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THE EFFECTS OF SONIC BOOM AND SIMILAR IMPULSIVE NOISE ON STRUCTURES

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U.S. Environmental Protection Agency
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ABSTRACT

A brief discussion is given of the physical nature of sonic booms, and other impulsive noises, and the parameters, such as over-pressure, duration, and mechanical impulse, which are used to characterize booms. This is followed by an overview of the response of structures - - particularly buildings -- to sonic booms and a review of the damage history observed due to supersonic overflights. The report concludes with a summary of the observed effects of impulsive noise on terrain and natural structures.

Effects of Sonic Booms and Other Impulsive Noises on Property

1. Introduction

Impulsive noise has its origin in transient events such as explosions and the passage of aircraft in supersonic flight. In both of these examples, the events cause intense shock waves that are perceived as one or more abrupt rises in sound pressure. In this section, the effects of impulsive noise will be discussed in terms of sonic booms generated by supersonic aircraft. However, if the appropriate parameters are known, the discussion is also applicable to explosions and other impulsive noise sources.

Much of the data on the effects of sonic booms comes from a comprehensive series of observations carried out by the Federal government. Three of the series were observations at cities in the Midwest. The cities, dates, and total number of overflights producing booms were as follows: St. Louis (1961-62), 150; Oklahoma City (1964), 1253; Chicago (1965), 49. Another series of experiments was carried out at Edwards Air Force Base in California (1966). Many of the results summarized in the following are drawn directly from the report of the Sonic Boom Panel (of the International Civil Aviation Organization-ICAO) which included data from the four series of tests.

2. Nature of Sonic Booms and Other Impulsive Noises

The passage of an aircraft whose speed is greater than the local speed of sound in the atmosphere generates an impulsive noise called a sonic boom. The boom is observed at ground level as a succession of two sharp bangs, separated by a short time interval. Different parts of such an aircraft radiate strong pressure waves in the air that grow into shocks. Far from the plane these coalesce into a bow (leading) shock and a trailing shock. The two shocks form cones in the atmosphere that intersect the earth's surface in hyperbolas. These intersections trace out a path called "the boom carpet". In a typical operation, an aircraft climbs subsonically to an altitude at which it accelerates to supersonic speed and first generates a boom. The boom follows in the wake of the aircraft until it decelerates to subsonic speeds. Thus the "boom carpet" stretches from the region at which the plane accelerates to supersonic operation to the region where it decelerates to subsonic speed. The length of a "boom carpet" may be thousands of miles. It should be emphasized that sonic booms occur in the wake of a supersonic aircraft at all times that it travels faster than the speed of sound, not only at the instant when the aircraft passes from a subsonic to a supersonic speed.

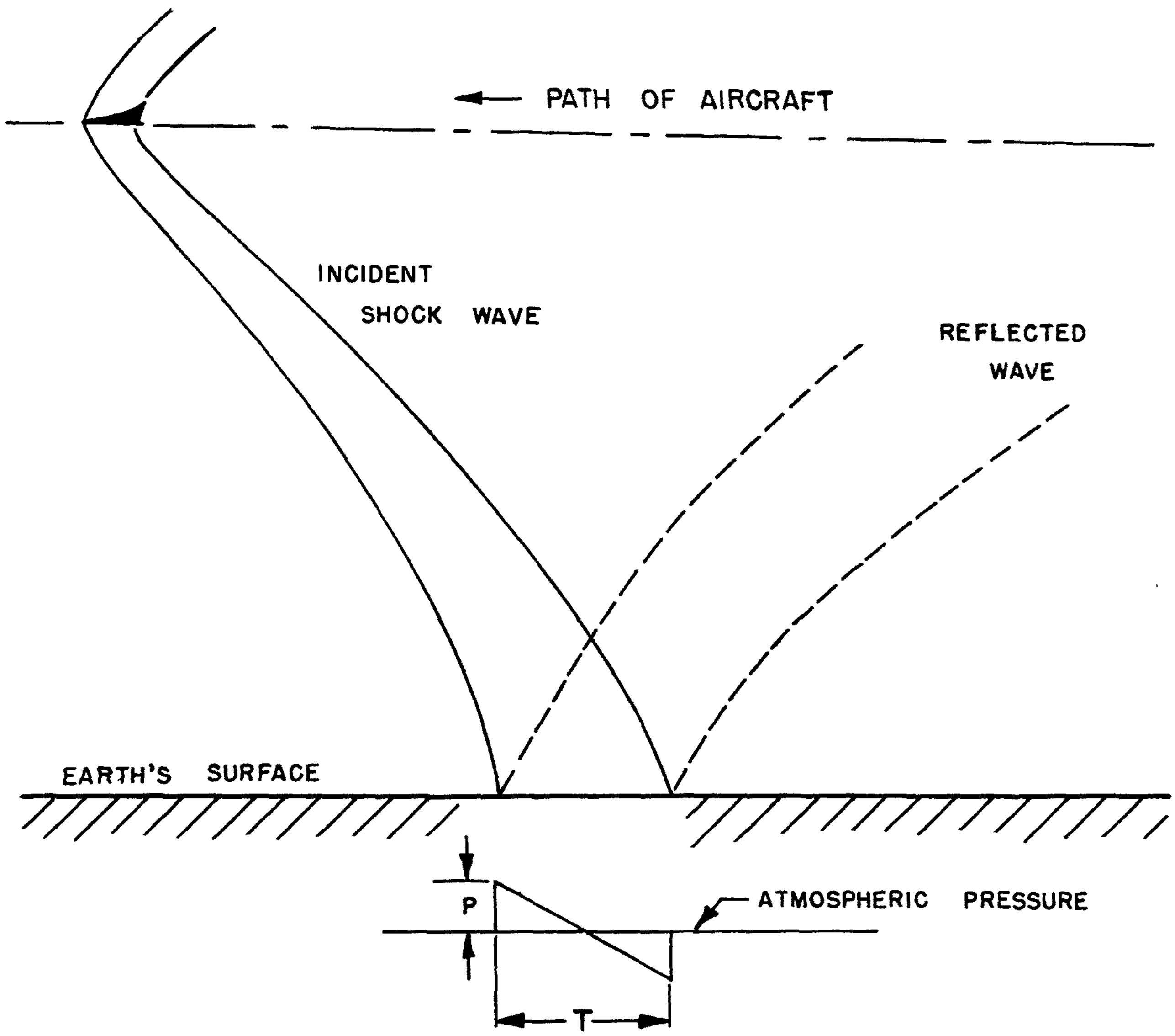

Figure 1.

Physical nature of the sonic boom phenomenon. The distance between the pressure jumps of the shock wave is drawn to a different scale than the altitude of the aircraft. Variation of sound pressure with time in an N-wave is shown in the lower sketch.

At a transducer on the earth's surface, the passage of a sonic boom is registered as an abrupt increase in pressure at the bow shock to a peak value greater than ambient called the over-pressure. The sound pressure then falls below ambient to a value called the under-pressure. There is then an abrupt rise in pressure back to ambient as the trailing shock passes. This change of pressure with time is called the "boom signature". The over-pressure $\underline{P}$ is roughly equal to the under-pressure. The waveform of the sonic boom's sound pressure is often observed to be an almost ideal N-wave of peak pressure $\underline{P}$ (see Figure 1). In such an N-wave the pressure jumps to a peak value $\underline{P}$, falls linearly (with time) to a negative value of the same magnitude, and then jumps back to the ambient atmospheric pressure. The peaks are separated by an interval of time $\underline{T}$.

The intensity of a sonic boom at the earth's surface and the width of the "boom carpet" that it traces are dependent on atmospheric conditions and airplane characteristics. The volume, weight, length, lift characteristics, altitude and Mach number of the aircraft affect both the amplitude and duration of the boom. Outside of the carpet the passage of the aircraft is heard only as a low-pitched rumble.

A convenient measure, for discussing the effects of sonic booms, is the number of boom-person exposures -- the experience of one sonic boom by one person. It is used as a measure of the number of times a sonic boom is experienced, either on different occasions by the same recipient, or on the same occasion by different recipients.

A useful survey of sonic boom theory may be found in an article by Hayes (1).*

3. Parameters Governing Response of Structures to Impulsive Noise

When the effects of sonic boom on structures are being considered it is useful to characterize booms by one or more of the following parameters:

1. The over-pressure, $\underline{P}$.
2. The time interval between shocks, $\underline{T}$.
3. The maximum mechanical impulse, $\underline{I}$. This is the time integral of the boom signature when the pressure is greater than ambient.

In an ideal N-wave, the maximum impulse is simply $I = PT/4$.

*Numbers in parentheses refer to papers and reports listed in Sec. 6 References.

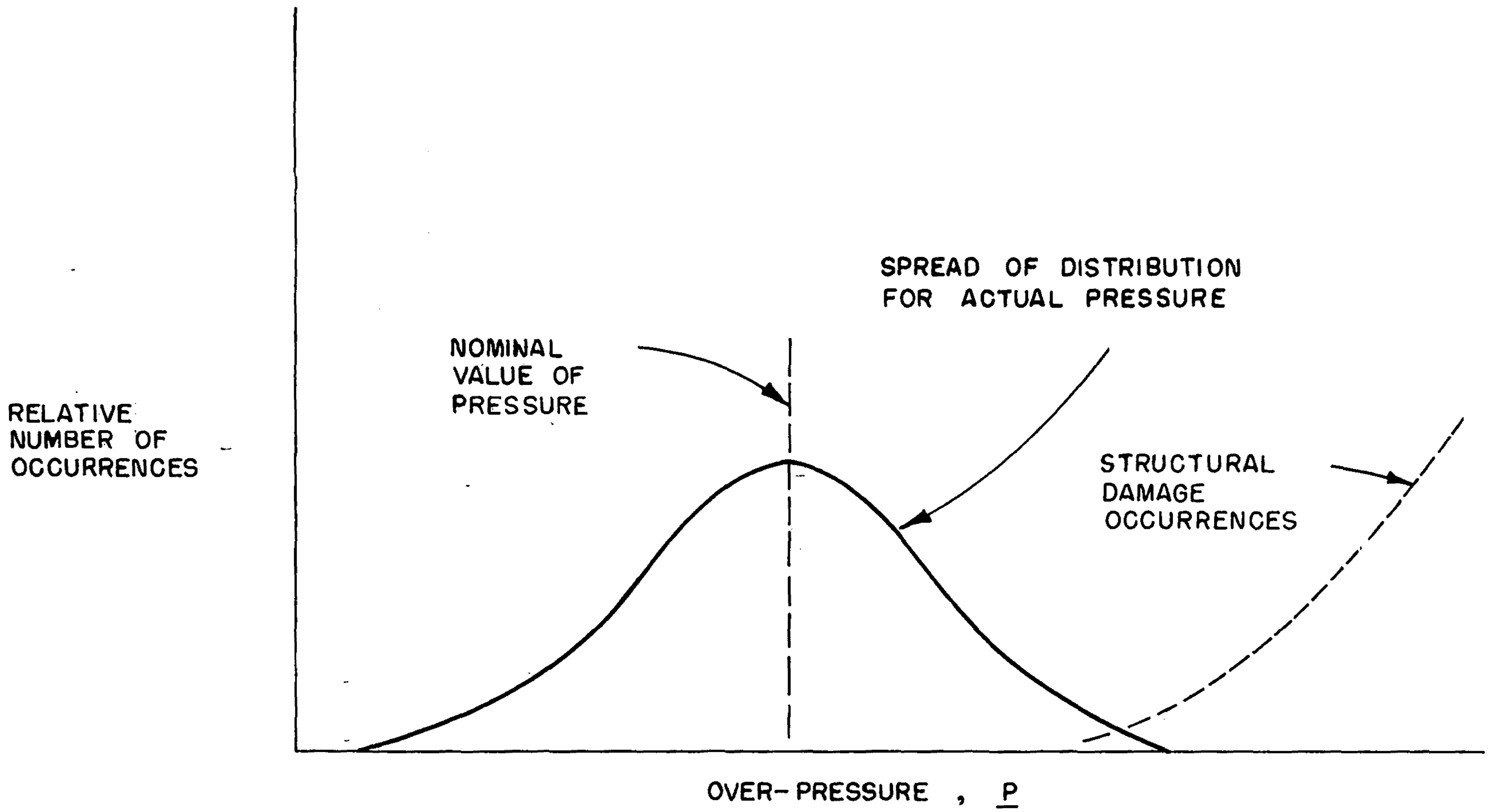

Figure 2.

Sonic Boom Schematic

Schematic showing nature of the sonic boom-induced damage problem. For booms of fixed time interval T; hence impulse I is proportional to P.

A sonic boom with an over-pressure of 100 newtons/m^2 (or about 2 lb/ft^2) is typical of signatures generated along the center line of the "boom carpet" by a supersonic bomber (or SST) cruising at 60,000 feet and a speed of Mach 2. In this example the width of the "boom carpet" would be approximately 90 nautical miles, and the interval T between shocks would be about 300 milliseconds.

Although a sonic boom is heard as two sharp bangs, most of the mechanical energy that it carries is contained in a band of very low frequencies well below the threshold of audibility. When the energy of a boom is analyzed into frequency components or bands, the component with most energy is close to a frequency equal to $1/T$. For a boom with T equal to 250 milliseconds, this frequency is less than 5 hertz. Most of the energy of the boom is carried in this band below 5 hertz.

The impulse from a sonic boom sets the components of a structure, for example the windows of a building, into vibration. If the natural time period of vibration of the component is approximately equal to the interval, T, of the boom, the response of the component will be relatively large. The response can be complex but it is useful to compare the actual component to a simple, one-dimensional oscillator. Such a simple system has a response governed by the maximum impulse, I, and by the peak pressure P. We might expect that:

1. If the vibrational period of the component is greater than T, then the vibrational response will be governed by the impulse I.
2. If the period is less than T, then the response will be governed by the peak pressure, P.
3. When the vibrational period and T are approximately equal (resonance), the response will be relatively large but limited by internal friction in the component.

It follows that the response of a <u>particular structure</u> to sonic booms will be highly variable among structures and unpredictable, owing to the factors cited above. But the response of a large <u>collection</u> of structures -- e.g., the buildings in a community -- will be fairly predictable in statistical terms. The variable factors will average out to a considerable degree. This suggests a statistical approach to the problem. For example, the number of validated damage claims per million boom-object exposures might be correlated against the peak pressure of the sonic boom.

Figure 2 presents a current view of the nature of the sonic boom-induced damage problem in statistical terms. The right hand curve shows how structural damage may be expected to increase with the over-pressure of specific sonic booms. However, for a given overflight, the sonic booms in a community show a spread about a nominal characteristic peak pressure due to atmospheric effects, etc. Thus even when the <u>nominal</u> value of the peak pressure is well below the threshold value for no damage, there will be some few actual booms -- represented by the upper end of the bell-shaped curve -- that overlap into the damage range. This implies that the damage threshold (not shown on the Figure) in terms of nominal peak pressure would be much lower than it is in terms of actual peak pressure. This is relevant to community damage claims for which only the nominal peak pressure -- if anything -- is cited.

4. Response of Structures to Sonic Booms

General. Sonic booms can induce transient vibrations in various types of structure. The manner in which a given structure vibrates is basically the result of the pressure signature distributed over the entire structure. The structural response will depend on the structure's location, size, shape, type of construction, manner of assembly, and state of maintenance, and on the special form of the sonic boom's pressure signature and its variation over the structure. The frequency-response characteristic of the structure will also have a major influence. Seismic transmission -- vibrational energy transmitted through the earth -- may also play a minor role in exciting the vibrations.

It appears that the structures most susceptible to sonic boom loads are buildings, be they residential, public, commercial, etc. By and large, the damage caused by sonic booms will be confined to brittle secondary structures, such as window glass and plaster. There is, however, an exceedingly small (but non-zero) probability of a greatly magnified boom striking a building whose primary structure is expectionally weak or faulty (near the end of its "lifetime"). In the case of extensive overland flights by supersonic transport aircraft, rare instances of structural collapse from this cause can be expected.

Representative indoor peak displacement amplitudes are 0.8 mm (0.032 in.) for an exterior wall of a wood frame residence structure and 0.5 mm (0.02 in.) for windows, at boom peak pressures of 108 N/m^2 (2.25 lb/ft^2). Deflections of this order and larger are observable in large plate glass windows under buffeting by moderate winds. This is not surprising, since the cited pressure could be produced locally by the impact of a 48 km/hr (26 knot) gust, although with a much different waveform.

Modern Structures and Components. A single sonic boom with an over-pressure of 100 newtons/m^2 at ground level causes little or no damage to modern residential buildings, other than to brittle secondary structures such as window glass and plaster. This result was amply demonstrated in the series of tests made by the Federal Government on the effects of sonic booms produced by supersonic aircraft flights. The most useful tests with instrumented and monitored structures are probably those conducted at Edwards Air Force Base in California (2) during 1966 to determine the response of "typical" house structures.

The structural response portion of the Edwards experiment was designed to meet the following objectives:

1. Determine the response or reaction of structures to sonic booms generated by XB-70, B-58, and F-104 aircraft.
2. Investigate any damage resulting from these sonic booms.
3. Develop a means of predicting structural response and possible damage from sonic booms generated by any supersonic aircraft (SST) based on data from aircraft used in the experiment.

With these objectives in mind, two test house structures and a bowling alley at Edwards Air Force Base and a two-story frame house structure in Lancaster, California, were instrumented.

The analysis of structural response data led to the following findings:

1. Sonic booms from large aircraft such as the XB-70 and an SST will affect a greater range of structural elements (those elements responsive to frequencies below 5 hertz) than will sonic booms from smaller aircraft such as the B-58 and F-104.
2. No damage that could be attributed to sonic booms was observed in the test structures during these experiments.
3. Three reports were received of glass damage to non-monitored structures at Edwards Air Force Base that could be attributed to sonic booms.

Similarly, instrumented tests conducted at the White Sands Missile Range, New Mexico, and at Oklahoma City, Oklahoma, in 1964 showed that damage was limited to the cracking of plaster and the breaking of window glass (3).

British experience has largely substantiated the U.S. findings. Measurements of the sonic boom from the Concorde when flying at an altitude of 45,000 feet at Mach 1.3 showed characteristic over-pressures of 110 newtons/m^2. The series of flights of the Concorde along the west coast of the United Kingdom showed that booms of such over-pressures would at most result in damage to plaster and window glass.

Most tests of the effects of sonic booms on structures have been made by the use of aircraft at level supersonic flight at high altitudes creating booms with over-pressures of the order of 50 to 250 newtons/m^2 (1 to 5 lb/ft^2). In that range of pressures there is little evidence of damage to modern residential buildings, except to plaster and window glass, and the probability that well-installed modern glass will fracture at such over-pressures in very low indeed (4).

However, booms from supersonic aircraft maneuvering at low altitudes have caused serious damage to structures. A well-documented example is the extensive damage to a new airport terminal at Ottawa, Canada, in 1959 when a subsonic jet fighter at 500 feet over the control tower accidentally went supersonic for a brief time (5). Damage, mostly to window glass, was estimated at $300,000. A similar incident caused extensive damage to window glass at the U.S. Air Force Academy on 31 May 1968.

One is led to the conclusion that the only structural material of importance fractured by sonic booms is glass. This conclusion is of great importance even though there seems little possibility of window glass fracturing under the impact of a boom with over-pressure in the range 50-250 newtons/m^2. Many high-rise modern buildings have facades that are as much as 80 percent glass, and an accidental boom such as that at Ottawa would have a catastrophic effect. It is not necessary to dwell on such improbable accidents, however, and instead we shall try to understand whether or not a large supersonic aircraft in its scheduled operations might cause window glass along the "boom carpet" to fracture.

Controlled tests such as those made by Parrott (6) have demonstrated that window glass will be shattered by sonic booms only when the over-pressures exceed 1000 newtons/m^2 (20 lb/ft^2). This limit is a factor of 10 larger than expected boom over-pressures from supersonic planes cruising at high altitudes. In general, glass in modern buildings is specified so that it will withstand wind pressures anticipated in a given locality. For example, glass in the new Sears Building in Chicago will withstand pressures of 3000 newtons/m^2 (60 lb/ft^2). On an average, glass windows are now installed so that they will withstand wind pressures of 3500-4000 newtons/m^2 (70-80 lb/ft^2). One would therefore expect that in a large city there would be windows meeting these modern design standards and windows that would shatter under pressures much less than those pressures, but greater than a lower limit of 1000 newtons/m^2. The question that we must therefore answer is whether a supersonic aircraft in its scheduled operations would ever generate booms with over-pressures at ground level greater than 1000 newtons/m^2.

Extensive measurements have been made of the variation in sonic boom signatures caused by atmospheric effects (7,8). The results support the conclusion that magnification of the over-pressure and the impulse generated by a supersonic plane in level flight at high altitudes is at most of the order of 3.

Another phenomenon that leads to a magnification of boom pressure occurs when an aircraft accelerates from subsonic speed. The boom generated by the plane during the transition results from a focussing effect, and may be much greater than that associated with the plane in level supersonic flight. Such a boom is called a "focussed boom" or a "superboom". It differs from the boom associated with cruising supersonic flight in that it does not move with the plane and its impact is felt only within a narrow crescent several hundred meters wide. The focussing that we have described is caused by acceleration and the resulting boom called an "acceleration superboom". Turning maneuvering and atmospheric refraction can also cause focussing, and a resulting magnification of the over-pressure.

Focus factors of the order of 10 have been reported in French field tests, Operation Jericho, and Pierce has made a study to determine whether such factors are reasonable (9). Pierce tentatively came to the conclusion that a factor of 7 seems more likely. In the design of the Boeing SST, it was anticipated that focussed booms with over-pressures as high as 750 newtons/m^2 could occur during transonic acceleration as compared with the predicted over-pressure of 100 newtons/m^2 for the SST in level supersonic flight (10).

A third phenomenon that leads to magnification of over-pressures is vibrational resonance within structures. These resonances may be of two kinds: those associated with vibrations in structural members such as beams and those associated with enclosed volumes such as rooms coupled with the exterior by windows and to the interior by doors. The second is of immediate interest. The first we shall consider briefly in a later paragraph.

A room coupled to the exterior by an open window and having an open door leading to another room will behave as a Helmholtz resonator. If an impulsive noise such as a sonic boom is incident on one of the open windows, one would anticipate that the maximum over-pressure measured within the room might be magnified by some factor. Such resonances have been studied by Koopman and Pollard (11), Pretlove (12), and Mayes and Newman (13). From this work it seems plausible that a magnification factor of 2 might be brought about by room resonances. This conclusion can be contrasted with reported resonance magnifications of 10 obtained by French scientists in field tests in rooms with open windows. It might be added, however, that room resonances are in practice phenomena associated with complicated, coupled systems, and a definitive answer awaits further study.

A fourth phenomenon that might contribute to the magnification of a sonic boom is that associated with reflection from a rigid surface. A single reflection from a rigid surface can cause a doubling of the boom over-pressure. Double reflections by two intersecting surfaces can quadruple the boom pressure. Slutsky and Arnold investigated this effect and found that a rigid fence did indeed cause such a doubling (14).

It seems highly improbable that all of these factors would come into play at the same time, but it does seem possible that magnification factors of 20 could occur. Such occurrences would be unusual and most likely limited in geographical extent. The relative importance of such effects is still uncertain.

Most of the energy in a sonic boom is associated with spectral components of the order of 5 hertz or less, and it might be expected that strong structural resonances would be found in large buildings with resonances in that region. Such responses of large buildings to sonic booms have apparently not been studied, and the usual conclusion is that such structures are damped enough to inhibit the build-up of vibrations initiated by impulsive sources. The British studies reported by Newbury (15) showed that structural vibrations could indeed build up under the influence of sonic booms, and hence cast some doubt on that argument. One of the few large structures that might be damaged by a sonic boom is a long roof lightly attached to the main frame of a building.

The ICAO Sonic Boom Panel has studied the results of several series of tests (16). Their summary of physical and financial damage to buildings is as follows.

Although many laboratory studies on building components are currently in progress, very little well-documented information from systematic studies has been reported. Indications to date are that plate glass windows of 6 mm (0.25 in.) thickness and 2.1 m by 3.6 m (7 ft by 12 ft) dimensions have successfully withstood repeated simulated sonic boom loadings with a peak pressure of up to about 960 newtons/m^2 (20 lb/ft^2). Such windows were mounted with the care required in normal mounting with commercial frames, mullions and retainer clips.

Studies involving flights of aircraft over instrumented and monitored structures have been completed for a number of residential and commercial building structures, and for a variety of window configurations. Window experiments which involved conventional residential-type sashes and pane dimensions of 0.3 m by 0.3 m (1 ft by 1 ft) and 0.9 m by 0.9 m (3 ft by 3 ft) showed no observable damage at nominal peak pressures up to 144 newtons/m^2 (3 lb/ft^2) from high altitude flights and at peak pressures of about 960 newtons/m^2 (20 lb/ft^2) from low altitude flights.

Building structures located at Wallops Station, Virginia; St. Louis, Missouri; Oklahoma City, Oklahoma; and Edwards Air Force Base, California, were closely monitored during about 2000 supersonic overflights. No damage to windows, to wall plaster and so forth was observed due to nominal peak pressures that were as high as 288 newtons/m^2 (6 lb/ft^2 in the Edwards tests. A similar negative result has been reported in very recent tests conducted in Sweden extending to much higher peak pressures.

In the U. S. A. buildings, preliminary engineering surveys were made to determine the initial condition of the buildings. These surveys indicated the existence of several hundreds of plaster and paint cracks, some of which increased in length during the test period. It was not clear whether the observed extension of the cracks was greater than could have been expected as a result of the temperature and humidity variations during the same period.

In a special experiment at White Sands, New Mexico, involving about 1200 supersonic flights over 20 different types of residential and commercial structures, no damage of any kind was observed up to nominal peak pressures of 158 newtons/m^2 (3.3 lb/ft^2).

Measured vibrational accelerations and displacements in all monitored structures indicate that such occurrences as door closing, door slamming, and pedestrian traffic create accelerations in the structure of the same order of magnitude as those measured due to sonic booms.

In addition to the statistical nature of glass breakage, some inconsistency between laboratory and community data will undoubtedly exist due to the willingness of claims adjusters to allow small claims rather than pursue the investigation to proof of damage cause.

During controlled flight programs (but with unmonitored building structures) at Oklahoma City; Edwards, California; Chicago, Illinois; and St. Louis, Missouri, many reports were received of building damage to both commercial and residential structures. The nominal peak pressure values differed from program to program and, among the programs, covered the range from approximately 48 newtons/m^2 to 154 newtons/m^2 (1.0 to 3.2 lb/ft^2). As an illustration of the type of damage reported, the following information is presented from an analysis of the complaint reports in the St. Louis area. The median peak pressure appears to have been of the order of 86 newtons/m^2 (1.8 lb/ft^2) and the distribution by frequency of occurrence (in percent) of adjudged valid claims for category of damaged elements is as follows:

	Percent
Glass.	37
Plaster only	22
Glass and plaster.	11
Bric-a-brac	18.5
Tiles and fixtures	7.5
Other structural damage. . . .	4

TABLE 1 - SONIC BOOM DAMAGE DATA

Boom dates	Metropolitan population	Total SS overflights	Median peak overpressure		Boom-person exposures (millions)	Number of complaints	Number of claims filed	Number of claims paid	Value of claims paid
			N/m^2	lb/ft^2					
St. Louis, 1961-62	*2,600,000	150	86	1.8	390.0	5,000	1,624	825	$58,648
Oklahoma City, 1964	† 512,000	1,253	58	1.2	642.0	15,452	4,901	289	123,061
Chicago, 1965	6,221,000	49	86	1.8	304.5	7,116	2,964	1,442	114,763
Total	9,333,000	1,452	†† 84	1.76	1,336.5	27,568	9,489	2,556	$ 296,472

*Metropolitan area as given in National Geographic Atlas, 1963 edition, rounded off to nearest thousand population.
† Greater St. Louis population affected by boom.
†† Average.

TABLE 2.-ANALYSIS OF SONIC BOOM DAMAGE DATA

	Complaints per million BPE	Claims per million BPE	Paid-out claims per million BPE	Paid-out damage per million BPE
St. Louis	12.8	4.16	2.11	$151
Oklahoma City	24.1	7.63	.45	192
Chicago	23.4	9.75	4.74	377
Weighted average	20.6	7.10	1.91	$ 222

Engineering evaluations were made of a portion of the complaints received and it was judged by competent engineers and architects that about one-third of the alleged-damage incidents were valid. The validated complaints included those where the sonic boom was interpreted as a possible triggering mechanism in the presence of other factors affecting structural integrity.

Financial Damage to Buildings. In the foregoing, the physical nature of the sonic boom damage problem has been brought out. Another measure of the extent of damage is the number of claims filed. In this connection Concorde 001 carried out 43 supersonic flights over France under conditions different from expected commercial flight operations in that, for example, a great number of focused booms were generated during maneuvers at supersonic speed. Furthermore, during these flights 27 focused booms due to transonic acceleration reached the ground. For 40 million boom-person exposures (BPE) 56 claims were lodged and are presently being processed. The financial settlement of claims judged to be justified is at present unknown.

In the last decade, military aircraft have logged several hundred thousand hours of supersonic flight training time over the continental United States. Damage claims from such training operations arise from peak pressures that occasionally range as high as 4800 newtons/m^2 (100 lb/ft^2). Of all the paid claims 65 percent were for glass and 18 percent were for plaster damage.

Tests in three cities -- St. Louis (1961-1962), Oklahoma City (1964) and Chicago (1965) -- account for the overwhelming bulk of the systematic study of boom-person exposures in published reports to date. The data on boom-person exposures, numbers of complaints, claims filed, and finally value of damages awarded are given in Table 1. The data are analyzed and reduced on the basis of boom-person exposures (BPE) in Table 2. But perhaps the most useful yardstick of structural damage is the amount of money paid out in settlement of damage claims per million boom-person exposures in these three highly publicized tests. For the circumstances and cities of these surveys this averages to about $220 per million boom-person exposures.

Care must be taken in applying the above estimate of damage costs per million boom-person exposures in other contexts; for example, at other average boom intensities. The samples of costs underlying the estimate vary by more than a factor of two; thus no consistent pattern of costs among the cities has emerged. (Errors in consistency in estimating the population affected in the different cities may be a factor.) Also structural damage susceptibility, varying building codes, repair costs, reimbursement policies (whether lenient or strict), all probably vary widely among cities and countries.

Concluding Remarks. Laboratory and controlled overflight experiments with monitored structures were generally negative as regards sonic boom damage from peak pressures up to 960 newtons/m^2 (20 lb/ft^2); there was some extension of plaster and paint cracks. Controlled overflights with unmonitored structures subjected to a range of nominal peak pressures from about 48 to 154 newtons/m^2 (1 to 3.2 lb/ft^2) resulted in damage claims, predominantly for glass, of the order of one per 100,000 population per flight, i.e., 100,000 boom-person exposures, with about one in three being judged valid. Such claims-per-exposure statistics, while useful as rules of thumb, cannot begin to adequately reflect the structural variables needed to predict response in new situations.

Flight test series in Oklahoma City, Chicago and St. Louis resulted in over 10^9 boom-person exposures. The associated property damage resulted in paid-out claims averaging about $220 per million boom-person exposures. However, the payment criteria were different in Oklahoma City, Chicago and St. Louis and numerous small claims were paid without investigation or inspection. On the average, frequency of paid claims for glass damage far exceeded that for plaster damage.

Prestressing, stress concentrations and faulty material often found in structures are considered to account for part of the difference between the results of the two sets of experiments. Another part of the difference is attributed to random modifications of the booms, as discussed in connection with Figure 2. The remainder is considered to arise from the prior history of the unmonitored structures. A structure may accumulate damage (often not visible) from vibration, weathering, aging, etc., which eventually terminates its life. The sonic boom could be another such contributor, and invisible damage could be considered to accumulate with repeated exposure. An uncertainty that the sonic boom poses is how it compares in its effect with the effects due to the existing environment. Visible damage from a sonic boom, when it occurs, will depend in part on how much of the lifetime of the structure has already been consumed.

Historical Buildings. Historical and archeological structures are examples of man-made buildings that have aged. In order to determine the effects of sonic booms on historical structures, part of Exercise Trafalgar was devoted to studies of the effect of sonic booms on ancient buildings. This exercise was a series of supersonic test flights for the British-assembled Concorde 002 along the west coast of the United Kingdom.

The possible effect of sonic booms on cathedrals was studied by comparing the vibrational responses likely to be induced by sonic booms typical of the Concorde overflights with those induced by the existing environment. Small explosive charges were used to simulate the sonic bangs. Warren (10) has reported that the results show the sonic boom is a significant addition to the existing environment for many parts of the fabric of a cathedral. However, the level of vibration induced would still be well below the level that would cause instantaneous damage. He concluded that the problem becomes one of attempting to assess the long-term effect of repeated booms.

The results of the British studies on historical structures accords well the the statement of the Sonic Boom Panel of the International Civil Aviation Organization (16):

> "The notion of a 'lifetime' of a given structure may throw further light on the problem of sonic-boom induced damage. This is a new concept that is not yet commonly used by building engineers. Every structure accumulates damage (much of it not visible) from a variety of environmental conditions: wind loads, mechanically induced vibrations, temperature and humidity changes, weathering, general aging, etc. This may eventually terminate its life. Cumulative damage may therefore be referred to in a context approximating structural fatigue. The likelihood of visible damage owing to a sonic boom thus depends upon how far the structure is along its lifetime.
>
> "A structure or structural element near the end of its lifetime would have a lowered threshold for damage and conversely. That is to say, the stress that will break a structural element is not invariable with time, but varies during its lifetime."

There have been no controlled experiments of the effect of sonic booms on archeological or natural structures. The extent of our knowledge is limited to information received by the National Park Service. In 1967, the Service reported (17) the following parks had reportedly been damaged by sonic booms:

1. Canyon de Chelly National Monument, Arizona. Prehistoric cliff dwellings in Canyon de Muerto were damaged on 1 August 1966 by fall of overhanging cliffs immediately after a sonic boom. In all, 83 such booms were noted over the monument. Booms from low flying aircraft caused ground vibrations that could be felt.
2. Bryce Canyon National Park, Utah. From November 2, 1965 to February 23, 1967, 15 sonic booms were recorded. On 12 October 1966, three booms were followed by the fall of 10-15 tons of earth and rock from a formation along the Navajo Loop Trail.
3. Mesa Verde National Park, Colorado. Daily booms rattled windows and lighting fixtures in administration buildings but no damage was reported in Mesa Verde Cliff dwellings.

5. Effect of Impulsive Noise on Terrain and Natural Structures

Earth Surfaces. Sonic booms apply moving loads to the earth's surface. On land there are two major effects. One is the "static" deformation which travels with the surface load, and the second is a train of Rayleigh surface waves which travel at a different speed. The former is always the larger effect. The maximum ground motion recorded in tests is about 100 times the largest seismic noise background, but is still less than one percent of the accepted seismic damage threshold for residential structures (18). The tests showed further that peak particle velocities recorded at a depth of 44 feet were attenuated by a factor of 75 relative to those at the surface. It seems very unlikely that sonic booms could trigger earthquakes.

In other tests summarized by the ICAO Sonic Boom Panel (16), the ground response varied somewhat depending on the type of soil involved, but a general result of the studies was that induced particle velocities of about 50 to 500 microns/sec (0.002 to 0.02 inches/sec.) were associated with nominal peak pressures of 24 to 240 N/m^2 (0.5 to 5.0 lb/ft^2). This compares to a value of about 150 microns per second which is associated with the footsteps of a 90 kg (200 lb) man. The effective areas covered on the ground are, of course, very different; the boom-induced motions are correlated over distances of the order of miles, whereas footstep-induced motions decay within tens of feet. Earthquake tremors which are measured with sensitive instruments but imperceptible to humans are also of this same order of magnitude. Sonic boom induced particles velocities are on the average approximately two orders of magnitude less than the damage threshold accepted by the U. S. Bureau of Mines and other agencies for blasting operations.

Further significant findings of the tests were that the disturbances were limited to a thin surface layer of the earth and that no evidence of focusing of seismic energy was observed. Although reports have been received concerning cracked concrete driveways and broken underground pipes due to sonic booms, aside from one instance, investigations produced no scientific support for such allegations. There have been reports of landslides and cliff failures attributed to sonic booms. These reports have not been documented sufficiently well for summarizing here.

Of particular concern is the possiblity of avalanches being triggered by sonic booms. Accordingly, a series of tests has been conducted with eighteen flights producing nominal peak pressures up to 500 N/m^2 (10.4 lb/ft^2) over a mountainous, snow-covered area that ordinarily has potential avalanche conditions. During the tests, avalanche hazards were rated by the U. S. Forest Service to be "low", but it was possible to release one avalanche with a high explosive projectile from an avalauncher. Another occurred from an unknown cause. The sonic booms triggered no avalanches and had no measurable effect on the creep behavior of the snow layers in these tests.

In summary, the motion of the ground due to sonic boom excitation is of relatively small amplitude. The fact that measurable ground motions exist, taken together with the explosive character of air loading, suggests that avalanches might be triggered by sonic booms incident on unstable snow accumulations; up to now, however, no direct evidence of cause and effect is available. From a scientific point of view, there are and will continue to be a large number of unstable terrain features that could be affected by the sonic boom differently depending upon their degree of instability or particular structural status.

The cited test series in which sonic booms failed to trigger snow avalanches were carried out under "low" avalanche hazard conditions. Furthermore, the differences between triggering snow and earth avalanches need to be better understood.

Water Surfaces. In deep water a moving underwater pressure field accompanies the boom carpet over the surface. The pressure wave formed just beneath the surface is almost identical to that of the N-wave in air, both in the amount of peak pressure and in wave form, but it is rapidly attenuated with depth. Furthermore, the pressure jumps disappear and are replaced by slowly varying pressures. It does not seem probable that a pressure field in water could cause structural damage.

6. References

There exists an extensive literature on the physical effects of the sonic boom mostly arising from research and development sponsored by the United States, British, and French governments during the 1960's, and described in agency reports that are often difficult of access. It is worthwhile to note several bibliographies that have been compiled to index this material. They are:

a. Federal Aviation Agency, Bibliographic List No. 13, "Aircraft Noise and Sonic Boom," October 1966. Selected references for the period 1960-1966.

b. Royal Aircraft Establishment, Ministry of Technology, London. "Bibliography on Sonic Bangs," Library Bib'y No. 287, dated January, 1968. References include U.S. as well as French and British reports.

c. Department of Transportation, Library Services Division, "Aircraft Noise and Sonic Boom," Bibliographic List No. 2, dated December, 1969.

At the time of preparation of this report, a paper by Brian Clarkson and W. H. Mayes on sonic-boom induced damage to structures was not available, but it is scheduled to appear in a forthcoming issue of the Journal of the Acoustical Society of America.

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1. Wallace D. Hayes, "Sonic Boom," pp. 269-291, in Annual Review of Fluid Mechanics, Vol. 3 (1971). Annual Reviews, Inc., Palo Alto, Calif.

2. Stanford Research Institute, "Sonic Boom Experiments at Edwards Air Force Base," a report prepared for the National Sonic Boom Evaluation Office, 28 July 1971. AD No. 655 310.

3. John H. Wiggins, Jr., "Effect of Sonic Boom on Structural Behavior," Materials Research and Standards 7, 235-245 (1967).

4. R. W. McKinley, "Response of Glass in Windows to Sonic Booms," Materials Research and Standards 4, 594-600 (1964).

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6. T. L. Parrott, "Experimental Studies of Glass Breakage due to Sonic Booms," Sound 1, 18-21 (1962).

7. I. Edward Garrick, "Atmospheric Effects on the Sonic Boom," pp. 3-17 in Second Conference on Sonic Boom Research, May, 1968. NASA Document SP-180.

8. Domenic J. Maglieri, "Sonic Boom Ground Pressure Measurements for Flights at Altitudes in Excess of 70,000 Feet and at Mach Numbers up to 3.0," pp. 19-27 in Second Conference on Sonic Boom Research, May, 1968. NASA Document SP-180.

9. Allan D. Pierce, "Maximum Overpressures of Sonic Booms Near the Cusps of Caustics," paper delivered at Purdue Noise Control Conference, Purdue University, 1971.

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11. G. Koopman and H. Pollard, "Model Studies of Helmholtz Resonators in Rooms with Windows and Doorways," J. Sound Vib. 16, 489-503 (1971).

12. A. J. Pretlove, "Free Vibrations of a Rectangular Panel Backed by a Closed Rectangular Cavity," J. Sound Vib. 2, 197-209 (1965).

13. William H. Mayes and James W. Newman, Jr., "An Analytical Study of the Response of a Single-degree of Freedom System to Sonic-Boom-Type Loading," LWP-154, Langley Research Center, NASA, 16 February 1966.

14. S. Slutsky and L. Arnold, "Coupled Elastic and Acoustic Response of Room Interiors to Sonic Booms," pp. 227-240 in Third Conference on Sonic Boom Research, October 1970. NASA Document SP-255.

15. C. W. Newberry, "Measuring the Sonic Boom and Its Effect on Buildings," Materials Research and Standards 4, 601-611 (1964); "The Response of Buildings to Sonic Boom" J. Sound Vib. 6, 406-418 (1967).

16. ICAO Sonic Boom Panel Report DOC 6694, SBP/II, 12 October 1970, reprinted in Noise Control 1971, Hearings Before the Subcommittee on Public Health and Environment, House of Representatives, 92nd U.S. Congress, June 16-24, 1971. Serial No. 92-30. U.S. Government Printing Office.

17. Letter from Harthorn L. Bill, assistant director of the National Park Service, to U.S. Senator Clifford P. Case, dated 23 February 1967.

18. J. C. Cook, T. T. Goforth and R. K. Cook, "Seismic and Underwater Responses to the Sonic Boom," paper presented at Sonic Boom Symposium II, Houston, Texas, 3 November 1970, to appear in Journal of the Acoustical Society of America. T. T. Goforth and J. A. McDonald, "Seismic Effects of Sonic Booms," NASA Cr-1137, September 1968.