Air Blast and Ground Shock Waves Generated at Long Distances from Demolitions of High Explosives[1]

M. A. Cook, R. T. Keyes and W. O. Ursenbach

Institute of Metals and Explosives Research, University of Utah

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ABSTRACT

A summary of air blast wave and seismic wave measurements at long distances from chemical detonations obtained during a survey of demolition activities at installations of the Field Service Division, Ordnance Ammunition Command, is presented. Disturbances to surrounding residents as a result of demolition activities were found to be traceable solely to air blast waves, seismic disturbances generated directly by the demolition being far too small at the distances in question to be of consequence. The intensities of the air blast waves were found to depend primarily on weather conditions at the time of detonation, and less than one might expect on the quantity of explosive detonated. Under ideal conditions for blast wave propagation as much as five-fold enhancement above "normal" intensity of the air blast wave pressure was noted, while under conditions least favorable for propagating the blast wave as much as a twenty-fold reduction from "normal" was measured. Comparison of results with information concerning damage to structures from air blast and seismic disturbances revealed that no damage was being caused by the demolition activities.

1. Introduction

With the cessation of hostilities and the subsequent continued improvements in weaponry it has become necessary for service installations to dispose of large quantities of explosive-loaded shells and bombs. With some of the devices the explosive may be removed by hot-water washout while the explosive in others may be destroyed by burning. However, in the interests of economy and efficiency much of the material must be destroyed by detonation. Such demolition activity, unfortunately, frequently incurs complaints from residents living near the demolition site. Complaints have ranged from slight objections such as excessive noise to claims of structural damage to residences, e.g., cracked plaster, cracked foundations and other structural damages. These complaints have been made by persons living in the range from about 2500 ft to as much as 40 mi from the governmental demolition activities. While it was well known that those unfamiliar with the characteristics of long range air blast and ground shock from high explosives tended greatly to overestimate their damage potential and attributed (usually honestly) many flaws in their residences to these disturbances where actually the blasts were in no way responsible, the various service organizations carrying out demolitions activities have not been unmindful of complaints concerning their demolition activities. In 1954 (following several similar smaller scale studies between 1950 and 1954) the Institute of Metals and Explosives Research of the University of Utah undertook, at the request of Army Ordnance, to measure air blast and ground shock wave intensities in areas surrounding installations of the Field Service Division, Ordnance Ammunition Command, to assess the possibilities of damages resulting from these activities, and to correlate the results with meteorological and geological data. The depots investigated comprised in all a total of seventeen demolition activities located throughout the United States (see Fig. 1); thus these studies represented a wide range of conditions. This paper summarizes the results of these extensive studies.

The effects arising from the detonation of high explosives may be separated into two categories, namely (1) those arising from the propagation of ground shock or seismic waves, and (2) those arising from propagation of air blast waves. It was recognized early in the program also that the air blast wave impacting the ground may give rise to induced seismic waves, and that the induced seismic waves were of greater importance than the direct seismic waves (Cook, 1958).

When a charge of explosive is detonated, a blast wave is created which at long range propagates with a peak pressure π_m which falls off almost in proportion to distance. The idealized equation relating peak pressure to the size of and distance from a detonating charge is (Cook, 1958)

$$\pi_m = c'[(WnRT_4)^{\frac{1}{3}}/S]^{c_2},$$

where W is the weight of the explosive, n is the moles of gas per pound, R is the universal gas constant, T_4 is

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the temperature of the gases at the point at which expansion ceases, S is the distance, and c' and c_2 are empirical constants. This equation applies closely at short range (up to say about 100 to 1000 charge diameters) but breaks down at long range owing to the great influence of meteorological conditions upon the propagation of air blast waves. All of the components in the inner parentheses are related to the quantity and type of the explosive. The type of explosive, however, is in general much less important in long range blast than the quantity since service explosives do not vary a great deal in available energy per pound. Therefore, Eq (1) may be approximated to give

$$\pi_m \doteq c_1(W^{\frac{1}{3}}/d)^{c_2}. \tag{2}$$

The value of c_2 is expected to be near unity, while that of c_1 depends upon the units used. Both of them may, however, be readily determined experimentally.

Anomalies due to meteorological factors on the propagation of air blast waves have been known for many decades. For example, during the funeral services for Queen Victoria, a gun salute was heard at remote distances, while at closer distances no sound was observed. Gutenberg (1951), Cox (1954), and other investigators have shown that wind, temperature, or combinations of these may cause considerable bending or refraction of sound and blast waves and may thus produce large variations in the intensity of the blast wave at distant points from a blast, such as to differ by orders of magnitude from that predicted by Eq (1). Though humidity may influence the blast wave, the magnitude of its effect is much less and may be ignored for most purposes.

Research by the Bureau of Mines (Thoenen and Windes, 1942) on seismic effects from quarry blasting indicated propagation through a homogeneous medium may be represented by

$$A = 0.027(W)^{\frac{1}{2}}/d, \tag{3}$$

where A is the displacement amplitude of the seismic wave in inches, W is the charge weight in pounds, and d is the distance in feet. Thoenen and Windes (1942) also reported that the amplitude of a ground shock wave generated by high explosives was represented at relatively close range by

$$A = (W^{\frac{2}{3}}/100)(0.07e^{-0.0143d} + 0.001). \tag{4}$$

Carder and Cloud (1959) suggested from results of measurements of large underground blasts that the exponent of W may be more nearly 0.75. Berge and Cook (1959) in measuring the amplitudes at long distances from large underground detonations concluded that the displacement amplitude should be represented by the equation

$$A = kf(W)/d^{\frac{3}{2}}, \tag{5}$$

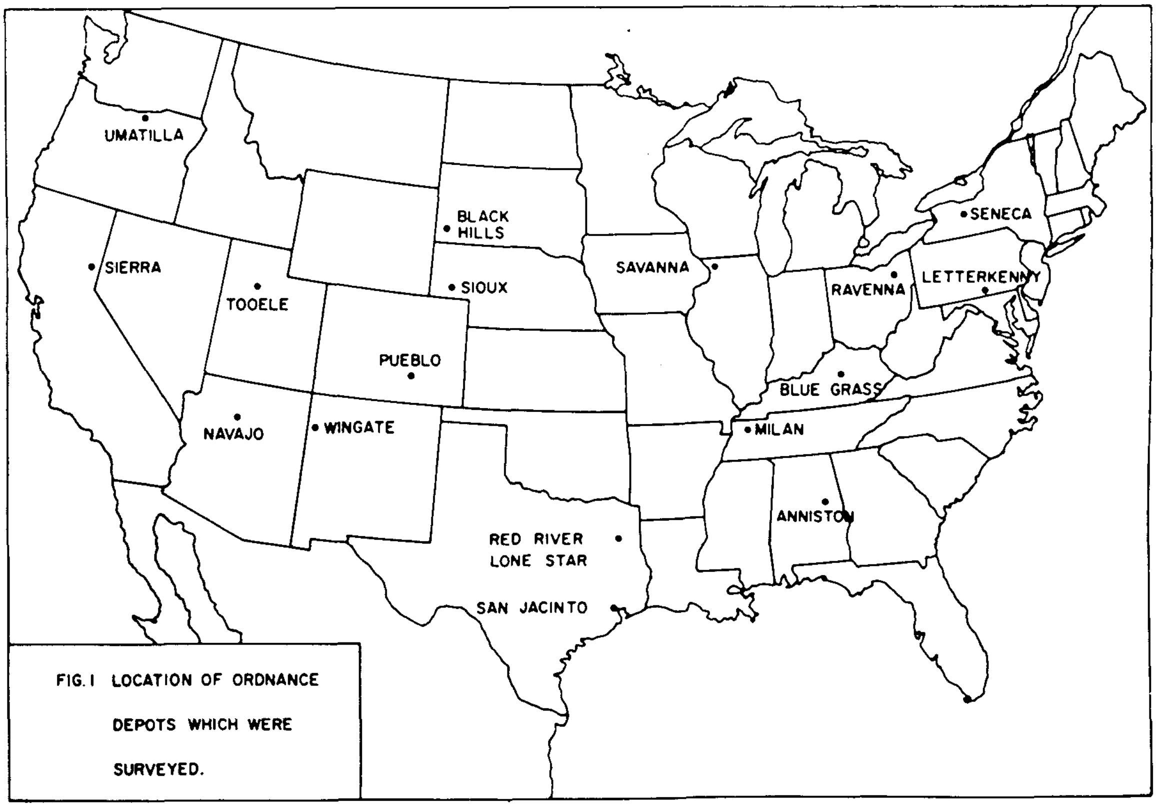

FIG. 1. Location of ordnance depots which were surveyed.

where k is a constant, and $f(W)$ is an unspecified function of the weight.

A large experimental program extending over a period of ten years was carried out by the U. S. Bureau of Mines to determine the magnitude of ground shock from quarry blasting necessary to produce damage to structures (Thoenen and Windes, 1942). Their experiments consisted of vibrating ceiling, floor, and wall panels of houses by means of a mechanical shaker, the shaker being adjustable over a wide range as to the frequencies and amplitudes of the disturbances which it created. The amplitudes of these induced disturbances were measured by means of a seismometer, and then the effects of the mechanically induced vibrations were correlated to vibrations produced by quarry blasting. The above experiments disclosed that the initial indications of damages are the extension of old cracks in plaster and possibly dust falling from them. As the severity of the disturbance is increased, new fine cracks are formed and the plaster may flake or spall slightly. Still more intense vibration will produce larger cracks, and under certain conditions areas of plaster may loosen and fall. Damages to foundations, pipes, wells, etc., require much more intense ground shock.

Some individuals have maintained that damages may result from a minimum disturbance if the dominant frequency of the ground wave equals one of the resonant frequencies of the structure, since under such conditions, as long as the wave persists the amplitude of the structure's vibrations corresponding to the frequency would increase to a value limited only by the damping inherently possessed by the structure. The Bureau of Mines investigations showed, however, through vibrating wall and floor panels at their resonant frequencies by means of the mechanical shaker, that resonant type damage was no more likely than damage produced at other frequencies because of the large inherent damping possessed by the structures tested.

One of the important end results of the above experiments was the establishment of an index of damage to structures resulting from ground shock. This index is defined by the equation

$$I=(4\pi f^2 A)/(12g),$$

where A is the maximum displacement (displacement amplitude) of the building's ceiling or wall panels, etc., in inches, f is the frequency (cycles/sec), and g is the acceleration due to gravity (32.2 ft $\sec^{-2}$). It is therefore proportional to acceleration assuming the motion of the structure is sinusoidal. Initial indications of damages were found for indices in the range from 0.1 to 1.0. No damages whatsoever were noticed for indices below 0.1, and therefore structural vibrations possessing accelerations below 0.1 g may be considered perfectly safe.

Frequently, when one is interested in determining whether or not a given level of ground disturbance will produce damage to a structure in the vicinity, one wishes to base conclusions upon the magnitude of the ground disturbance itself rather than actual measurements of vibration within a structure. In this case, the index can be computed from actual motion of the earth's surface under influence of ground shock. The Bureau of Mines in computing this index used the amplitude of the earth's motion and the natural frequency of the structural elements in question rather than the frequency of the ground wave, the reasoning being that the structure would be shocked into motion with an amplitude approximately equal to the ground wave amplitude, and then because of the relatively short duration of the wave, the structural element would vibrate at its own natural frequency. In computing indices from the data obtained in this study, however, the frequencies of the waves themselves were used, and since ground shock frequencies may be as much as 10 times larger than the natural frequencies of structural elements, these indices may be 100 times higher than the Bureau of Mines predictions. This was done to make certain that ground shock effects could not possibly be underestimated.

Recently, Langefors *et al.* (1958) investigated the relationship of displacement amplitude and frequency to damage potential in connection with underground blasting close to buildings. Their findings were in excellent agreement with those of the Bureau of Mines when the displacement amplitude at which damage might be expected at a particular frequency was considered. Langefors further pointed out that the displacement amplitude of the vibration became irritating and disagreeable to laymen well before the level was reached at which damage was to be expected.

The problem of damages produced by air shock, like the problem of damage produced by seismic waves, is rather complex, the reason being due to differences in construction. As an extreme example, plaster may be caused to fall from some houses merely by slamming a door. Concerning damages from air shock to ordinary structures most individuals first think of plaster damage. Investigators, however, seem in agreement that for structures in reasonably sound condition initial damages by air shock are evidenced by the breakage of windows (Poulter, 1955; Windes, 1943) and much more intense air disturbances are required to inflict plaster damage when the plaster is in reasonably good condition. Damages to foundations and cisterns, etc., of course, cannot be caused by air shock from demolition blasts alone.

To establish a safe level for air disturbances stemming from demolition activities, values were determined for peak pressure of air blast waves which were required to fracture windows, and then a level considerably below this was arbitrarily chosen as the safe level. One study listed a peak pressure of 100 lb ft^{-2} as the pressure required to fracture ordinary windows (Poulter, 1955) while another investigation (Windes, 1943) yielded 144 to 288 lb ft^{-2} as the pressure required. Results from this laboratory (Ursenbach *et al.*, 1958), were in fair agreement with these conclusions wherein it was determined that 84 lb ft^{-2} were required to fracture a 2-ft by 2-ft window pane of double strength glass. For a 3-ft by 3-ft pane the pressure was 66 lb ft^{-2}, and with a 4-ft by 4-ft pane 40 lb ft^{12} were required. Windows much larger than 4 ft by 4 ft are in general made of plate glass which by virtue of its greater thickness would be more difficult to break. On the basis of the above results a peak pressure for air blast waves of 10 lb ft^{-2} was considered to be a conservative safe maximum.

2. Method of investigation

Since weather was considered to exert the most important influence on air blast intensity at long distances, it was early determined that the most economical and satisfactory method of investigation was to determine the meteorological conditions at the time of measurement and then to correlate these results with the actual measured intensity of the air blast. Ground shock is, of course, independent of weather conditions, but this applies only to the direct ground shock and not to induced ground shock. Clearly, therefore, meteorological conditions were a necessary part of all measurements in this investigation. Efforts were made wherever possible to obtain readings in the areas where weather conditions indicated that "abnormal sound" and air blast intensities would be measured. Since selection of bad weather conditions was not always possible in long range programs a good sampling of all possible bad and good weather conditions was actually obtained. The surveys thus included simultaneous measurement of wind and temperature to altitudes as high as 5000 ft above ground as well as the peak air blast pressure and ground shock amplitude and acceleration. Light aircraft were used to obtain temperature measurements and in some cases wind velocity and direction. At other times, actual winds aloft were determined using well-known pilot balloon techniques. All weather measurements, where practical, were compared with available U. S. Weather Bureau data. Air blast pressure measurements were made with low frequency microphones capable of recording pressures as low as 0.01 lb ft^{-2} with essentially flat frequency response from dc to 10 kc or with accurately calibrated commercial microphones. Almost all of the recordings were obtained using Brush Electronic recorders and amplifiers. These instruments gave very satisfactory recording response from $\frac{1}{2}$ cps to 100 cps which was adequate since tests with cathode ray oscilloscopes indicated that the most of the energy in air blast waves and in ground shock waves was to be found within the frequency limits of these recorders.

All ground shock measurements were obtained using S-36 seismometers manufactured by Houston Technical Laboratories (now Texas Instruments) with a natural frequency of 2 cps. These seismometers were sufficiently sensitive to measure deflections the order of 0.0000001 inch. They were buried to their full length in the ground, and the soil was firmly tamped around them. Only the vertical component of the ground vibration was measured since it was expected that this component would be of the same order as the other modes and in many cases probably exceeded them.

On several occasions actual measurements were made in residences whose owners had complained. In addition to the air blast and ground shock instrumentation, vibration pickups were placed at strategic locations in the homes, thus recording both horizontal and vertical disturbances induced by the air blast or ground shock waves. These pickups were capable of recording accelerations well below the level of potential damage based on the acceleration criteria for damage to homes as a result of vibrations as discussed above.

Fig. 2 shows an actual Brush oscillograph recording, while Fig. 3 shows a typical detonation of a test charge. The detonation of the explosives followed procedures established at the various depots. Synchronization of the recordings with the firing of the charges was accomplished either by radio or by telephone. Charges were fired on the ground, above the ground, and buried under various depths of dirt cover. In general the explosive weight was expressed in terms of the equivalent

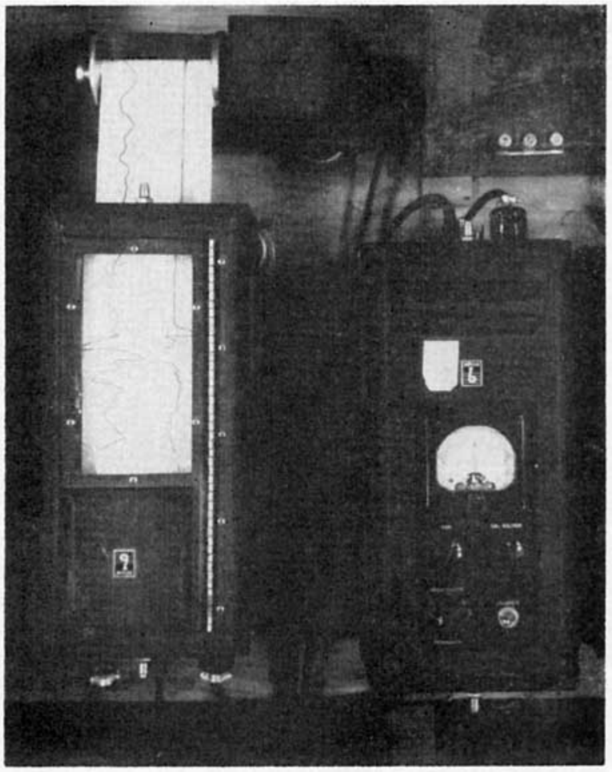

FIG. 2. Photograph of trace during recording.

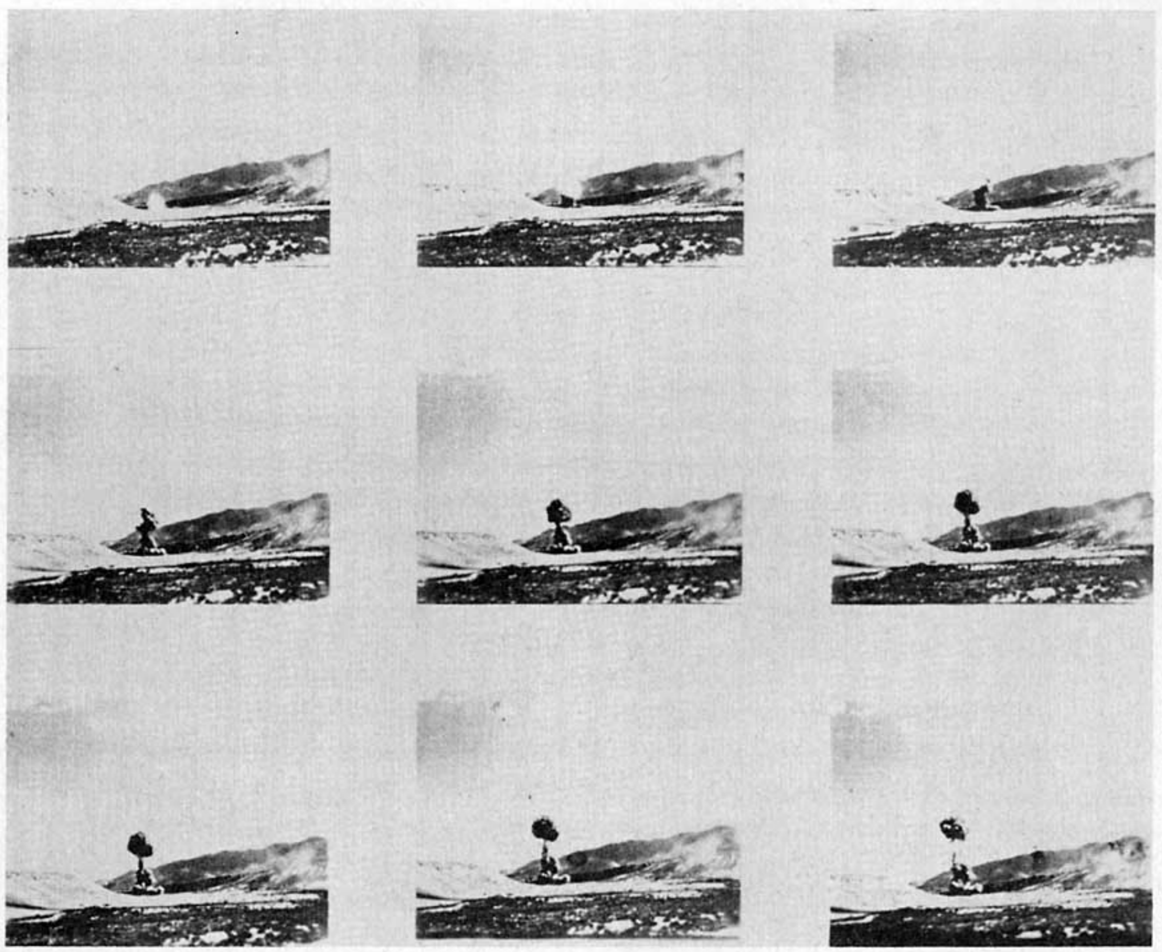

Fig. 3. A typical demolition shot (5000-lb TNT equivalent).

weight of TNT required to produce the same effects. However, at large distances variations in the blast intensity were far greater than could be attributed to differences between explosives, and conversions to TNT weight equivalent were thus in general meaningless.

3. Results and discussion

The data accumulated in the surveys and additional fundamental work carried out in this program represented measurements for approximately 4000 explosions involving detonating charges ranging in weight from 5 lb to 25,000 lb. Measurements were obtained at distances ranging from 2000 ft to over 40 mi from the point of detonation. The results presented in this paper do not include all measurements but are representative of the results obtained.

Meteorological data. Temperature and wind direction and velocity measurements obtained at various altitudes above the ground were reduced to resultant speed of sound for the direction of the measuring point with respect to the demolition ground. It has been observed by previous investigators (Gutenberg, 1951; Cox *et al.*, 1954) that when the resultant sound speed at some height above the ground exceeds that at the surface, blast waves may be returned to the earth at a distance which depends on the height and magnitude of the sound speed inversion. Thus, air blast pressures at that distance would exceed that which would be obtained if no such influence were felt. Equations from Cox (1954) were made more tractable by Pack (1958) in order that landing distances of various sound rays could be determined with relative ease. From the measured weather conditions it was then possible to determine the location at which more intense air blast pressure would be expected.

From several of the weather and air blast pressure measurements it was possible to determine a normal pressure for a particular charge and distance. In this sense "normal" is used to define that condition where there would be no effect whatever from wind and temperature upon the direction of propagation of the air blast wave, i.e., as in spherical expansion. This information was used to prepare a nomograph (Fig. 4) which in turn could be used to determine whether the measured air blast pressure at a given point for a given charge was influenced by the weather.[2] If the pressure were greater than that indicated by the nomograph, one would assume that weather conditions were "unfavorable," i.e., such that sound was being refracted to the measurement site. If, on the other hand, the pressure was less than indicated by the nomograph one would assume that the weather conditions were "favorable," such as to reduce the wave intensity at the point of movement. In every case where this technique was employed, excellent correlations were obtained.

It was observed that there was considerable fluctuation in weather, even over short periods of time. Fig. 5a, b and c show some results of measurements obtained at fixed distances from constant charges detonated at intervals of one or two min. Also included are plots of the sound speed as a function of height obtained simultaneously with the measurements. The air blast measurements were obtained simultaneously with two microphone systems having different response characteristics. In this manner, any shift in the dominant frequency could be detected. The dashed line gives the pressure which would be expected without any weather influence, i.e., in strictly spherical expansion. When the sound speed did not exceed the ground level speed, the intensities measured were lower than "normal." When the sound speed did not exceed that at the ground but was not much less it was possible for a gust of wind to cause sound to return (see Fig. 5c). When the sound speed exceeded that at the ground level, the measured pressures were found to be in excess of those considered to be normal (Fig. 5b).

The normal data shown in the nomograph were used in Eq (2) to establish c_1 and c_2 from which the following equation for normal (spherically expanding) blast waves was obtained:

$$\pi_m = 950W^{0.31}/d^{0.94} \qquad (6)$$

for peak pressure π_m in lb ft^{-2}, W in lb TNT equivalent and distance in ft.

Representative data were used to prepare the plot in Fig. 6a in which is plotted $\pi_m/W^{1/3}$ against reciprocal distance, d^{-1}, ignoring the negligible (for present purposes) deviation of c_2 from unity. The tremendous deviation in the results from the "normal" represented by the straight line shown is very significant. In view of the spread of the measurements shown in Figs. 5a, b, and c this variation is, of course, not surprising.

To show that deviations from the "normal" were not connected in any way with the size of shots, Fig. 6 presents the results coded to permit one to examine the influence of charge weights. Any effect of charge size beyond that expressed by Eq (6) was obviously masked by meteorologically induced variations. While large variations in air blast pressure for a charge at a certain distance were often encountered, it was apparent that the pressure would not rise above a factor of approximately five under the most adverse conditions. This was not considered to be a rigid rule but rather an indication of the maximum pressure which might be expected. On the other hand, twenty-fold reductions in pressure from the normal pressure were experienced. Incidentally, the fact that more results showed deviations (in order of magnitude) below than above "normal" reflects the efforts of the various demolition activities to select favorable weather conditions to reduce annoyance in surrounding areas.

The highest pressure amplitude (9.9 lb ft^{-2}) was recorded at a distance of 10,000 ft from a 1120 lb charge. In no other case were the measured pressures greater than 3.5 lb ft^{-2}, although charges up to 25,000 lb of high explosive were detonated. The lower limit of meas-

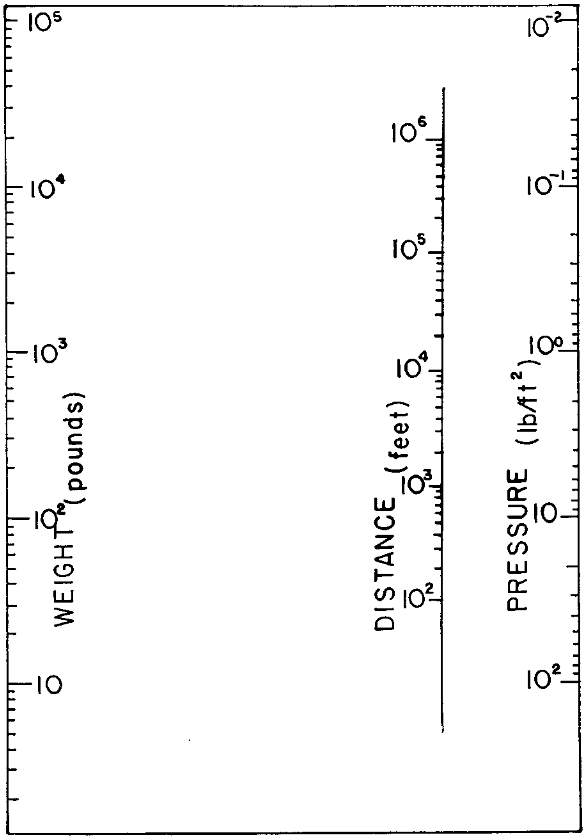

FIG. 4. Nomograph relating air blast pressure to distance and charge size for "normal" weather conditions (i.e., for spherical expansion).

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[2] It should be noted that the "normal" used here is somewhat different than that reported by Ballistics Research Laboratories, Report No. 1118, entitled "Forecasting the Focus of Air Blast Due to Meteorological Conditions," which gives higher over-pressures at distances less than five mi and lower ones for distances greater than five mi. However, variability due to meteorological conditions is such as to make the "normal" curve somewhat uncertain.

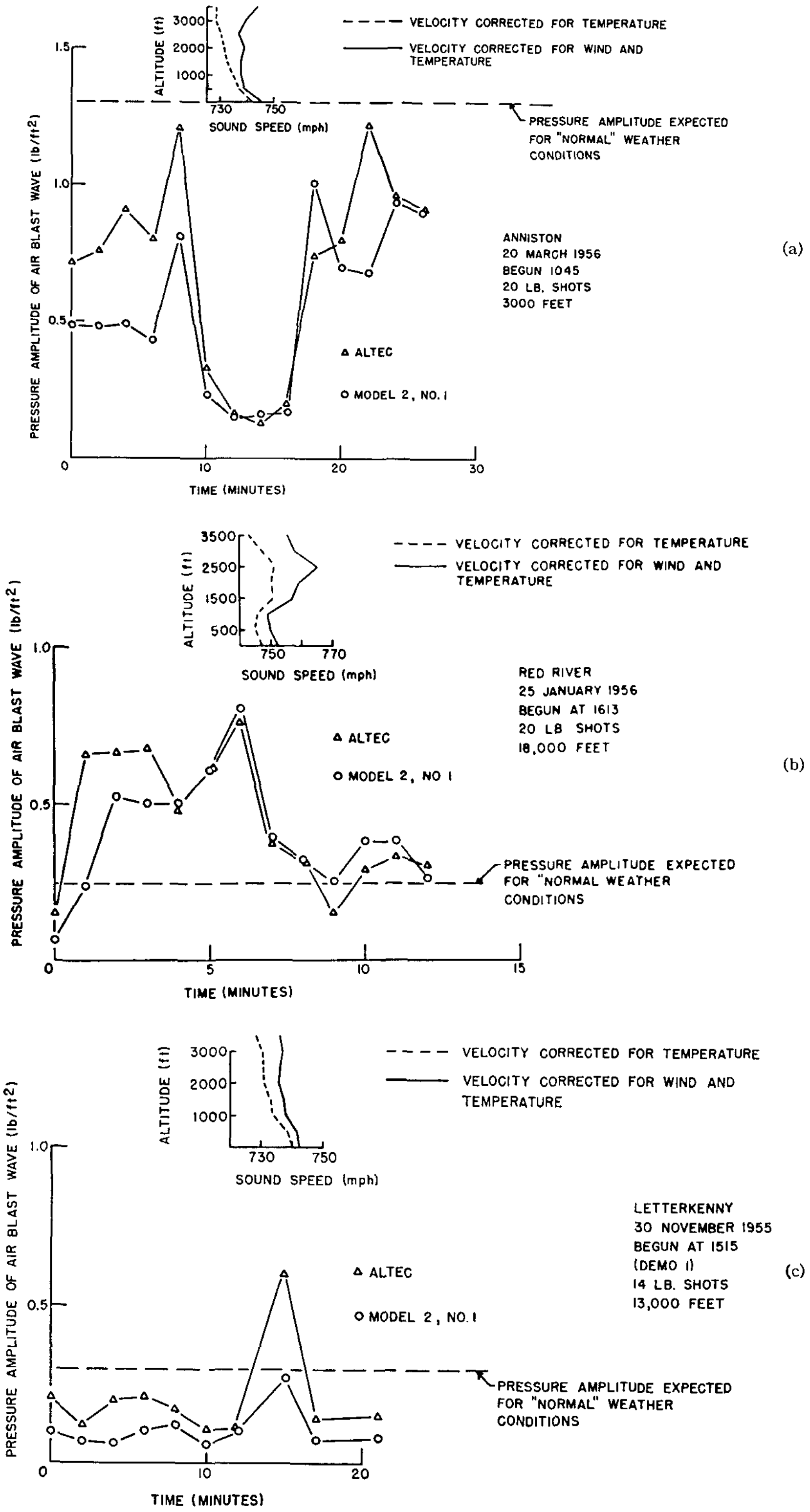
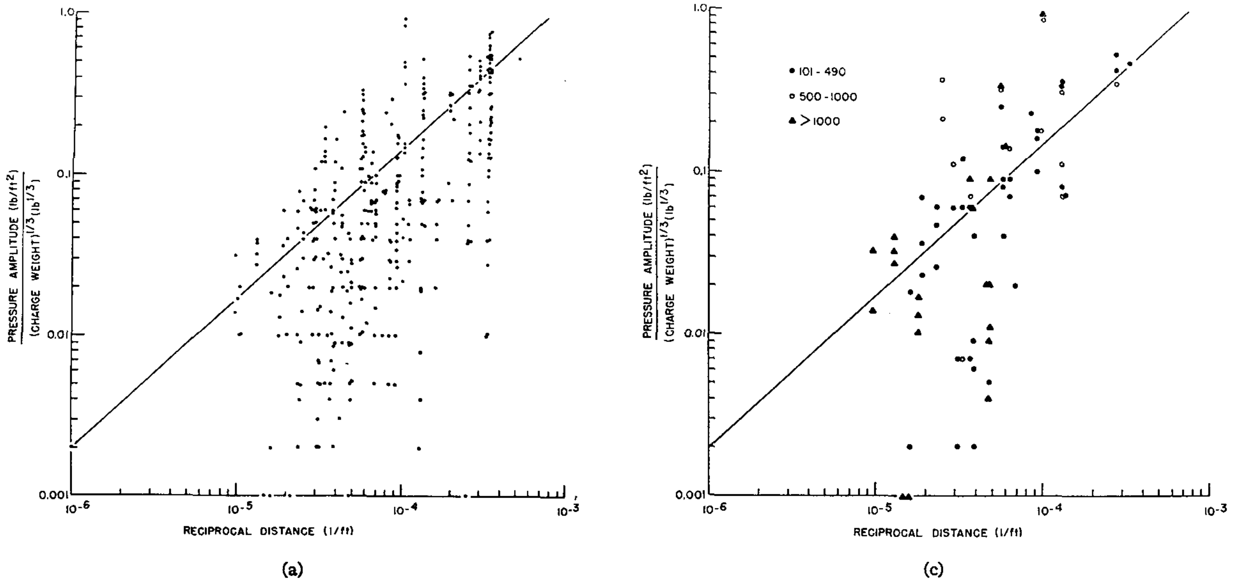


Fig. 5. Pressure variations at constant weight and distance caused by variation in time of meteorological conditions. (a) Sound speed above ground less than at ground level. (b) Sound speed above ground greater than at ground level. (c) Sound speed slightly less above ground than at ground level with possible wind gusts.



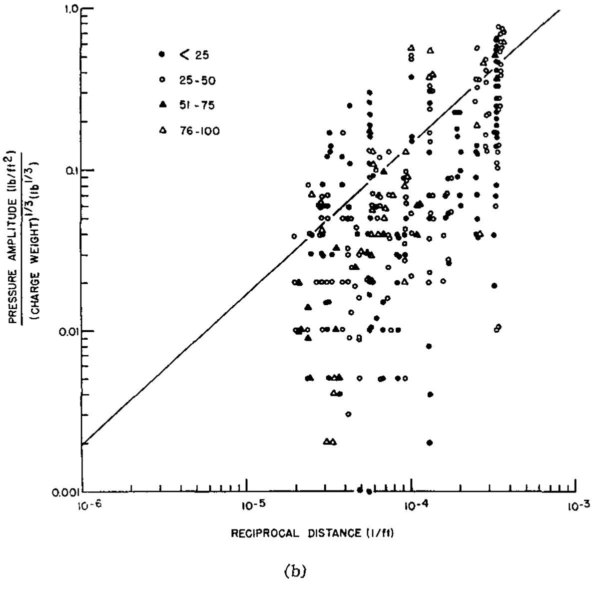


FIG. 6. Distribution of air blast pressures obtained during the surveys. (a) Distribution of air blast pressures measured for all charges in a survey. (b) Distribution of air blast pressures from charges up to 100 lb TNT equivalent. (c) Distribution of air blast pressures from charges greater than 100 lb TNT equivalent.

ured pressure was zero, charges fired being as great as 25,000 lb of explosive for which no air blast pressure or ground disturbance could be detected at the points of measurement, some of which were well within 40 mi of the blast.

Ground shock. Reproducible data on direct ground shock at the various installations were difficult to obtain. Because of induced ground shock propagating toward the measuring site from impact at regions closer to the point of detonation, it was frequently difficult to identify a pure direct ground shock wave. In many instances terrain and strata varied considerably from location to location, and data gained at one location could not be reliably related to those obtained at another. The acceleration indices determined, as mentioned previously, for all the seismic waves originating from demolitions at the ordnance installations were in all cases far below even the caution zone of 0.1–1.0. Hence, there is no possibility that the demolition activities being carried out were damaging to surrounding residential areas by virtue of seismic disturbances.

It was felt that much of the difficulty experienced in obtaining reproducible ground shock data was due to the fact that the charges, as prepared for demolition, did not uniformly transmit energy to the earth. Some of the charges were fired on the surface of the earth while others were covered with earth to depths as great as 15 ft. Obviously the amount of energy coupled into the ground depends strongly on the amount of cover over the explosive charge. In order to check this situation and to obtain some data with which to assess the various equations, a series of charges were detonated at the Tooele Ordnance Depot under controlled conditions and in as uniform soil as could be found. The results of these tests are shown in Fig. 7. The data are well fitted by the straight line which has the equation (in antilog form)

$$A = 0.88 W^{\frac{2}{3}} / d^{\frac{3}{2}}. \tag{7}$$

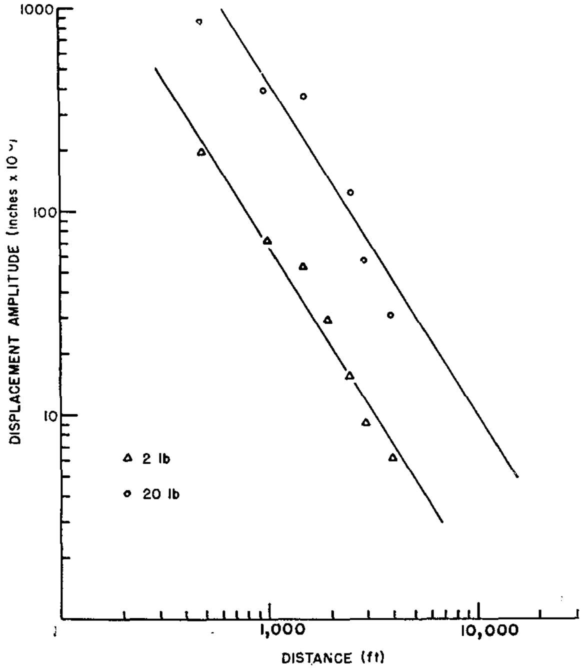


FIG. 7. Direct ground shock measurements obtained in uniform ground.

Several measurements of maximum displacement amplitude found at various depots are listed in Table 1 together with the computed value from Eq (3), (4) and (7). Two observed values were listed in some cases since there was a question as to which portion of the trace actually represented the direct ground shock wave. Apparently the problem of loading was sufficiently great that no decision could be made from the survey data to support any particular equation relating amplitude of seismic waves to charge weight and distances.

Induced ground shock. By far the greatest earth disturbance detected at any of the measuring sites was the induced ground shock. This wave was generated by the impact of the air blast wave upon the earth. Its amplitude was observed to be dependent on the frequency and the pressure of the air wave. When the frequency of the air blast wave was near the frequency of the observed ground vibration, the amplitude of the induced ground wave was much greater than if the frequencies were widely separated. In some cases the earth would respond to multiples of the characteristic frequency giving a much higher amplitude. As is shown in Fig. 8 the acceleration associated with the induced wave was highly dependent on the pressure of the air blast wave. In the cases displayed, when the difference in frequency was fairly constant the data lay quite closely to a straight line. Random variation in air blast frequency gave rise to random distribution of the data.

One special case observed is worthy of note. When the air blast frequency was approximately equal to the frequency noted in the ground waves, and under conditions which gave rise to return of the sound wave to the earth, the air blast wave and the induced ground shock wave appeared to be closely coupled. Under these conditions, a strong ground shock wave would be observed prior to the arrival of the air blast wave. When the air blast wave arrived, there was often a short-lived interference with the recorded induced wave, but the strong wave reappeared immediately thereafter. When measurements were made in sandy soil such as that around the Savanna Ordnance Depot, this coupling was observed to continue for as much as 30 sec after the passage of the air blast wave.

In practically every case the induced ground shock was much greater in displacement amplitude and acceleration than that of the direct ground wave. However, again the associated acceleration indices were always well below the caution level.

TABLE 1. Comparison of observed and computed displacement amplitude.

Depot	Charge wt. (lb)	Distance (ft)	A (inches) *	A (inches) **	A (inches) ***	A (inches) (observed)
Black Hills	6,700	17,000	1.3×10^{-4}	2.6×10^{-3}	1.5×10^{-4}	8.6×10^{-5} 2.5×10^{-4}
Blue Grass	100	2,900	9.3×10^{-5}	4.4×10^{-3}	1.5×10^{-4}	$8\ \times10^{-6}$
Red River	10,000	8,000	3.4×10^{-4}	4.8×10^{-3}	6.0×10^{-4}	1.6×10^{-4} 9.6×10^{-5}
Savana	100	5,000	5.4×10^{-5}	2.2×10^{-4}	5.5×10^{-5}	4.4×10^{-6}
Seneca	100	3,000	9.0×10^{-5}	4.4×10^{-4}	1.5×10^{-4}	9.2×10^{-6}
Sioux	100	3,000	9.0×10^{-5}	4.4×10^{-4}	1.5×10^{-4}	1.3×10^{-4}
Umatilla	300	3,000	1.5×10^{-4}	8.1×10^{-4}	3.0×10^{-4}	5.7×10^{-5} 6.7×10^{-4}
Wingate	10,000	21,000	1.3×10^{-4}	—	1.4×10^{-4}	1.0×10^{-5} 1.4×10^{-4}

* Calculated from Eq (3).
** Calculated from Eq (4).
*** Calculated from Eq (7).

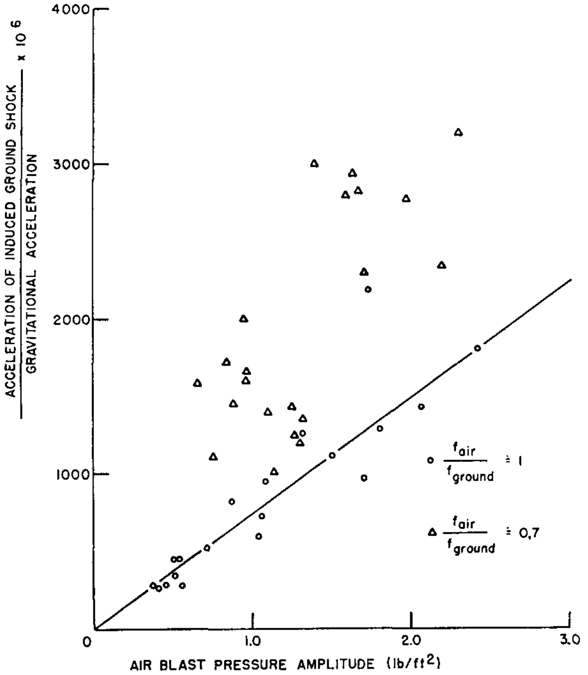


FIG. 8. Dependence of induced ground shock on air blast pressures as a function of the dominant frequencies of ground vs. air wave.

Induced vibration in structures. Tests were carried out in a number of homes of complainants located in the vicinity of depot installations. During the course of these tests both horizontal and vertical components of vibrations generated in the structures upon the arrival of air blast waves were measured with seismometers and vibration pickups. Also, observations were made of the vibrations generated in these structures from normal household movements and everyday disturbances such as traffic, wind, etc. In no cases were the acceleration indices produced by demolitions greater than the caution value. On the other hand, it was not uncommon for the acceleration indices associated with vibrations generated by normal household movements and everyday disturbances to exceed those from demolitions. Almost without exception when homes of complainants were tested, they were found to be vibrant within themselves. This quality can be related to the construction details of the building.

Magnitude of air blast as a potential source of damage. As mentioned earlier the highest air blast pressure recorded during the surveys was 9.9 lb ft^{-2}. This peak pressure was measured from a 1120 lb charge at a distance of 10,000 ft. In no other cases did the peak pressure exceed 3.5 lb ft^{-2}. The 9.9 lb ft^{-2} pressure was just slightly less than the 10 lb ft^{-2} safety level for pressure amplitude that was arbitrarily established as being several times below the level required to fracture the most easily broken windows, which in turn was considered to be the first sign of damage to structure. The 9.9 lb ft^{-2} pressure amplitude might be capable of pulling a sash intact outward from its mounting if the mounting were sufficiently loose. This, however, should not be construed as damage caused by demolition activities because with a window frame in such a poor condition it would likely only be a matter of time until some natural disturbance caused the window to fall from its mounting.

4. Conclusions

1. Seismic waves generated directly by demolitions were of far too small a magnitude to give rise to damages to residences in the vicinity of the demolition ranges studied. In fact, such seismic disturbances were far too weak even to be a source of complaint. The only seismic waves of any significance at the distances involved were induced seismic waves generated by the air blast wave impacting the ground.
2. The major effects and the complaints noted from the demolition of high explosives could be attributed without exception to air blast waves.
3. Disturbances to areas surrounding depots arising from air blast waves generated during detonations were dependent primarily on weather conditions at the time of the detonation and surprisingly insensitive to the quantity of explosive detonated. Experience during the surveys showed that under adverse weather conditions the pressure amplitude could be enhanced by as much as five times. On the other hand, under ideal conditions twenty-fold reductions in pressure were noted.
4. While air blast pressures measured during the survey sometimes were of sufficient magnitude to be annoying to persons living near the installations, they were in all cases below the threshold for inflicting damage on dwellings.
5. No scientific evidence was found in this study to indicate that the demolition activities in any way caused damage to any residences or other buildings in the surrounding areas. Slight psychological annoyance thus appeared to be the most severe justifiable claim.

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