wave-shape progression from peaked to rounded to peaked.

When measurements have been made at given locations for large numbers of flights, one can make statistical analyses of overpressure variations. Samples of such variation data are given in figure 8 as cumulative frequency distributions and histograms showing probability of occurrence. In the left-hand plot are overpressure distributions for a fighter aircraft; the right-hand plot has similar data for a bomber aircraft. I show the probability of reaching or exceeding a given ratio of the measured overpressure value to the maximum predicted value. Straight lines representing normal distributions for the logarithm of pressure have been faired through the data as an aid in interpretation. The data fall near the straight lines; thus approximately normal distributions are indicated. The data for both aircraft for the on-the-track case have approximately the same slope, thus suggesting that similar variability occurs irrespective of signature length. The fighter aircraft data for a 16-km lateral observation point do, however, show greater variability. This variability is believed to result from the longer ray paths in the lower layers of the atmosphere. Other data suggest that the time of day and seasonal changes can also affect signature variability to some degree.

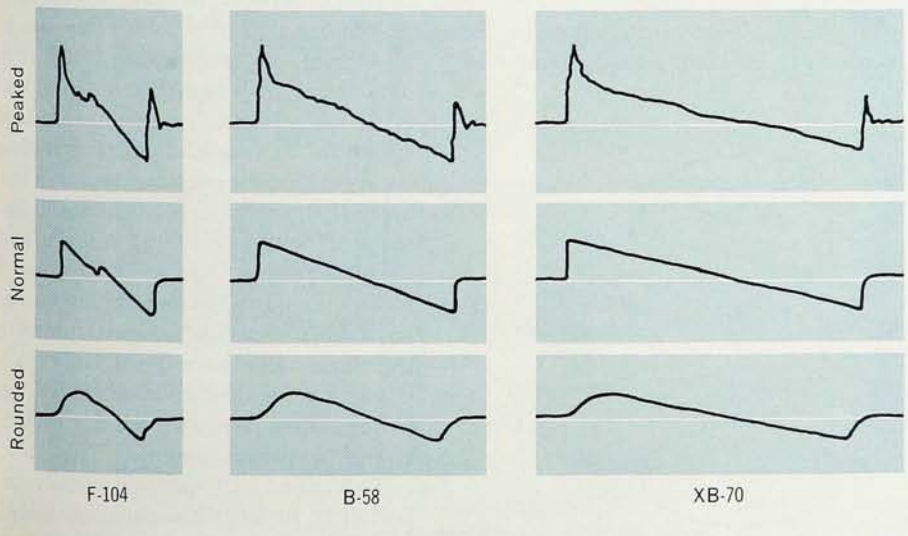
Reactions to sonic booms

Sonic-boom waves from proposed supersonic transport operations will sweep over large areas of the earth's surface and may have significant effects on people within these exposed areas. There is considerable concern about the manner in which people and structures respond to sonic booms and how such responses will affect acceptance of overland supersonic flight. While outdoors a person may be exposed to waves that impinge directly on him; or he may be inside a building where the waves impinge first on the building structure. In this case the building acts as a filter that determines the nature of the exposure stimuli reaching the observer.

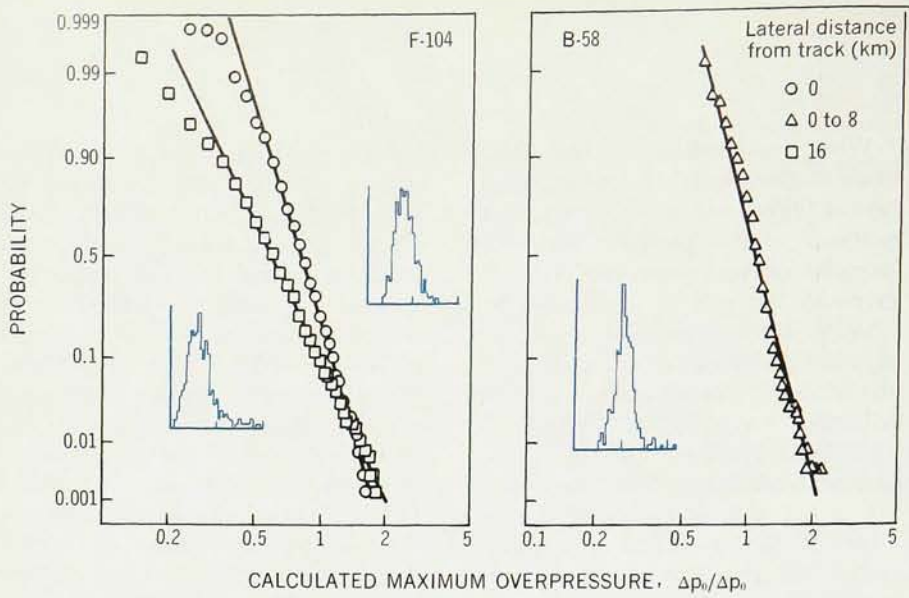
Subjective reactions. With outdoor exposure the person experiences sudden explosive sounds that come without warning and resemble thunder or nearby explosions. For large aircraft the observer will probably hear booms associated with each of the two rapid compressions of the N wave. For smaller aircraft only one boom may be observed because of the smaller time interval (figure 7). The loudness of the booms and the associated startle effects do not appear to depend on the overall time duration but are dependent on the peak overpressure and the rate of onset of overpressure (rise time). The shorter rise time is associated with the louder boom.[4] It is interesting to note that thunder has an energy spectrum very similar to those of figure 4 in the audible frequency range although the signature shapes are markedly different.

The evidence is mixed regarding possible adaptation to sonic booms. On the average there is a definite trend toward increased tolerance to sonic booms by those most familiar with them.[3] Furthermore deer herds near the low-level bombing ranges of Eglin Air Force Base, Florida manifest no appreciable awareness of repeated booms with greater-than-normal intensity. There are, however, certain individuals who display a hypersensitivity to transient noises. For these people as well as for some types of animals adaptation may be difficult.

The ingredients of the inside-exposure situation are included in the chain diagram of figure 9. Sonic-boom-induced excitation of the building will probably involve mainly air loads although in some specific situations the ground excitation path may be impor-



VARIATION of measured sonic-boom pressure signatures at ground level for small, medium and large aircraft traveling in steady, level flight. —FIG. 7



PROBABILITY OF EQUALING OR EXCEEDING a given value of the ratio of measured to calculated maximum overpressures for fighter (F-104) and bomber (B-58) aircraft and for steady-level flight conditions. **—FIG. 8**

tant. Such building vibrations can be observed directly by the subject, and he may also discover vibration-induced noise or, in the extreme case, associated superficial damage to the structure. Given booms may be less acceptable when observed inside because of the associated vibrations.[3,6]

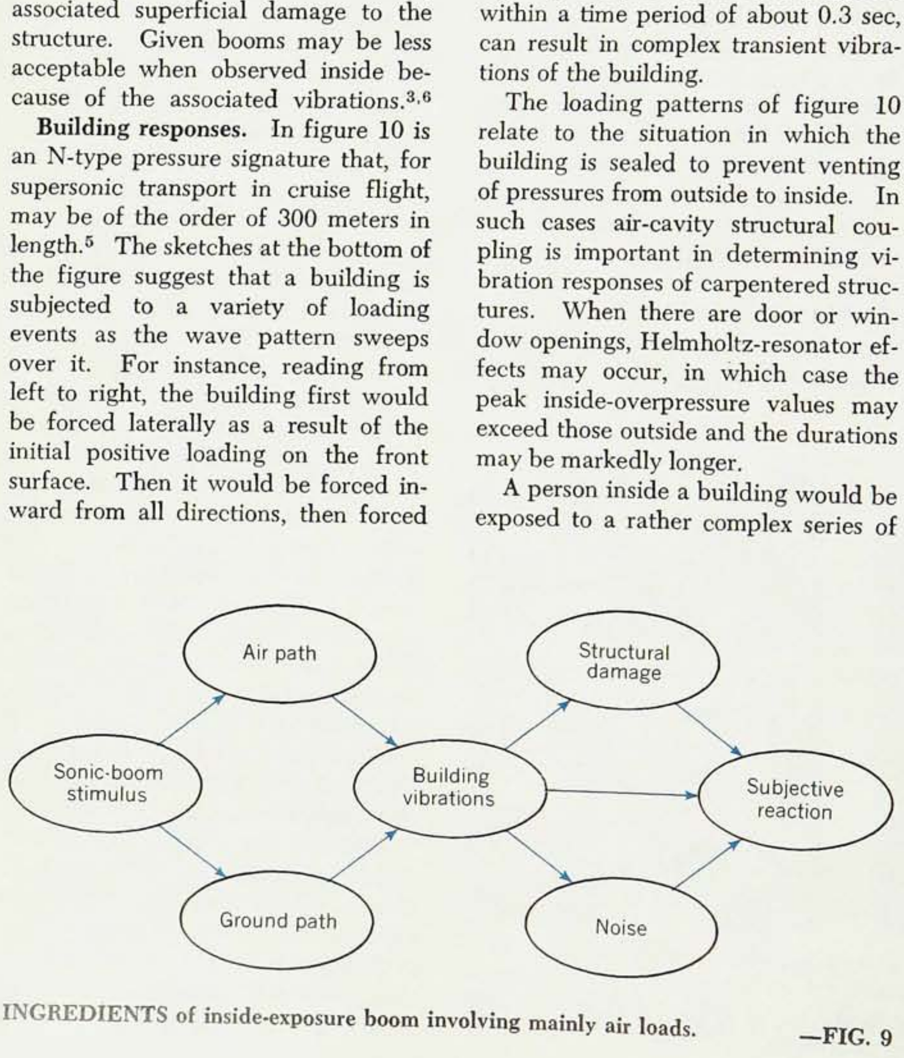
Building responses. In figure 10 is an N-type pressure signature that, for supersonic transport in cruise flight, may be of the order of 300 meters in length.[5] The sketches at the bottom of the figure suggest that a building is subjected to a variety of loading events as the wave pattern sweeps over it. For instance, reading from left to right, the building first would be forced laterally as a result of the initial positive loading on the front surface. Then it would be forced inward from all directions, then forced outward and finally forced laterally again because of negative pressures acting on the back surface. This loading sequence, which would be applied within a time period of about 0.3 sec, can result in complex transient vibrations of the building.

The loading patterns of figure 10 relate to the situation in which the building is sealed to prevent venting of pressures from outside to inside. In such cases air-cavity structural coupling is important in determining vibration responses of carpentered structures. When there are door or window openings, Helmholtz-resonator effects may occur, in which case the peak inside-overpressure values may exceed those outside and the durations may be markedly longer.

A person inside a building would be exposed to a rather complex series of stimuli, including sound, sight and vibration.[2] The nature of sound and vibration stimuli is illustrated in figure 11 for one particular case. The top trace is measured outside-pressure exposure, and the three bottom traces represent building responses. One of these represents the pressure variation inside the building owing to its vibratory motions and the cavity resonances. Although this is a pressure disturbance, it generally occurs in a frequency range that is inaudible to humans. The audible portion of this signal as measured with a separate microphone system has the characteristic shape of the next lower trace and is an order of magnitude lower in amplitude. This audible portion of the pressure signal is associated with high-frequency vibrations of the building structure, particularly wall panels and furnishings. The bottom trace represents the vibration of the floor that would be sensed by a person either directly or through the furniture. Wall accelerations are similar in nature to those of the bottom trace but generally have greater amplitude. Measurements in one- and two-story houses have produced wall accelerations up to about 0.7 g for boom overpressures of about 1.5 grams/cm² (3 lb/ft²). The stresses associated with such building motions are approximately an order of magnitude lower than the design stresses and are lower than those sometimes associated with such activities as door slamming, running, jumping, etc.

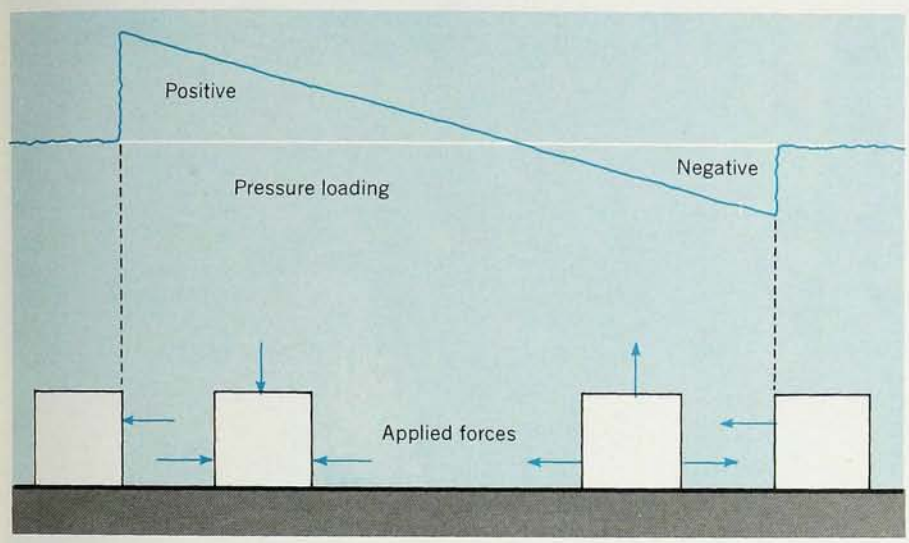
Damage reports. One of the more complex aspects of the sonic-boom problem is that of reported damage to buildings. It is significant that the majority of such reports refer to superficial damage involving the secondary structure or nonload-carrying members; thus safety considerations are not important except for unusual and infrequent cases of falling objects and glass fragments.[6] Even though many claims of superficial damage are associated with very low nominal pressure exposures, few have been truly validated by simultaneous observations; hence claims payments are not indicative of damage caused.

The superficial damage usually reported is, in large measure, associated with stress concentrations in the structure. Stress concentrations in build-

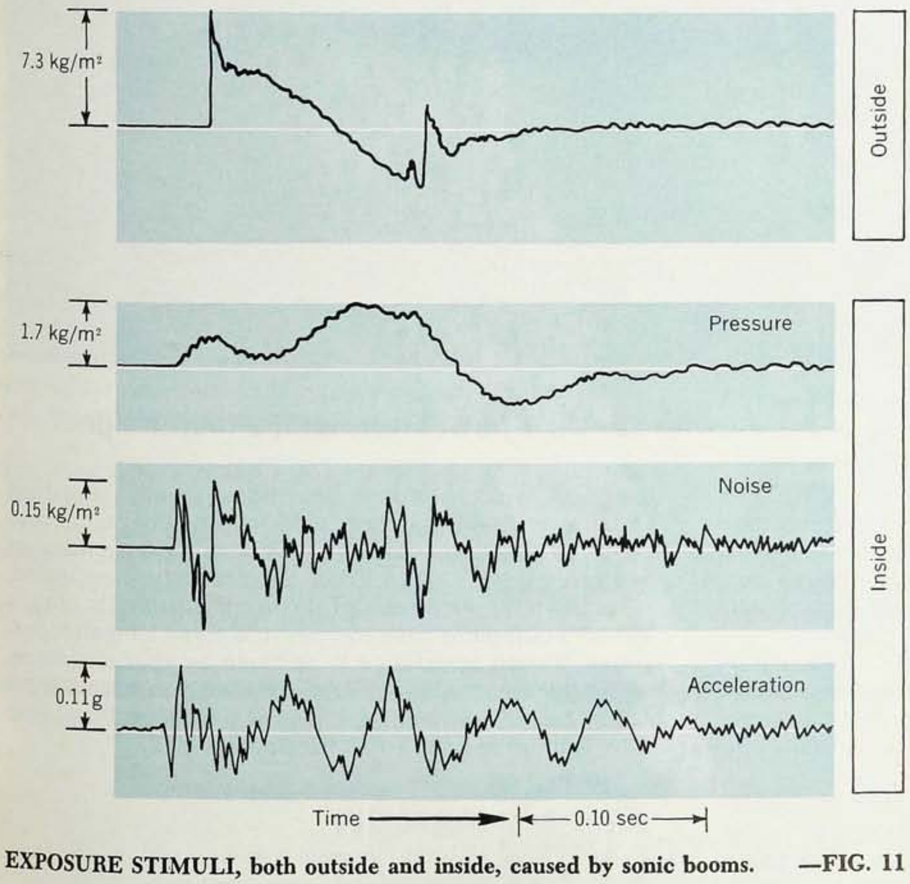


INGREDIENTS of inside-exposure boom involving mainly air loads. **—FIG. 9**

ings may be due to factors such as curing of green lumber, dehydration, settling, poor workmanship, etc. Such factors exist in varying degrees in all carpentered structures and could contribute to failures when a triggering load is applied. The overpressure of a sonic boom has this triggering capability as do vehicular traffic, thunder and wind storms, heavy falling objects and even routine household activities. Well constructed buildings in good repair would not experience serious damage, nor is it likely that they would experience superficial damage. Such superficial damage has been initiated in controlled tests only after repeated overpressures of about 5 grams/cm^2 (5–10 lb/ft^2).[7] Nevertheless numerous complaints are filed in good faith, and there orderly processing is one of the difficult problems resulting from supersonic-aircraft operations.



LOADING EVENTS on buildings that result in complex transient vibrations. —**FIG. 10**



EXPOSURE STIMULI, both outside and inside, caused by sonic booms. —**FIG. 11**

Not all complaints are amenable to logical analyses. Some have been received about sonic booms from scheduled supersonic flights that were canceled. One such caller merely said that she would call back after the next flight. Sonic booms have been blamed for a variety of happenings including the gradual shrinkage of furniture, the breaking of a brassiere strap and the opening of a door to allow entrance by an intruder!

Because booms can startle people and shake buildings and their contents, there is serious concern for public acceptance of the sonic boom. As a result, supersonic transport will be limited initially to overwater operations. There are those who would ban the supersonic transport altogether, and a society for this purpose has been formed. Others are taking a more realistic approach. Consideration is being given to the development of advanced-design aircraft that would minimize the effects of sonic booms. Backup research is already underway.

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