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LABORATORY INVESTIGATION OF DIFFRACTION AND REFLECTION OF SONIC BOOMS BY BUILDINGS

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16. Abstract

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SUMMARY

A method is described for simulating the acoustic phenomena that occur when an N-wave passes over a building. Information concerning the enhanced overpressure in front of the building and the shielding effect of the building on the region behind it is obtained from comparative pressure measurements and from schlieren photographs of the shock pattern. The effects of varying parameters such as the shock-ground angle and the building size and shape are studied.

INTRODUCTION

Most experimental studies of sonic-boom overpressures have been largely restricted to flat-earth measurements (e.g., ref. 1). However, investigation of sonic-boom effects in the vicinity of buildings is potentially of more interest because of the high concentration of population and of damageable structures in such regions.

It is desirable to simulate these effects in the laboratory insofar as possible, not only because the expense of such tests is an insignificant fraction of the cost of flight tests, but also because of the public nuisance of flight testing over populated areas. A further advantage is that building sizes, shapes, and arrangements relative to the shock wave can readily be varied in the laboratory so that parametric studies are possible.

The purpose of the present paper is to describe a technique for simulating the fundamental phenomena that occur when a weak shock wave passes over a building and to present some representative data obtained by the method. These data consist of microphone measurements of overpressures in the vicinity of the building and schlieren photographs of the shock-wave configurations near the building. The microphone measurements provide information on the buildup of pressure near the front base corner of the building and the reduction of pressure behind the building due to its shielding effect. The schlieren photographs give information on the geometry of the direct, reflected, and diffracted waves.

SYMBOLS

p	overpressure at microphone location
p_i	overpressure in incidence wave, measured in free air
p_g	overpressure at ground surface, without building
λ	wavelength of N-wave

SIMULATION METHOD

General Description

The nature of the diffraction phenomena resulting from an obstacle in the path of a sound wave depends fundamentally on the size of the obstacle relative to the wavelength. The problem of diffraction of an N-wave about a large building is one in which the linear dimensions of the obstacle are of the same order as a wavelength. This problem is especially appropriate for experimentation because the theory does not simplify in this case as it does when the wavelength is either much larger or much smaller than the obstacle (ref. 2, ch. X). For this reason the models of structures used in the present investigation were scaled in accordance with the length of the N-wave.

A schematic drawing of the apparatus is shown in figure 1. A spherical N-wave is produced by a spark at the focus of a parabolic mirror. The spherical wave reflects from the mirror as a plane wave and is directed toward a ground surface on which the model structure is mounted. The angle between the ground surface and the shock wave can be adjusted.

The shock-ground angle does not necessarily represent the complement of the flight Mach angle as would be the case for flight in a uniform atmosphere in a line directly over the building and perpendicular to a wall of the building. The shock-ground angle is not related in such a simple way to the flight Mach number for flight in a nonuniform atmosphere or for a building located off the ground track of the flight. Therefore, in order for the data to have a more general interpretation, they are presented in terms of the shock-ground angle rather than the flight Mach angle.

Comparison With Other Simulation Techniques

Other methods that have been used for laboratory simulation of sonic-boom effects include shock tubes and projectile ranges. For the present study, the shock tube was ruled out as being much more expensive to construct, slower, and more expensive and more troublesome to operate. Furthermore, shock tubes normally produce a step-function wave rather than a N-wave, and the overpressure is considerably in excess of that generally associated with sonic-boom phenomena.

Projectile ranges are similarly more expensive and troublesome to operate, but they do produce the desired N-wave signature with the appropriate overpressures. They have the further advantage over other methods that the wave geometry is conical, as in flight in a uniform atmosphere. However, within a region whose dimensions are small relative to its radius of curvature, the wave is essentially a plane wave. Such is certainly the case for the problem considered herein, since the region considered is of the order of a wavelength, whereas the radius of curvature of a conical wave would be very large relative to the wavelength except for flights at extremely low altitudes. Therefore, the use of a plane wave rather than a conical wave does not weaken the simulation in the present investigation.

The N-wave produced by the spark was very consistent in both wavelength and amplitude. The excellent repeatability of results produced in successive shots makes it possible to conduct studies of the type illustrated in figure 2. Such a sequence could not be obtained with a single shot even with the fastest available schlieren motion-picture apparatus, which would take successive frames with the wave displaced about 3 wavelengths.

One limitation of the present method is that the wavelength is so short that the microphone does not measure the true strength of the leading shock. The microphone dimension is 1/8 wavelength. The microphone measures an average value at the peak, and consequently many data points must be obtained while varying some parameter in order that conclusions may be drawn from the comparative values rather than absolute overpressures.

APPARATUS AND PROCEDURE

Description of Apparatus

In the following description of the apparatus, the dimensions of each essential item that was used in this study are listed. However, this apparatus was chosen primarily because of its availability, and it should be emphasized that the applicability of the experimental method is not critically dependent on the dimensions.

N-wave.- The spark that produced the N-wave was formed in the 0.50-mm spark gap between the pointed tips of two tungsten electrodes. The electrodes were 3.12 mm in diameter and 30 cm in length. They were mounted at an angle of 60° with respect to each other in a plane perpendicular to the mirror axis with the spark gap located at the focal point of the mirror. The mirror was parabolic and had a 64.8-cm diameter and a 24.6-cm focal length. The spark produced a spherical N-wave that was reflected from the mirror as a plane N-wave. (The part of the direct spherical N-wave that traversed the model structure preceded the plane wave by about 20 wavelengths and was much smaller in amplitude because of spherical spreading.) With this arrangement, the peripheral equipment produced negligible diffraction effects in the reflected acoustical N-wave. The spark power was furnished by switching across the gap a 1.0-μF capacitor which was charged to a high dc voltage, nominally 6000 volts. Switching was accomplished with an external circuit by means of a 5C22 thyratron tube.

Ground surface.- The ground surface is shown in figure 1 at a 45° angle to the incident N-wave. This surface was a rectangular sheet of aluminum 41 cm wide, 56 cm long, and 6.35 mm thick. The smooth, rigid reflecting surface it presented to the N-wave simulated the ground within the vicinity of the building model, where the short wavelength of the N-wave is analogous to a sonic boom. The relationship between the wave direction and ground surface could be changed to control the angle between the shock and the model structure (analogous to controlling the Mach number). This variation in the shock-ground angle was accomplished by mounting the ground surface on pivots.

Model structures (buildings).- Various sizes and shapes of buildings, or model structures, were mounted with their vertical axes perpendicular to the plane of the ground surface. In order to eliminate errors in successive measured overpressures, the microphone was fixed at one location on the ground surface for ground measurements and was suspended freely in the air for zone measurements, and the model structure was positioned as desired with respect to the microphone. The building models were made from metal and wood. They varied in height from 1/8 wavelength to 5 wavelengths and in width from 1/2 wavelength to a width greater than that of the mirror.

Measurements and schlieren system.- The overpressures were measured with a single condenser microphone having a 3.2-mm diaphragm with a protective grid. This microphone had a nominal accuracy of ± 2 dB at frequencies up to 140 kHz. Figure 3 shows a typical signature obtained with the microphone mounted flush with the ground surface, which was set at an angle of 45° to the incoming wave. The signature is somewhat distorted from the true N-wave form. This distortion results from the failure of the microphone to reproduce the higher Fourier components of such a short N-wave, as well as from the fact that the dimensions of the diaphragm are not negligible in comparison with the length of the N-wave. As a result, for example, no reflection factors greater than about 1.8 were measured at the ground surface, although the theoretical maximum value is 2.

Because of these limitations, each of the peak overpressure measurements was divided by an appropriate reference measurement, and the data were plotted in such a way as to display the effects of varying some parameter. The microphone data are especially amenable to this kind of treatment because the system provides excellent reproducibility of data even though the absolute values are not accurate.

A conventional off-axis schlieren system was used to obtain photographs of the transient shock waves. A 75-watt xenon lamp with a flash duration of 1.5 μsec was used with two parabolic mirrors (each 30.5 cm in diameter) and a vertical knife edge. A time sequence of typical schlieren photographs is shown in figure 2.

Procedure for Obtaining Pressure Signatures and Schlieren Photographs

The N-wave was created by a spark at the focus of the parabolic mirror, and the microphone output was observed and recorded by a camera mounted on a dual-beam oscilloscope. In order to observe the desired or the appropriate part of the microphone response, the sweep of the oscilloscope was delayed by an amount of time approximately equal to the transit time of the wave from the spark gap to the mirror and back to the microphone. This delay was accomplished by means of the variable time-delay circuit incorporated in the oscilloscope. In order to insure that the N-wave which was observed and photographed on the oscilloscope screen was the desired N-wave, a schlieren photograph was also taken at this time. The schlieren flash was synchronized with the microphone output by using the output gate pulse of the oscilloscope to trigger the schlieren xenon lamp.

By using the variable time delay to record a time sequence of pressure waveforms and the corresponding time sequence of schlieren photographs, each significant overpressure could be identified as being the direct wave, a wave reflected from a corner, a wave diffracted from an edge, or some other wave.

RESULTS AND DISCUSSION

The general features of the wave pattern that is formed when an N-wave passes over a building are shown in both a diagram and a photograph in figure 4. For simplicity and clarity in distinguishing the various regions of the wave pattern, the effects of a single shock wave are shown (the tail wave is omitted), and the building is treated as if it were a two-dimensional structure. An elementary analysis of this case is treated in reference 3.

Various regions of the wave pattern may be distinguished, as follows:

(1) Region 1 is the direct wave.

(2) Region 2 is the wave reflected from the ground. The peak overpressure in this wave is the same as that in the direct wave for a perfect reflecting surface.

(3) Region 3 is the wave reflected from the front face of the building. The overpressure in this wave is of the same order as the overpressure in the direct wave near the building. This pressure varies with building height and shock-wave angle, as shown in a subsequent discussion.

(4) Region 4 is the part of the direct wave that is diffracted around the upper rear corner of the building. Its strength is near that of the direct wave at the point of tangency, but the strength near the building is lower by an amount that depends on the distance in wavelengths traversed from the corner of the building.

(5) Region 5 consists of the compression wave diffracted from the upper front corner. It is relatively weak; at a radius of a wavelength or so the pressures associated with this wave were barely above the noise level.

(6) Region 6 is the expansion wave diffracted from the upper rear corner, and it is also quite weak.

(7) Region 7 is the wave reflected from the top of the building.

Most of these regions can be distinguished in the sequence of schlieren photographs depicting an N-wave passing over a building. (See fig. 2.) In order to separate these sections of the wave, the building was made unusually large relative to the wavelength.

The wave pattern for a building of finite width is even more complex, but the most important difference is the existence of waves diffracted around the ends of the building. These waves are similar to that discussed previously as region 4.

Overpressures in "Shadow Zone" Behind Building

A straight line drawn through the upper rear corner of the building in the direction of propagation of the direct wave can be considered to represent the boundary of a "shadow zone" into which the direct wave does not propagate. Some shielding effect of the building occurs in this region, but inasmuch as building dimensions are not ordinarily large relative to the signature wavelength, the diffraction of sound into this region is considerable. This effect is shown clearly in figure 5 for a two-dimensional building. For such wide buildings, as the building height is increased, the pressures in the shadow zone near the building decrease and the distance behind the building that is influenced by the presence of the building increases. Thus, as might be expected, the shielding effect of the building increases with its height. The results also indicate that the shielding effect is greater for larger shock-ground angles.

This shielding effect is more complicated for buildings of finite width. Figure 6 shows the pressure measured on the ground at the center back of the building for buildings of various heights and widths. For buildings of finite width, this pressure does not decrease monotonically with increasing building height. Although there is a general tendency for the building height to increase its shielding effect, there is an additional variation which is due to the phase of the wave diffracted over the top relative to the phase of the waves diffracted around the ends of the building. This effect is especially apparent in figure 6(a), where the shock wave is parallel to the face of the building. The locations of the peaks in the data indicate the expected result – that at the center back of the building the waves diffracted around the ends are in phase with the one diffracted over the top when the width of the building is twice its height.

Effects of Energy Loss for Diffracted Waves

In figure 5 the theoretical edge of the shadow zone is indicated for each case. The overpressure is reduced for some distance beyond the shadow zone because of loss of energy by diffraction into the shadow zone.

Figure 7 shows schematically the measured distribution of overpressure behind a building that is traversed by an N-wave at angles of 30° and 60° to the ground. These measurements were made by suspending the microphone in the air. The width of the region that is affected by loss of energy to the diffracted waves grows rapidly at first, but after a short distance its growth is much more gradual. Figure 7 also indicates that there is no sharp drop in the overpressure at the theoretical edge of the shadow zone but that the variation is smooth as the microphone is moved from the unaffected region well into the shadow zone. This result is consistent with the ground pressures shown in figure 5.

Pressures in Front of Building

The overpressure near the top of the forward face of a tall building should be the direct wave overpressure multiplied by the reflection factor for the building. On the ground ahead of the building, the direct-wave overpressure is multiplied by the ground reflection factor. As the base of the building is approached along the ground, the microphone measurements indicate that the wave reflected from the building overlaps the direct wave measured at the ground, and at the base they are superimposed.

The overpressures measured on the ground at the forward base of two-dimensional buildings of various heights are shown in figure 8. As previously indicated, these pressures are somewhat less than the theoretical values because of the averaging effect resulting from the large size of the microphone relative to the wavelength. However, considerable information can be obtained by observing the variation of pressure with building height. When the shock angle with the ground is small (60° to the building), the overpressures on the ground at the forward base of the building are reduced significantly as the building height is decreased below 3/4 wavelength. When the shock-ground angle is large (30° to the building), this reduction of overpressure with decreasing building height does not occur until the building height is reduced to 1/4 wavelength. These results indicate that for a large building the reduction of overpressure due to diffraction would extend over a greater part of the front face of a building for a small shock-ground angle than for a larger angle and that (except possibly for exceptionally large buildings) the overpressure at the forward base of a building would not reach the level of 4 times the incident pressure (or 2 times p_g) that would be expected for large buildings.

These results can be understood by considering the discussion of the previous section. Each ray of the wave is reflected from the front face of the building at an angle equal to the angle of incidence. The ray reflected from the top corner of the building is a cutoff ray with no reflected wave above it. That is, the region above this ray is a shadow zone with respect to the reflected wave. The energy associated with the waves diffracted into this shadow zone must come from the region below the cutoff ray, as indicated schematically in figure 9. This figure indicates that the region in which the overpressure is reduced because of loss into the shadow zone extends over a larger part of the building when the shock-ground angle is small (fig. 9(b)) than when it is large (fig. 9(a)). This behavior is consistent with the results of figure 8.

These results are independent of building width except possibly very near the ends of the building. Inasmuch as the peak pressure depends only on the incident wave and the directly reflected wave, any effect of the shadow zones created at the ends of the building would reach the microphone after this peak pressure is recorded.

Other Building Shapes

It is of interest to inquire whether unusual building shapes are better or worse than the rectangular block shape from the standpoint of sonic-boom shielding or magnification. Figure 10 shows some test results for an L-shaped building. If the "L" faces the incoming wave so that reflections from both sides and from the ground coincide at the base vertex, the amplitude here is considerably magnified, as expected. When the wave is incident from the other direction, not only is the pressure at the forward base of the building lower, but there is a significant shielding of the "courtyard" of the "L."

Figure 11 presents data for a wave at an incident angle of 30° to cylindrical buildings. As the building diameter increases, the pressures at the forward base approach that measured for a flat-face building. Behind the building the pressures depend on the phase addition of waves coming over and around the building.

SUMMARY OF RESULTS

A method has been developed for the laboratory simulation of the diffraction and reflection phenomena that occur from an N-wave. The method utilizes a plane N-wave obtained from the reflection of a spherical N-wave generated by a spark at the focus of a parabolic mirror. Building models of various shapes and sizes were exposed to these N-waves, and the results may be summarized as follows.

The variation of overpressure obtained by varying microphone location, building dimensions, and shock angle yields significant information on the reflection and diffraction phenomena that occur when a shock wave passes over a building. The area in the shadow zone behind the building is not entirely shielded from the boom but is subjected to the waves diffracted into this region. Although the shielding effect generally tends to increase with building dimensions, the actual pressure at any point in the shadow zone depends on the phase of the wave diffracted over the top relative to the phase of the waves diffracted around the ends of the building.

The overpressures within a certain region of the direct wave adjacent to the shadow zone are reduced as a result of the loss of energy by diffraction into the shadow zone. This type of mechanism also, in effect, reduces the reflection coefficient on the forward face of a building for some distance down from the top edge, so that for a relatively low building the overpressure over the entire forward face is somewhat reduced.

Although the averaging effect resulting from using a microphone that was large relative to the wavelength prevented an accurate measurement of the peak overpressure at the forward base of the building, significant intensification of the overpressure in this region was measured. However, the results indicate that (except possibly for exceptionally large buildings) diffraction phenomena would prevent this overpressure from reaching the level of 4 times the incident pressure that would be expected for large buildings.

Measurements obtained from L-shaped buildings and cylindrical buildings indicate that significant reduction in the forward base pressure can be obtained by appropriate architectural design.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., March 18, 1970.

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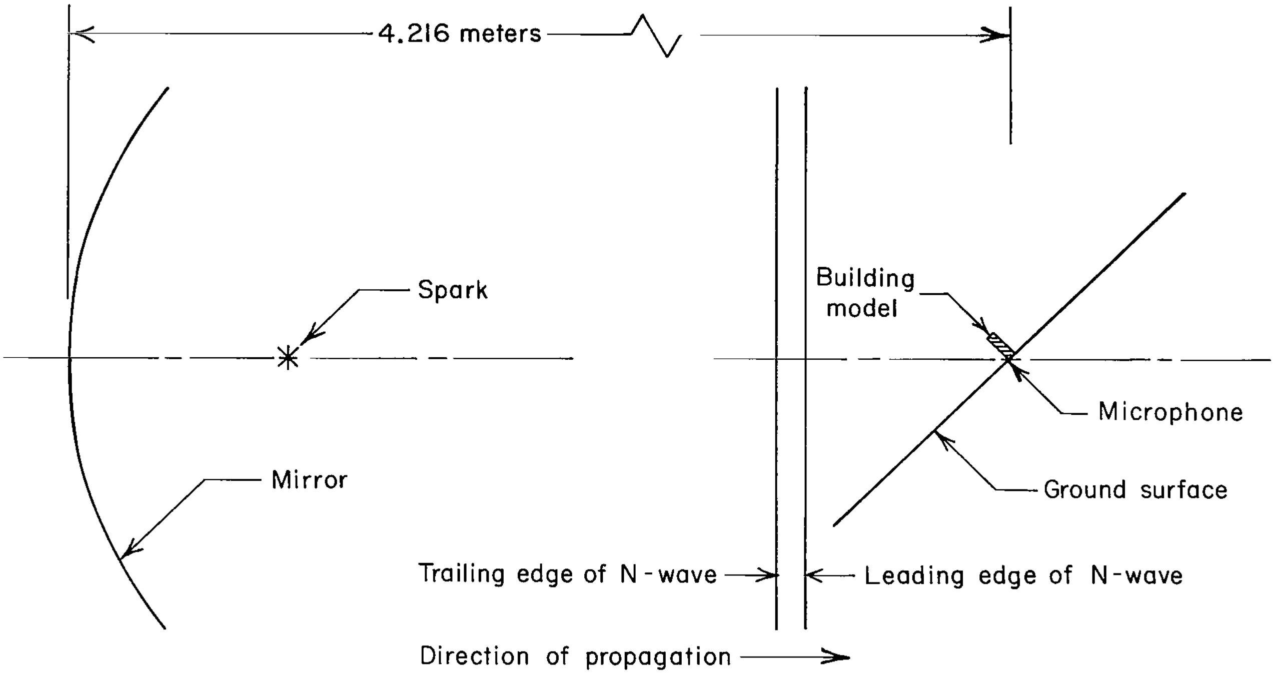

Figure 1.- Diagram of test apparatus.

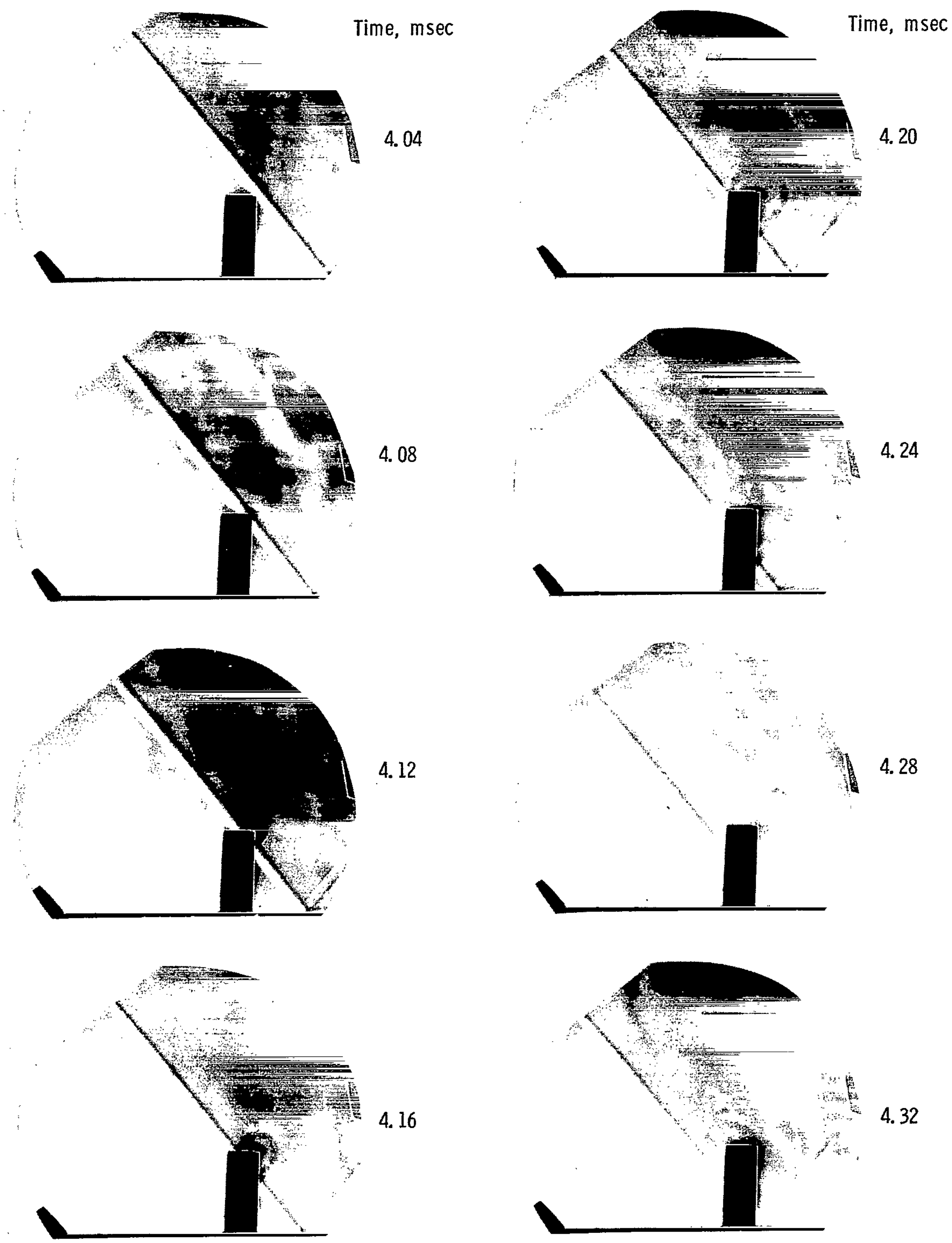

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Figure 2.- Schlieren time sequence of N-wave passing over large building model at angle of 40°. Direction of propagation is from right to left.

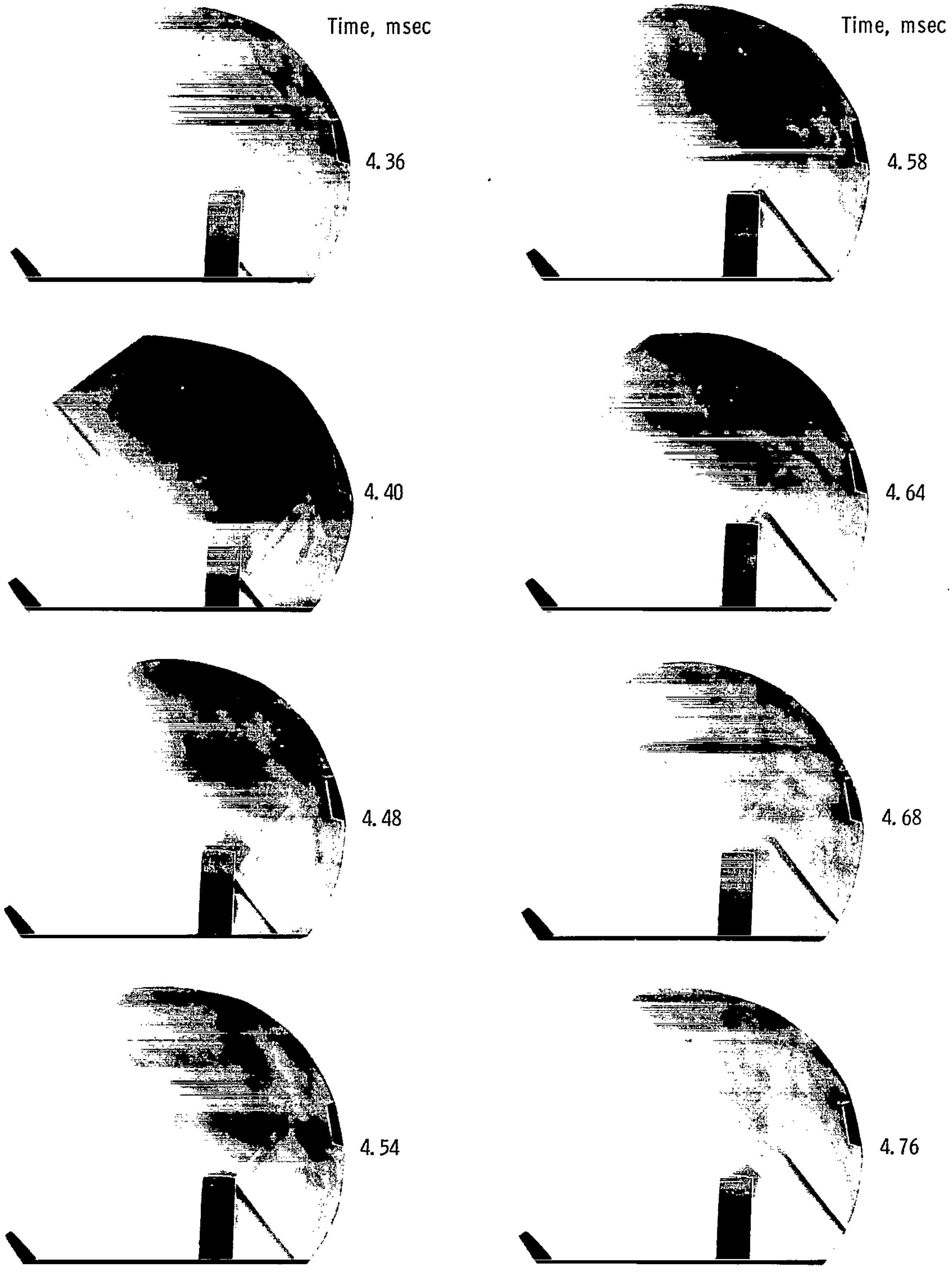


Figure 2.- Concluded. L-70-1568

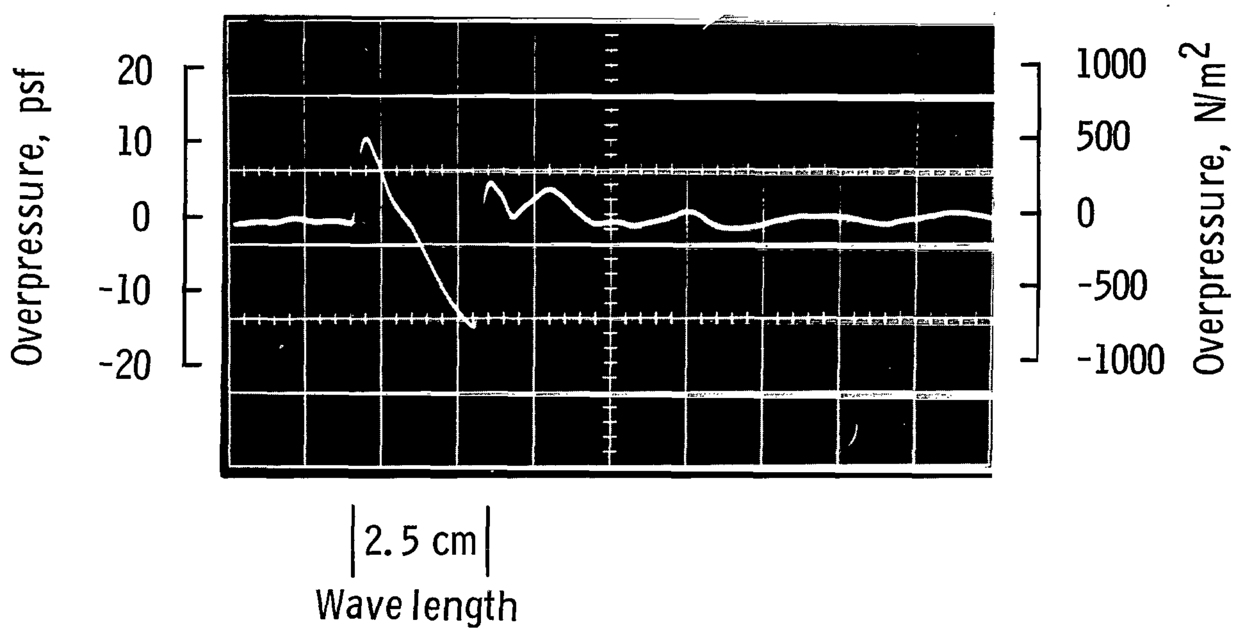
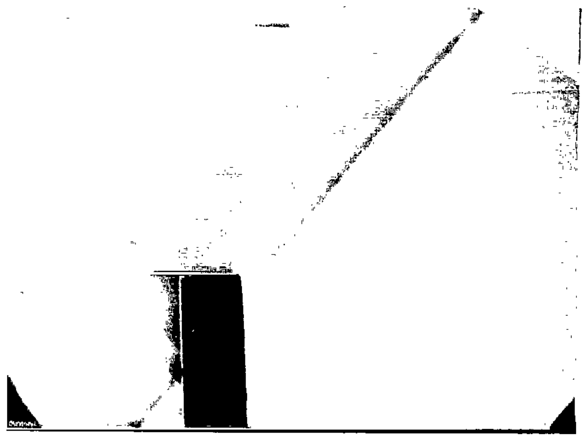
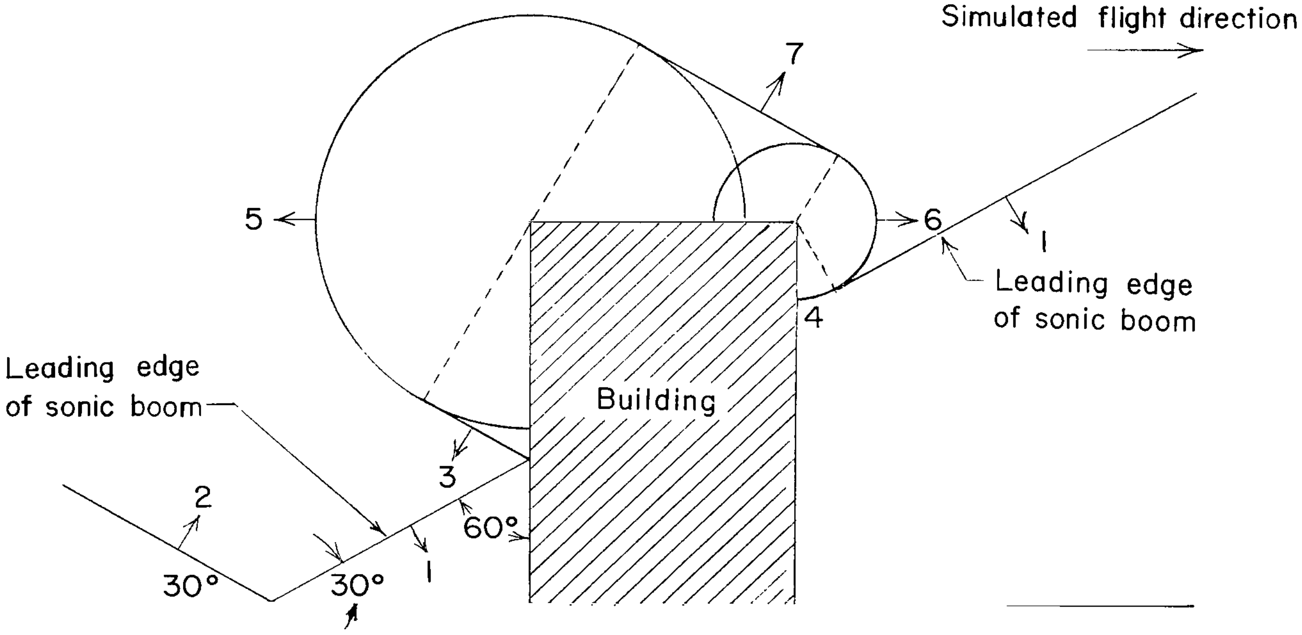


Figure 3.- Typical signature of N-wave when microphone is mounted flush with ground surface. Oscilloscope sweep speed, 50 μsec/cm.



(a) Photograph of N-wave at angle of 40° to building. L-70-1569



(b) Schematic drawing of shock wave at angle of 60° to building.

Figure 4.- Reflection and diffraction of shock wave passing over a building. Arrows indicate direction of propagation of shock waves.

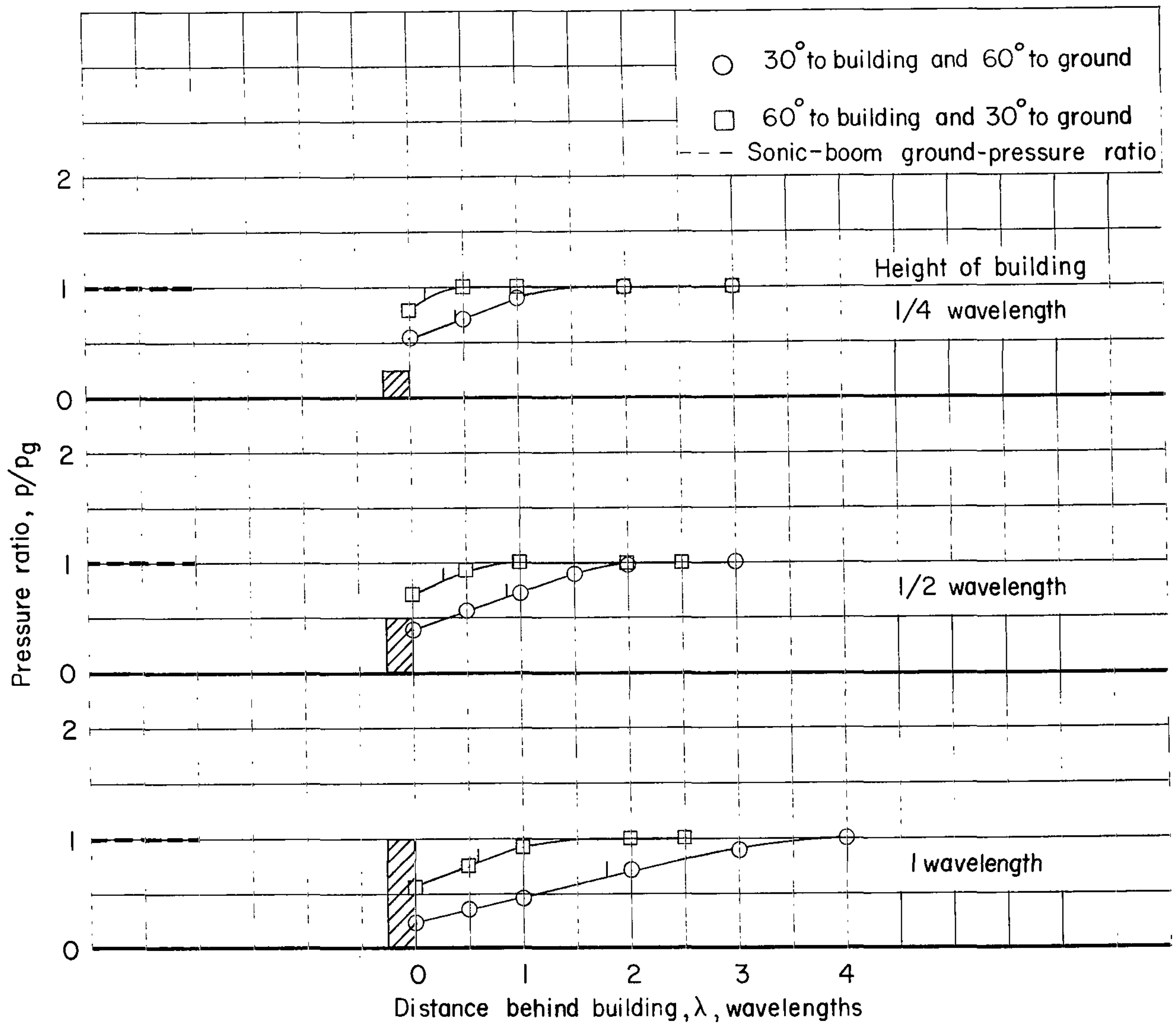


Figure 5.- Ground pressure ratio behind buildings of infinite width due to sonic booms at angles of 30° and 60°. Tick marks indicate theoretical edge of shadow zone.

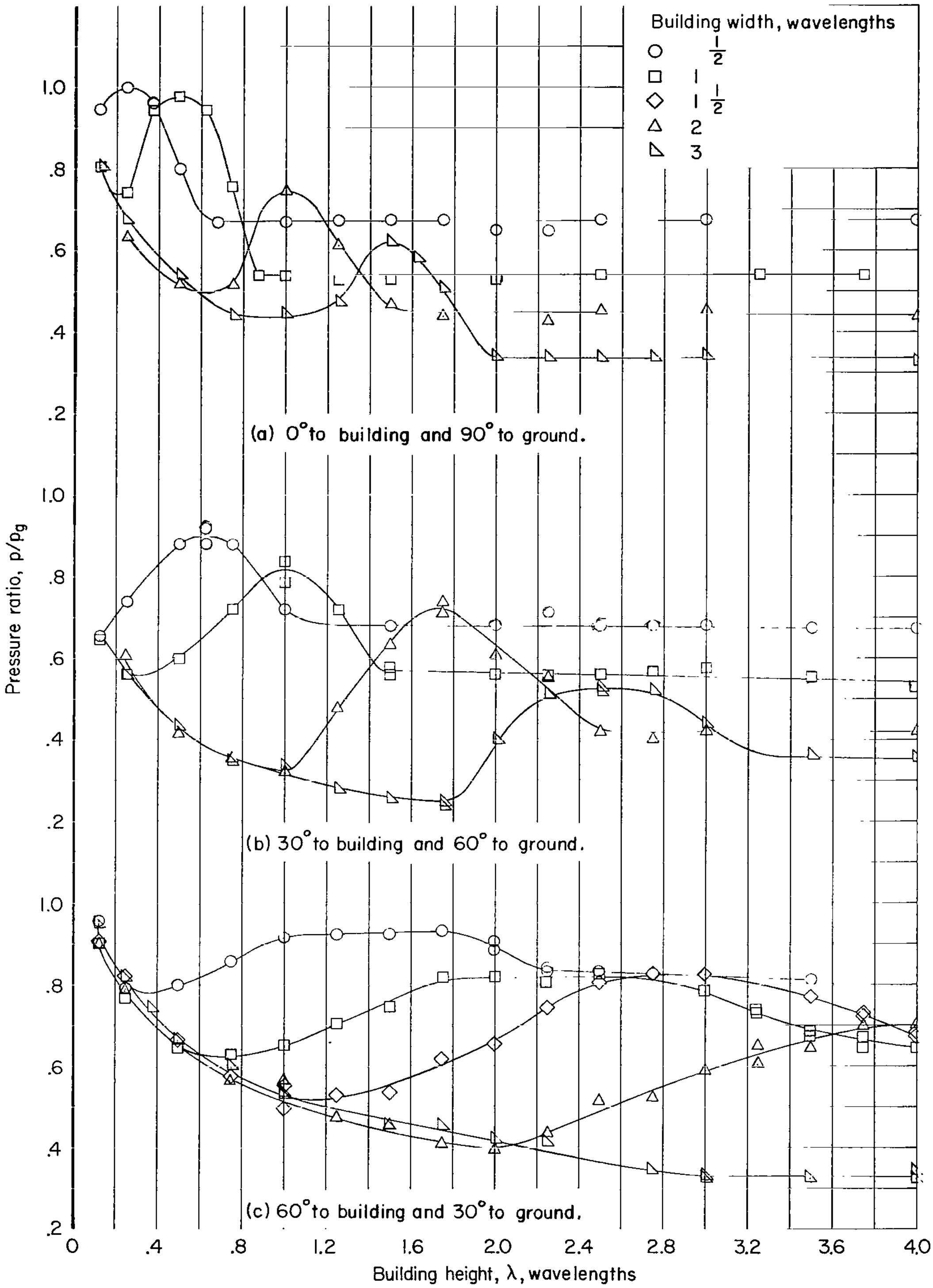


Figure 6.- Pressure ratio on ground at center back of buildings of various heights and widths.

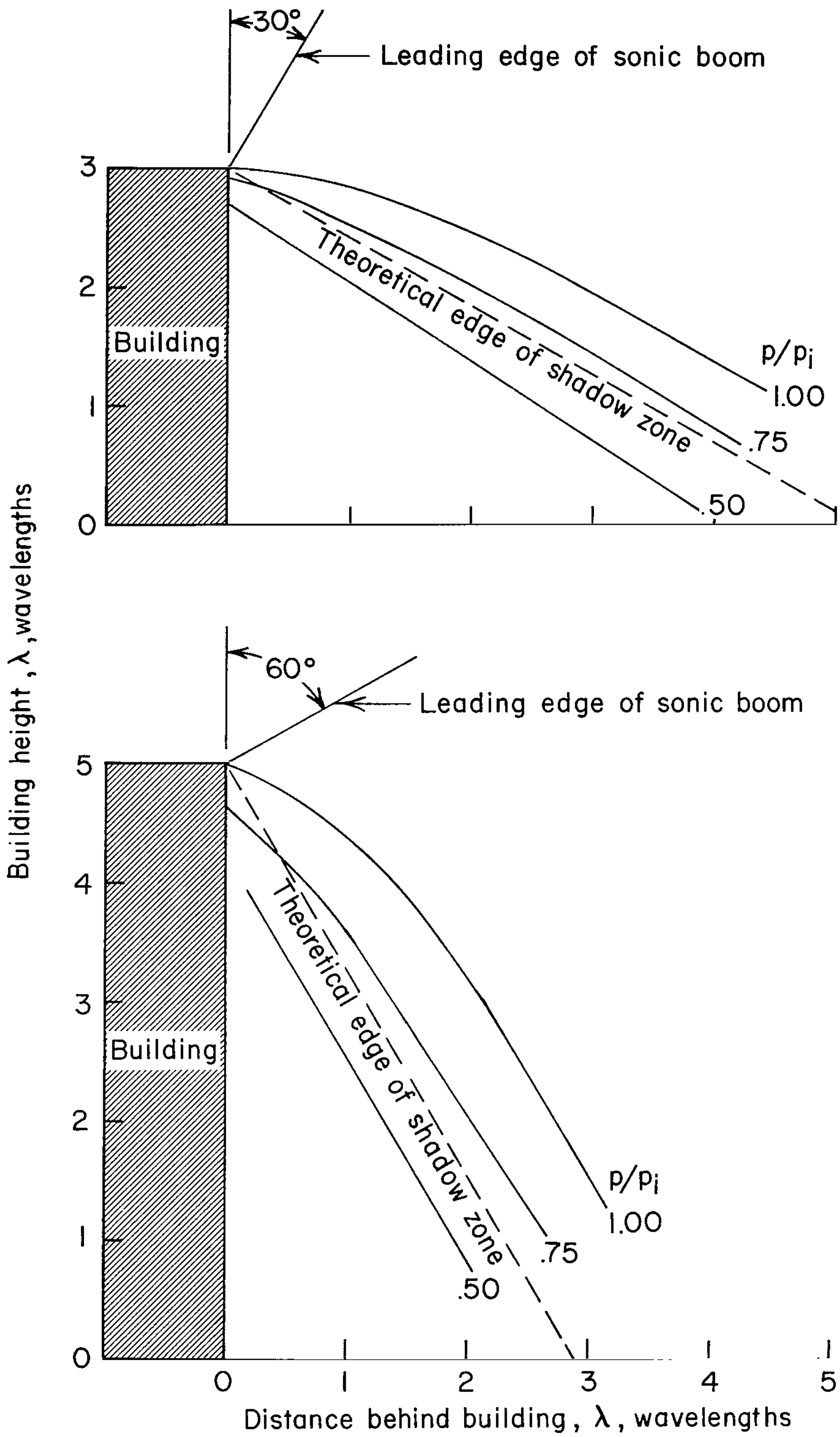


Figure 7.- Pressure behind buildings of various heights and infinite width due to sonic booms at angles of 30° and 60°.

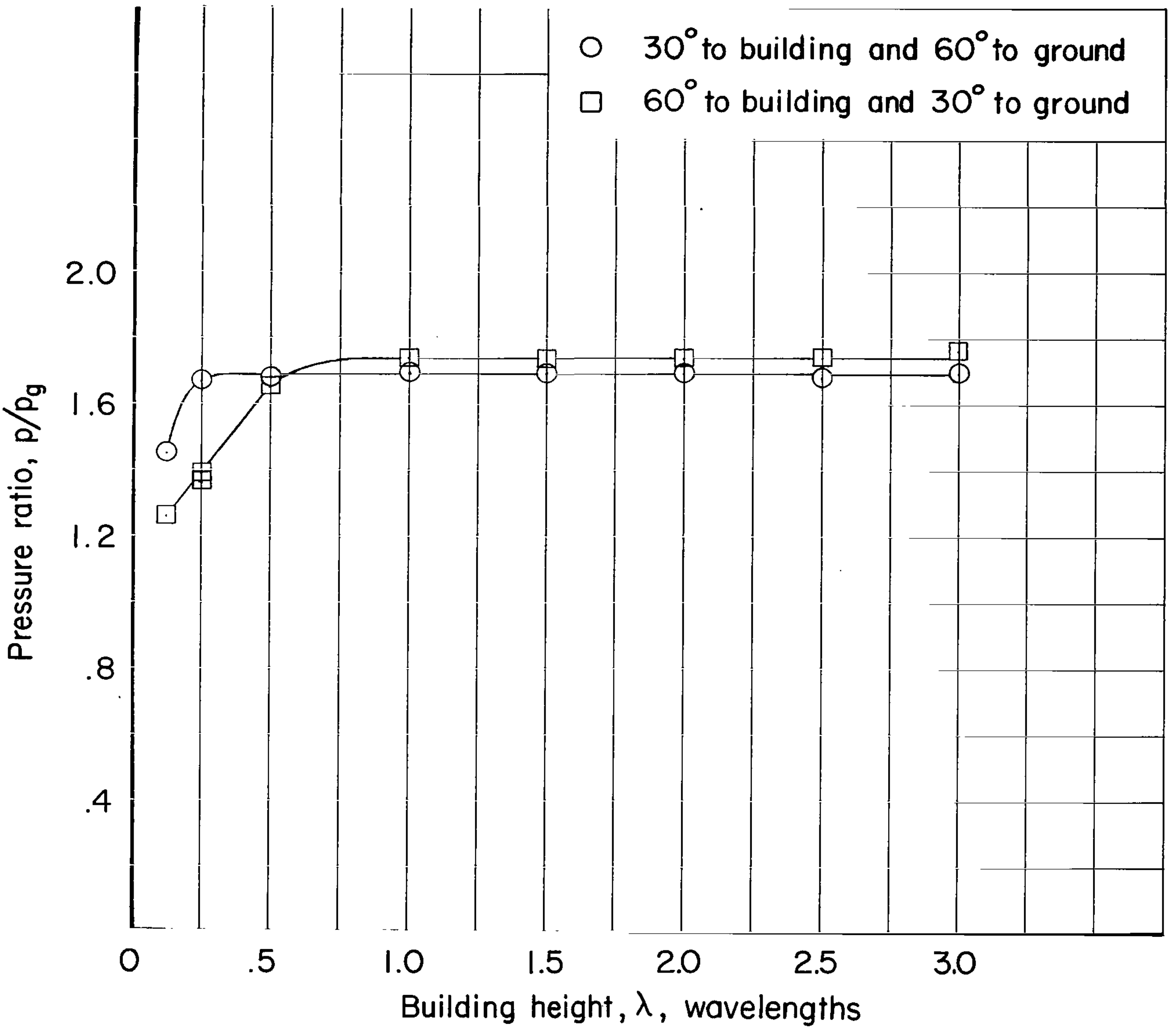
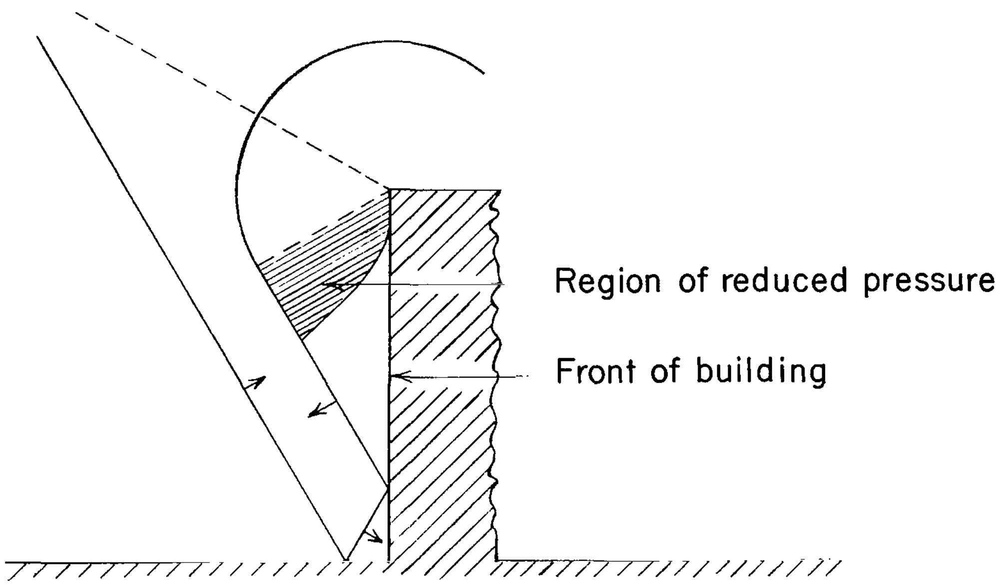
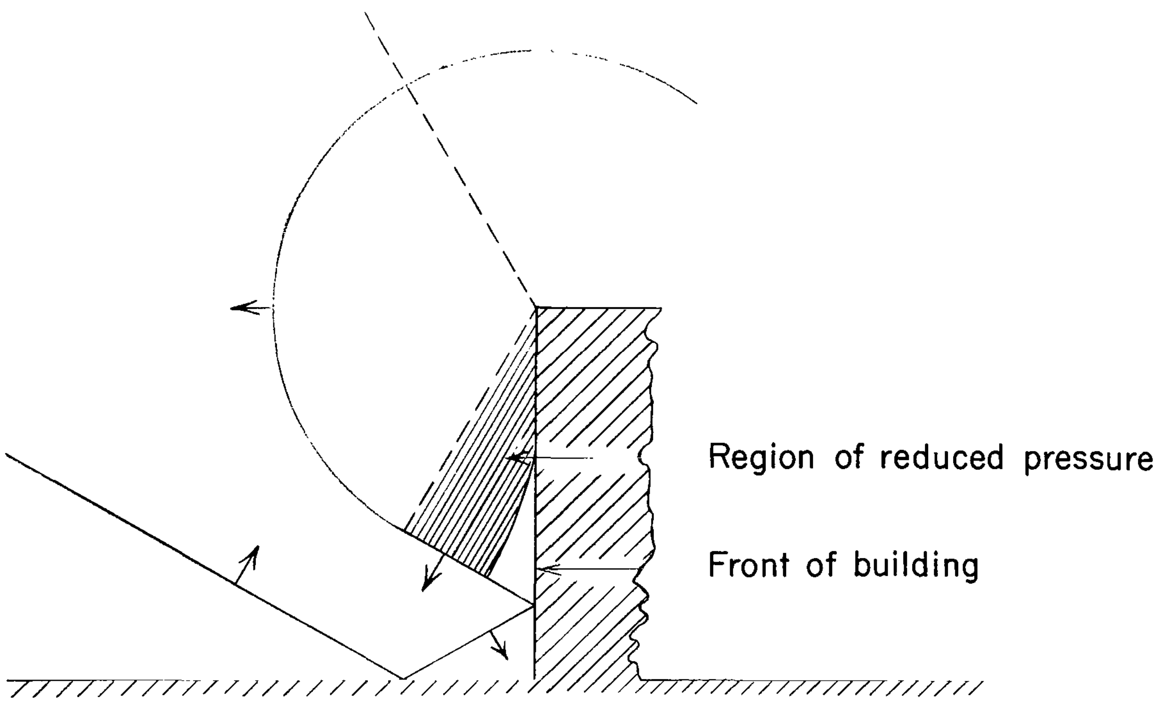


Figure 8.- Maximum pressure in front base corner of buildings of various heights and infinite width due to sonic booms at angles of 30° and 60°.



(a) 30° to building and 60° to ground.



(b) 60° to building and 30° to ground.

Figure 9.- Schematic drawing illustrating region of reduced pressure in front of a building. Solid lines indicate shock wave at leading edge of sonic boom and arrows indicate direction of propagation.

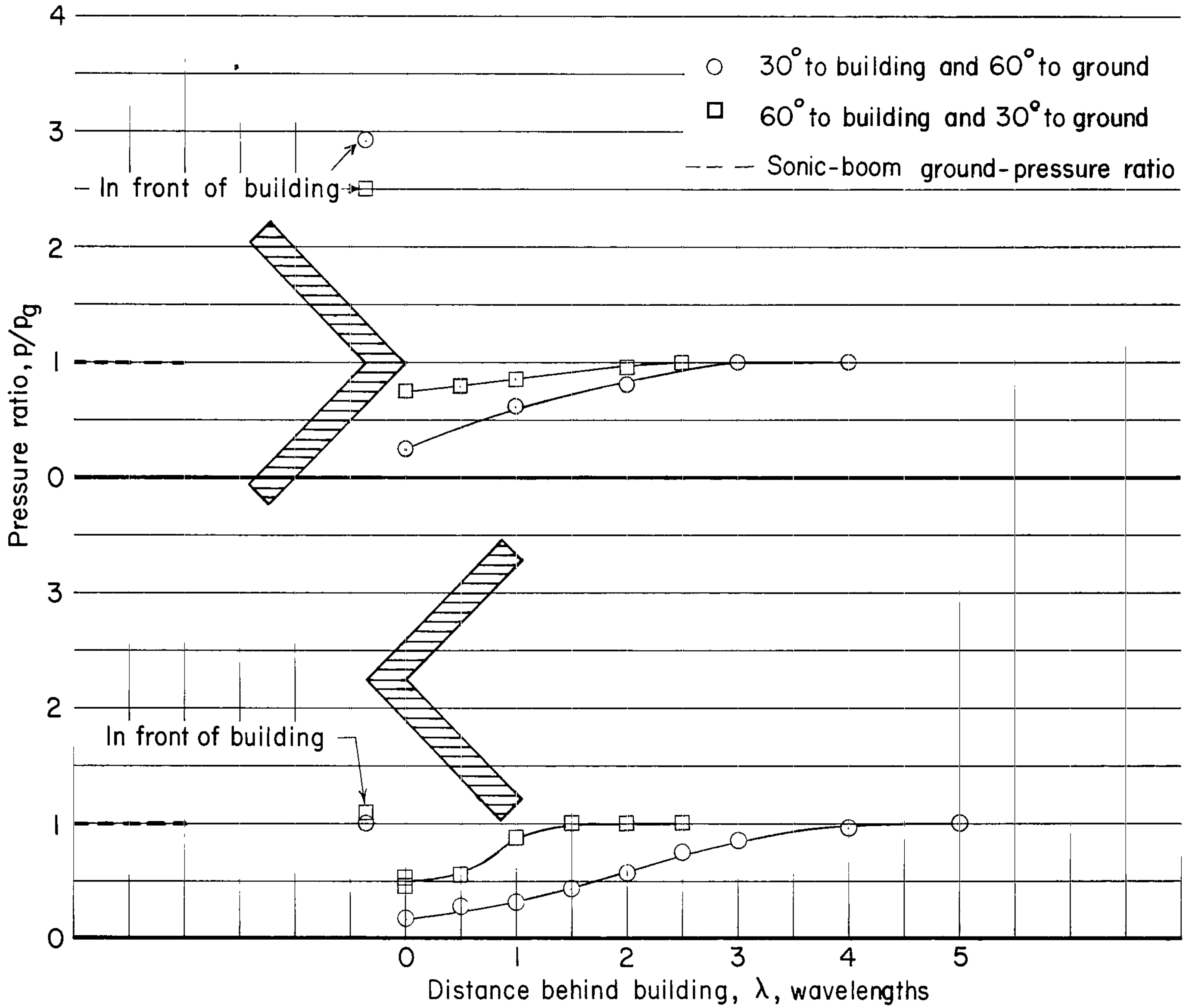
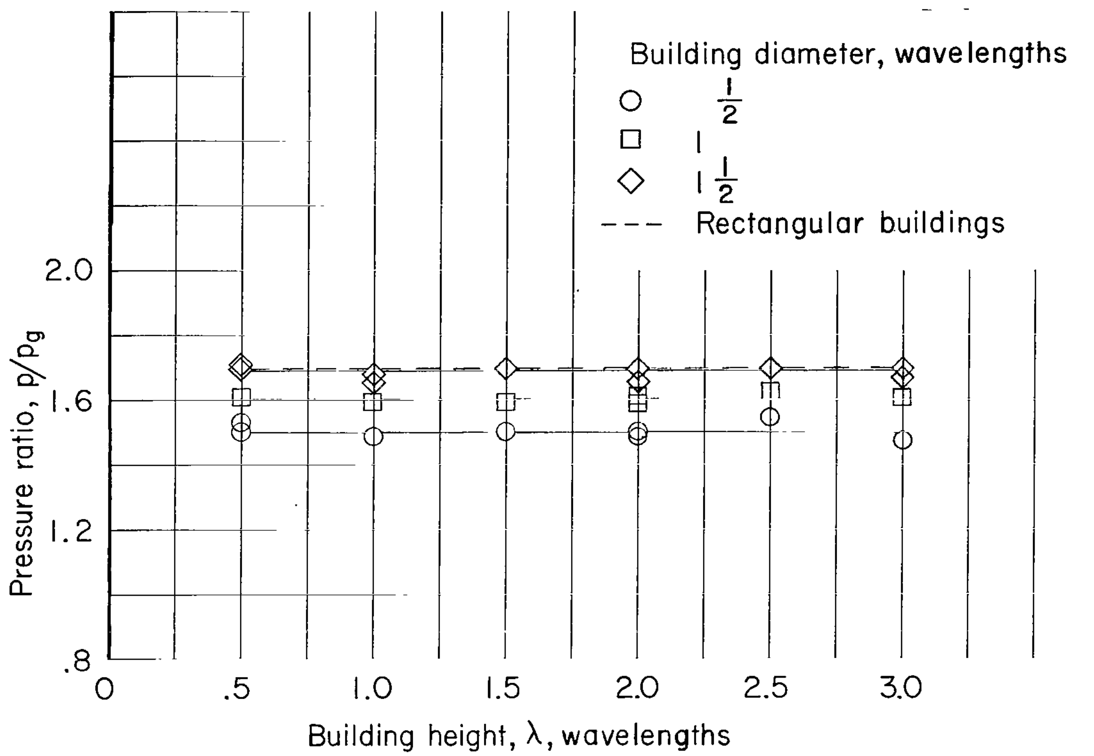
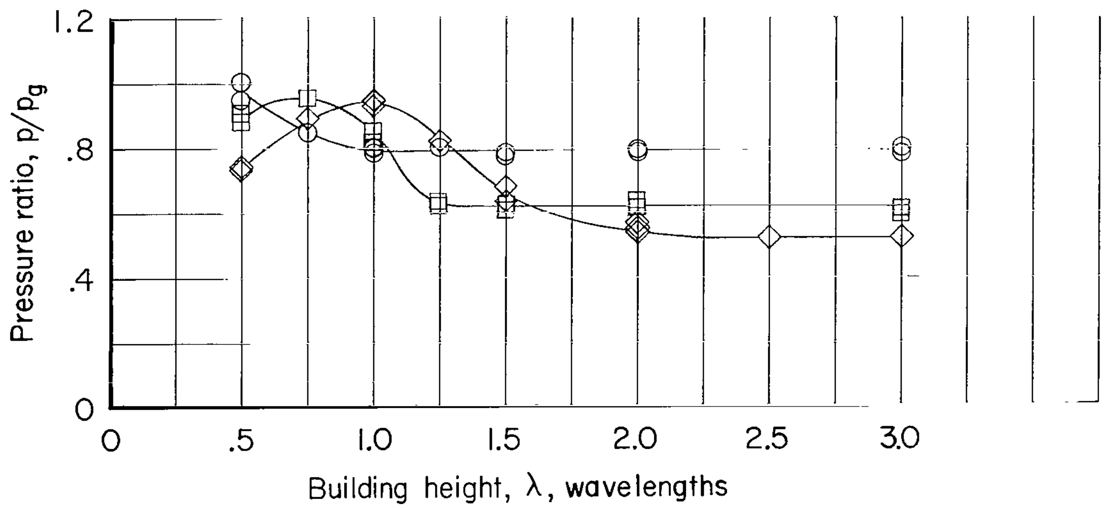


Figure 10.- Ground pressure in front of and behind the intersecting corner of an L-shaped building 1 wavelength high and $1\frac{1}{2}$ wavelengths on each side due to sonic booms at angles of 30° and 60°.



(a) Pressure in front of building.



(b) Pressure behind building.

Figure 11.- Pressure ratio on ground in front of and behind cylindrical buildings due to sonic booms at angle of 30° to building and 60° to ground.

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