The thermochemistry of carbon

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The experimental study of the blast from bombs and bare charges

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The paper gives an account of investigations on the blast from bare and cased charges of explosive ranging in weight from a few pounds to several thousand pounds.

The measuring technique, involving the use of piezo-electric gauges with cathode-ray oscillographs, is described, and features of theoretical interest or of practical importance are illustrated.

It is shown that, at any rate at distances large compared with the dimensions of the charge, the scale relationship, deduced from simple dimensional theory, holds good over a wide range of charge weight. The importance of this finding in relation to model and full-scale investigations of bomb behaviour is discussed.

Comparisons of the measured velocity of the blast wave with that calculated, by the Rankine-Hugoniot formula, from the maximum excess pressure behind the shock-front show that the recorded values are in good agreement with those deduced theoretically. Observed and calculated rates of decay of maximum excess pressure are also in reasonable agreement.

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INTRODUCTION

Just prior to the outbreak of war in 1939 the Home Office (A.R.P. Dept.) sought information from the Building Research Station of the Department of Scientific and Industrial Research as to the effect on buildings of the blast from bombs. A mathematical analysis, carried out by Dr E. N. Fox, showed that certain basic data were required. A search of the available literature yielded very little of value; the results of a few measurements of the blast pressure from explosive charges had been published (see ref. (1)), but most of the measurements had been made so far away from the charge that no use could be made of them in an analysis concerned with damage. To produce the required information, a research was therefore initiated, first, to devise accurate and convenient methods of recording the pressure-time curves near explosions, and, secondly, to use these methods to obtain blast data for a representative series of bombs and charges.

The apparatus, developed as the result of work started at the Building Research Station, and continued at the Road Research Laboratory of the Department of Scientific and Industrial Research after the outbreak of war, has been used to measure the blast pressures from explosive charges ranging from a few ounces in weight to the largest bombs in Service use. Similar apparatus now provides a standard method of assessing the blast performance of new munitions.

The present paper, having described the apparatus, reviews some of the results obtained, up to the end of December 1942, in the course of investigations undertaken by the Road Research Laboratory, initially for the Research and Experiments Department of the Ministry of Home Security, and later for the Ministry of Supply.

EXPERIMENTAL

At the outset it was known that the initial pressure rise in a blast wave is very steep, and it was realized that mechanical methods of recording were likely to be unsatisfactory. The following requirements have to be met by a satisfactory recording apparatus:

(1) the sensitive element or gauge must have a high natural frequency, since the initial pressure rise in the blast wave is very steep;
(2) the gauge must be capable of use with cables at least 100 yd. long;
(3) the recording apparatus must deal with several records simultaneously; and
(4) it must record without distortion the highest frequency accurately reproduced by the gauge and amplifier;
(5) it is essential that the whole apparatus be as simple as possible, since most of the work is done under field conditions.
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Of several electrical methods of pressure recording considered, one depending on the piezo-electric properties of quartz was finally adopted, and the apparatus was designed to satisfy the above requirements. The piezo-electric quartz gauge, developed for the work, has a natural frequency of about 40,000 (type 1) or 70,000 (type 2) cyc./sec., and can be used with leads 500 yd. long; the recording apparatus, which is of very simple design, requires no external power supplies, and each recording unit gives photographic registration of the output from three gauges on separate cathode-ray oscillographs. Several such recording units may be operated simultaneously.

The gauges. An appropriately cut piezo-electric crystal, when compressed or elongated, develops a charge on two of its faces; the quantity of charge is proportional to the applied load and is developed without appreciable time delay. To utilize the phenomenon, the charge, collected on electrodes cemented to the two faces, is applied to a condenser of known capacity and the resulting voltage is recorded. Quartz or tourmaline is generally used for pressure recording, and the gauges described below are designed for quartz crystals.

Figure 1 is a drawing of the simplest form of blast pressure gauge (type 1), while figure 2 shows an improved type (type 2), with double the sensitivity of the first. Photographs of the two gauges are reproduced in figure 3.

Figure 1. Piezo-electric blast pressure gauge—type 1.

The main body (1) of the type 1 gauge is a cylindrical block of steel, 2 in. in diameter by 1 in. thick, through which a single-core shielded cable (Telcon K.I.C.) is brought and secured by a fitting (4). Two circular (X-cut) quartz plates are mounted on the front plane surface of (1) and are covered by a duralumin plate (3) of slightly greater diameter. Between the crystals is placed an electrode of copper foil, to which the central wire of the cable is soldered. The pile of disks, consisting of the duralumin plate, the two crystals, and the central electrode are all cemented together and to the block (1) with a high melting-point bitumen. A steel ring (2), screwed to the block (1), fits round the plate (3), the annular space between the plate and ring (about
Figure 2. Blast pressure gauge—type 2.

Type 1

Type 2

Figure 3. Piezo-electric blast pressure gauges.
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1/1000 in. wide) being filled with a very viscous oil, which serves the double purpose of forming an airtight seal and of providing damping for the crystals.

The lowest natural frequency of 40,000 cyc./sec. from a gauge of this type is very probably due to flexural vibration of the steel block or ring, since the frequency of the longitudinal front-to-back vibration is found by calculation to be more than twice this figure.

Type 2 is similar in essentials but has two pairs of crystals, one on either side of a central steel plate. The crystals are connected electrically in parallel, so that for pressures the charges reinforce one another; as regards vibration of the central plate, however, the two pairs act in opposition, and no net charge results. The natural frequency of the type 2 gauge is about 70,000 cyc./sec.

Both types of gauge are used with their sensitive faces parallel with the direction of propagation of the blast.

When bare gauges are relatively near to a charge there is some transmission of heat from the blast wave to the sensitive face of the gauge. This tends to cause distortion of the crystal pile, giving rise to parasitic effects. A layer of vaseline over the face of the gauge hinders this heating and eliminates the trouble.

The recording unit. The complete recording unit, including three amplifiers and oscillographs, a drum camera and all battery supplies, is contained in two wooden boxes measuring respectively 35 × 22 × 15 in. and 31 × 18 × 6 in. (figure 4).

The arrangement of the electrical circuit of one of these triple units is given in figure 5.

The two-stage resistance capacity coupled amplifiers employing high-frequency pentodes (Mullard S.P.2's) give a voltage amplification of about 8000. The good low-frequency response, necessary to record accurately the long-duration blast waves from large bombs, is obtained by separating the anode and screen supplies to the first and second stages; all three first stages are fed from one battery and the second stages from another. The high-frequency response is adequate in relation to the characteristics of the gauge, the loss at 10,000 cyc./sec. being about 4%. One other feature of the amplifiers calls for comment; in the first stage of each amplifier, it is necessary to have a valve of high grid-filament resistance, to reduce leakage from the piezo-crystal to a minimum. Valves are considerably improved in this respect by under-running their filaments, and a good high-frequency pentode with a 3-ohm resistance in one valve leg, as shown in the circuit diagram, is very satisfactory, and will operate in a stable manner with a grid leak as high as 200 megohms. The arrangement has the further advantage of providing grid bias for the first stage. A 2 V accumulator supplies filament current for the three amplifiers, and three 120 V dry batteries
Figure 4a. Triple oscillograph unit.

Figure 4b. Rotary switch.
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supply anode current, one for the first stages, and two for the second stages. The amplifiers provide a substantially linear output of about 100 V.

The oscillographs at present in use (G.E.C. V.C.R. 138's) have 3 1/4 in. photographic screens. A high-tension voltage of 900 V is provided from dry batteries housed in a separate wooden box, which also contains a 100 V battery for the operation of relays. The fluorescent spots of the three oscillographs are normally suppressed by the negative bias on the intensity control electrode (figure 5) until the moment of recording, but, during the recording period, they are brought up to full intensity by a relay, which short-circuits the resistor which provides this negative bias. The relay coil has a resistance of about 1000 ohms and may be operated from any con-

Figure 5. Electrical circuit of a triple oscillograph unit.
venient distance, since the resistance of any reasonable length of connecting cable is small compared with that of the relay coil.

The recording spots are deflected in a horizontal direction only, and a time axis is provided by registering all three records on a 4 in. wide strip of photographic film or paper fastened round a 7 in. diameter drum in a removable camera. The camera is fitted with a dark slide, which, when open, allows the spots to be focused on the film by Kodascope F 1·6 lenses of 2 in. focal length. The drum is driven by a 6 V Klaxon motor, geared down to a speed of 2 rev./sec.

Synchronization of the recording and firing is accomplished by a motor-driven switch with rotating contacts (figure 4), which first operates the brightness control relay and then fires the explosive charge.

**Calibration.** Two methods have been used for the calibration of gauges. In the first air pressure is suddenly applied to the gauge. The apparatus (figure 6) consists essentially of two chambers separated by a thin diaphragm of cellophane or similar material. The gauge, coated with vaseline, is clamped over a hole in the bottom of the lower chamber (type 2 is placed inside the chamber), and is connected to a standard condenser and to the oscillograph in the usual manner. The upper chamber is pumped up by means

![Diagram of calibration apparatus.](image)

**Figure 6.** Diagram of calibration apparatus.

![Diagram of calibration records.](image)

**Figure 7.** Typical calibration records.
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of a bicycle pump, and the diaphragm is then punctured by a sharp point operated from outside. The diaphragm shatters and the pressure is applied suddenly to the gauge, the value of the final steady pressure being read off on a pressure gauge of the Bourdon type connected to the lower chamber. In order to ensure that the pressure change on expansion is substantially isothermal, and to damp out the natural frequency of vibration of the air in the apparatus, the lower chamber is packed fairly tightly with rag, when a trace of the form shown in figure 7 is produced. The vertical distance between the initial zero line and the deflected line is the deflexion due to the final steady pressure read from the Bourdon gauge. This gauge has been calibrated against a mercury column, and found to be accurate to within 1/10 lb./sq.in. at all values of pressure.

In addition to providing a gauge calibration, the method has the advantage that the slope of the oscillograph trace after the application of the steady pressure gives information about the time constant of the whole assembly—gage and amplifier.

![Electrical circuit of valve voltmeter used in static calibration.](image)

Instead of making use of the recording equipment for the calibration, it is generally more convenient and rather more accurate to determine the sensitivity of the gauge alone, that of the recording equipment being registered automatically in the manner described in the next paragraph. The gauge to be calibrated is subjected to a steady pressure, either by placing known weights on the sensitive face, or by applying known air pressures with the apparatus illustrated in figure 6; the latter method is preferable, since, for highest accuracy, it is essential to apply the calibrating pressure uniformly. The resulting voltages, developed across a standard condenser in parallel with the gauge, are measured by means of a valve voltmeter; a suitable circuit is shown in figure 8. For successful operation, the grid-filament resistance of the valve employed, and the insulation resistance of the gauge should be very high, so that errors due to the leakage of charge from the gauge during calibration are negligible.
Each time a record is made, the amplifier and oscillograph sensitivity are checked by an automatic calibrating circuit, which, immediately after the oscillograph spots are brought to full brightness, injects a damped sinusoidal voltage of known value into the earth lead. The calibrator consists of a choke, a condenser, and a 2 V cell, all in series with a resistor of a few ohms inserted in the earth lead common to all the amplifiers in use. It is actuated by a delayed relay in parallel with that bringing the spots to recording brightness.

In addition to its function of defining the sensitivity of the amplifier and oscillograph, the calibrating oscillation at the commencement of each record furnishes a datum point for the measurement of time, and, since the frequency of oscillation is known, it also enables the time scale to be calculated.

**Accuracy of measurement.** Factors influencing the accuracy of measurements of maximum pressure are:

1. The natural frequency of the gauge. Calculations of the amplitude of the oscillations at the natural frequency of the gauge are rendered difficult by the fact that the lowest natural frequency appears to be due, not to a thickness vibration of the crystal pile, but to a flexural vibration of the steel housing, excited by the impact of the blast on the gauge. In circumstances favourable to its excitation, however, the characteristic frequency may be detected on the record. To reduce errors caused thereby, a thin layer of sorbo rubber is wrapped round the curved surface of the gauge, leaving the faces carrying the sensitive disks exposed, when the amplitude is reduced to about 1 % of the maximum deflexion and is too small to be measured accurately. (This precaution is not always observed in bomb trials, where, as shown later, the maximum pressures may be relatively unimportant. Figures 9 and 10, for example, were obtained without sorbo screens on the gauges.)

2. The diameter of the sensitive disk. The normal method of setting up a blast pressure gauge being to suspend it with the sensitive face or faces parallel with the direction of travel of the blast wave, it is clear that the larger the diameter of the sensitive disk, the poorer is the reproduction of the fine structure of the blast wave. The extension of the gauge along the direction of travel of the blast results in a reduction of the slopes of lines and a rounding off of peaks in the blast record. In particular, the recorded maximum pressure, assuming no error due to gauge frequency, is always less than the true peak pressure.

The magnitude of the correction to the peak pressure to take account of the disk size has been estimated by assuming, for the positive phase of the blast wave, a shock front followed by an exponential decay curve.

Then, if the decay curve is represented by

\[ p = p_1 e^{-nt}, \]

* See next section.
Figure 9. Blast pressure records from a bare charge of 70 lb.
60/40 R.D.X./T.N.T.

Figure 10. Blast pressure records from a British 4000-lb. H.C. bomb
filled 60/40 amatol—100 and 125 ft.

Figure 10 (cont.). Blast pressure records from a British 4000-lb. H.C.
bomb filled 60/40 amatol—150 to 250 ft.
where \( p \) is the pressure at time \( t \) after the arrival of the shock front and \( p_1 \) is the maximum pressure in the wave, the recorded maximum pressure

\[
p_r = p_1 \left(1 - \frac{an}{c}\right)
\]

approximately,

where \( a \) is the radius of the sensitive disk, and \( c \) the velocity of the shock wave. The approximate correction given above is sufficiently accurate for the small corrections which are required in practice; as might be anticipated, the correction is mainly determined by the time taken for the shock front to pass over the disk in relation to the initial slope of the decay curve.

(3) *The frequency response of the amplifier.* Lack of response at high frequencies in the amplifier gives rise to a rounding off of peaks in the pressure record. An analysis, by A. R. Bryant (see ref. (2)), enables an estimate to be made of the reduction of the maximum value of the signal from the gauge in its passage through the amplifier.

Starting, as before, with a pressure wave of the form \( p = p_1 e^{-nt} \), he shows that the peak output voltage

\[
v_m = v_p e(ka)^{-n\tau(1-n\tau)}
\]

where \( v_p \) = peak input voltage from the gauge,
\( e \) = amplification factor at the middle of the frequency range,
\( \tau = \frac{1}{2nf_0} \) for a single-stage amplifier,
\( = \frac{1}{9.75f_0} \) for a two-stage amplifier with similar stages,
\( f_0 \) = upper frequency at which the amplification is 0.707\( e \),
\( k = 1 + \frac{1-n\tau}{n\tau} \left(1 - e^{-2a\sigma\tau}\right)\).

For small corrections, \( n\tau \) and \( e^{-2a\sigma\tau} \) are negligible compared with unity, and the expressions may be simplified to

\[
v_m = v_p e \left[1 + \frac{1}{2an}\right]^{-n\tau}
\]

The combined correction for gauge size and frequency response is therefore

\[
p_r = p_1 \left(1 - \frac{an}{c}\right) \left(1 + \frac{1}{2an}\right)^{-n\tau}
\]

Unless very sharp peaks occur in the record, the corrections are of importance only for small charges; for example, in a particular test with a 500 lb. M.C. bomb, at a distance of 40 ft., it was found that \( n = 1100 \) and \( c = 1800 \) ft./sec. \( a \) was 0.5 in., and \( f_0 \) was 30,000 cyc./sec., so that

\[
p_r = p_1 \times 0.974 \times 0.989
\]

\[= 0.965p_1.\]
Transmission-line phenomena in the cable. Mention must also be made of transmission-line phenomena, as, at first sight, they might appear to be of some importance in tests of large bombs, where it is necessary to use long cables to connect the gauges to the amplifiers. The usual transmission-line formulae are not directly applicable to the problem, as they assume a constant voltage generator of sinusoidal wave-form, whereas the piezoelectric gauge produces a transient charge. Calculations, based on the cable constants, of the velocity of a transient along the cable, however, indicate that line phenomena are unlikely to be of major importance even when long cables are in use. With the particular cable employed, this velocity is found to be about $490 \times 10^6$ ft./sec. The time taken to traverse the longest cable in use, 500 yd. in length, is therefore about 3 $\mu$sec. Assuming similar reflecting conditions at each end of the cable, the natural frequency of a 500 yd. cable is therefore about 166,000 cye./sec., and the effect of the cable is to introduce into the amplifier disturbances recurring at this frequency. As the time of rise to maximum voltage input to the amplifier is about $1/12,000$ sec., that is, about 14 times that taken for the wave to travel to and fro in the cable, the elimination of these line oscillations by attenuation in the amplifier is unlikely to be attended by any serious loss of accuracy.

The factors dealt with in the preceding paragraphs lead to systematic errors for which corrections have to be made. The various operations of calibration and recording also give rise to random errors, the magnitudes of which have been examined by carrying out these operations many times. The standard error of a single measurement of maximum pressure, determined in this way, was found to be about 2.8%.

With regard to the measurement of positive impulse, that is, the time integral of the positive phase, unless special precautions are taken, by far the most serious source of error is likely to be the generation of parasitic charges by violent movements of the cable connecting the gauge to the amplifier. Much can be done to reduce this by the correct choice of cable, and, in particular, by avoiding cables insulated with plastics; with the cable used in the present work, the errors due to cable signal are negligible except at positions very near to large bombs, where the gauges may be displaced several feet by the blast.

When pressure waves of considerable duration are recorded, it is desirable to arrange that the time constants of the gauge and amplifier circuits shall be long. It may readily be shown that if the positive phase is triangular, with a duration $t_1$, and the gauge has a parallel capacity $C$ and resistance $R$, i.e. a time constant $CR$, the ratio of the recorded impulse $I_r$ to the impulse $I$ delivered by a gauge with infinite time constant is

$$\frac{I_r}{I} = 1 - \frac{2}{3CR} t_1 + \frac{1}{2 CR^2} t_1^2$$

approximately.
assuming no distortion in the amplifier. A similar expression describes the behaviour of each stage of the amplifier, \( C \) in this case being the interstage coupling capacity and \( R \) the sum of the anode and grid resistances.

The time constants of the gauge circuit and of each stage of the amplifier are each about 4 sec. For a 500 lb. M.C. bomb, where the duration of the positive phase may be about 15 msec., the ratio \( I_p/I = 0.9975 \) for the gauge circuit. The overall error in the impulse measurement, including the contribution of the amplifier, if no correction were applied, would therefore be about 0.75%.

A closer determination of the experimental error may be made for impulse than for maximum pressure, and, assuming negligible cable signal, the standard error of a single observation of the positive impulse from a bomb has been found to be \( \pm 3\% \).

**Results**

Measurements have been made of the blast pressures produced by bare charges up to 2000 lb. in weight, by German bombs and mines weighing from 50 to 1000 kg., and by British bombs of all sizes.

*Typical records.* The normal type of pressure-time curve from a bare charge at all distances at which records have been obtained, and at considerable distances from a cased charge or bomb, consists of a shock-fronted positive phase, roughly triangular in shape, followed by a suction phase having a duration several times that of the positive and a lower maximum. The suction phase usually approximates in shape to one-half of a damped sine wave, but frequently departs from this normal form. Figure 9 illustrates pressure-time curves of this type.

Near a cased charge or bomb it is unusual to record a positive phase of this simple form; instead, the positive may consist of two or more shock-fronted waves superimposed (see figure 10), or may even be made up of a series of short-duration shock-fronted waves superimposed on a rounded pressure pulse. As the wave travels outwards, however, it gradually assumes a shape similar to that characteristic of a bare charge.

All records of the pressure from cased charges exhibit, in addition to the main features discussed above, numbers of small bow waves due to the fragments of the case. At all distances where measurements have hitherto been made, the fragments are ahead of the blast, so that the fragment bow waves are always recorded before as well as with the main blast wave.

*The scale relationship.* From dimensional theory, it can be shown that, for geometically similar charges of the same composition and density, the blast pressure-time curves from different charges should appear identical if the units of distance and time adopted are proportional to the linear dimensions of the charge. It follows that, if the maximum value of the excess pressure is plotted against the distance from the charge, taking the charge diameter as
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the unit of distance, the results for similar charges of different weights should all lie on one curve. The durations of the positive and negative phases at corresponding distances, i.e. at the same number of diameters from the charge, should be proportional to the respective charge diameters. Thus if the durations, divided by the appropriate charge diameters, are plotted against distance in charge diameters, the points should again fall on one curve. The impulse, i.e. the area under the pressure-time curve, clearly scales in a manner similar to the duration.

The scale relationship has been found to hold well, at any rate at distances large compared with the dimensions of the charge; the results from a series of bare charges of 70/30 T.N.T./C.E. are quoted below as an illustration of the agreement of the practical results with theory.

Each charge was in the form of a cylinder whose length was equal to its diameter, and each was exploded on the ground with its axis vertical. A list of the sizes and weights of the charges is as follows:

<table>
<thead>
<tr>
<th>Diameter of Charge (in.)</th>
<th>Weight of Charge (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2(\frac{3}{4})</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>32</td>
</tr>
<tr>
<td>10</td>
<td>44</td>
</tr>
<tr>
<td>12</td>
<td>76</td>
</tr>
</tbody>
</table>

Blast pressure records were taken at six distances from each charge, the gauges being hung about 4 ft. above the ground.

Reproductions of the blast pressure curves from some of the charges are given in figure 11.

Figure 12 shows the variation of the maximum excess pressure with distance (in charge diameters) from the various charges. Owing to the way in which excess pressure varies with distance it is convenient to plot on logarithmic scales, and this has accordingly been done. Figure 13 is a similar plot but with linear scales, of the maximum values of the negative pressure or suction. In figure 14 the positive durations, divided by the appropriate charge diameters, have been plotted against distance in charge diameters, and in figure 15 the positive hydrostatic impulses have been graphed in the same manner.

The maximum positive pressures and the impulses are seen to lie fairly well on single curves. The maximum negative pressures and the positive durations show greater variability but can also be represented by single curves. The variability of the experimental points in figure 13 is accounted for by the difficulty of measuring accurately the small deflexions representing the suction, and, in figure 14, is largely accounted for by irregularities in the pressure-time curves, due probably to reflected or diffracted waves from slight elevations or depressions in the ground.
Figure 11. Pressure-time curves from (a) 2\(\frac{1}{2}\) lb. T.N.T./C.E. charge, and (b) 44 lb. T.N.T.-C.E. charge.

Figure 12. Maximum excess pressures at various distances from cylindrical T.N.T./C.E. charges.

Figure 13. Maximum suction from T.N.T./C.E. charges.
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The scale relationship in bomb testing. The scale relationship is of great importance in bomb testing, since it enables predictions of the theoretically attainable performance of new bombs to be made from the results of tests with geometrically similar bombs already in service, thus providing a

![Graph showing positive pressure duration from T.N.T./C.E. charges.](image)

**Figure 14.** Duration of positive pressure from T.N.T./C.E. charges.

![Graph showing positive impulses from cylindrical T.N.T./C.E. charges.](image)

**Figure 15.** Positive impulses from cylindrical T.N.T./C.E. charges.

standard by which the performance of a new bomb may be judged. In practice it is found that, owing to irregularities in the pressure-time curves from bombs, the maximum pressures do not scale as accurately as the impulses; since, however, the impulses are, in any case, of greater importance in determining the damage produced by a bomb than are the maximum pressures, the assessment of bomb performance is based mainly on a con-
sideration of the hydrostatic impulses. An example of the scaling of the impulses from a series of bombs is given in figure 16, in which the results from German S.C. bombs weighing 250, 500 and 1000 kg. are plotted. In view of the fact that the bombs were not exactly similar the agreement is very good.

![Graph of positive impulses from German S.C. bombs.](image)

**Figure 16.** Positive impulses from German S.C. bombs.

An approach may be made to many problems of bomb design by means of tests on a model scale, with consequent saving of time and labour. A question which has recently received first investigation in this way is the influence of case thickness on the blast performance of bombs. The charges, each consisting of about $8\frac{1}{2}$ lb. of 60/40 R.D.X./T.N.T., were enclosed in cylindrical steel or brass cases with flat ends, the thickness of the ends being equal to that of the case. The length of the cavity containing the charge was in all cases twice its diameter. One end of each case was screwed, to allow the charge to be inserted, and had a small hole drilled through it to allow an electric detonator to be inserted. The charges were initiated by exploders consisting of about $2\frac{1}{2}$ oz. of tetryl. For comparison with the cased charges, the series also included two bare charges of the explosive. Particulars of the weights of the charges and cases and of the number of each kind fired are given in table 1, including the charge/weight ratio, that is, the ratio of the weight of charge to the total weight of case plus charge, expressed as a percentage.

Each charge was fired with its axis vertical, and its base resting on a steel plate 3 ft. square by $\frac{3}{4}$ in. thick, placed on the ground, the object of the plate being to eliminate the energy loss due to cratering of the ground. Nine piezo-electric gauges were placed at distances of 10 to 50 ft., six along one line radiating from the bomb, and three along a second line at right angles to the first.

Curves showing the variation of positive hydrostatic impulse with distance from the charge for each charge/weight ratio are reproduced in
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Table 1. Particulars of containers

<table>
<thead>
<tr>
<th>charge</th>
<th>empty weight</th>
<th>charge weight</th>
<th>charge/weight ratio</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>lb.</td>
<td>oz.</td>
<td>lb.</td>
</tr>
<tr>
<td>bare charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>—</td>
<td>—</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>—</td>
<td>—</td>
<td>8</td>
</tr>
<tr>
<td>cased charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>9 1/2</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>2 1/2</td>
<td>8</td>
</tr>
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<td>8 1/2</td>
<td>8</td>
</tr>
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<td>11 1/2</td>
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<td>148</td>
<td>15</td>
<td>8</td>
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<td>6</td>
<td>1</td>
<td>9 1/2</td>
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<td>7</td>
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<td>9</td>
<td>80</td>
<td>1 1/2</td>
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<tr>
<td>10</td>
<td>148</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 17. From these curves, the ratios of the positive impulses from the cased charges to the positive impulses from the bare charges at various distances have been determined, and are tabulated in Table 2. It will be observed that for any particular charge/weight ratio, the positive impulse is substantially the same fraction of the bare charge impulse at all distances from the cased charge. A single curve can therefore be drawn, for the particular explosive used, giving the fractional reduction of impulse, for constant charge weight, as a function of charge/weight ratio. This has been done in Figure 18.

The application of these results to actual bombs, which differ in shape from the simple cylindrical form employed in these tests, will not be discussed here, but it may be stated that, when allowance has been made for the difference in shape, the results have been found to agree well with those recorded in bomb tests.

Table 2. Ratios of positive impulses from cased charges to those from bare charges

<table>
<thead>
<tr>
<th>charge/weight ratio</th>
<th>ratio of positive impulse from cased charge to that from bare charge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 ft.</td>
</tr>
<tr>
<td>84.4</td>
<td>0.870</td>
</tr>
<tr>
<td>62</td>
<td>0.700</td>
</tr>
<tr>
<td>25</td>
<td>0.465</td>
</tr>
<tr>
<td>5.4</td>
<td>0.380</td>
</tr>
</tbody>
</table>

The velocity and rate of decay of the blast wave. Comparisons have been made (1) of the observed velocity of a blast wave with that calculated from the observed values of maximum pressure, and (2) of the observed rate of
Figure 17. Positive impulses from cased 60/40 R.D.X./T.N.T. charges of various charge/weight ratios.

Figure 18. Positive impulses from cased charges of various charge/weight ratios as fractions of the bare charge impulse.
The experimental study of blast from bombs and bare charges

decay of a blast wave with that calculated from the observed pressure-time curves. The results used were those obtained in the tests with T.N.T./C.E. charges described in a previous section.

The mean velocities of the blast wave over certain intervals can be obtained from the records by measuring the time interval between the arrival of the shock wave at the different gauges. The mean velocities may also be calculated, since there is a definite relationship, expressed by the Rankine-Hugoniot formula, between the velocity of a shock wave advancing into still air and the pressure immediately behind the shock surface. This formula has been expressed by Professor G. I. Taylor (see ref. (3)) in the form

\[
\frac{p - p_0}{p_0} = \frac{b^2 - a^2}{a^2} \cdot \frac{2\gamma}{\gamma + 1},
\]

where
- \( p \) = maximum pressure in the blast wave,
- \( p_0 \) = atmospheric pressure,
- \( b \) = velocity of the shock wave,
- \( a \) = velocity of sound in undisturbed air,
- \( \gamma \) = the ratio of the specific heats.

Over the range 0 < \( p \) < 5 atmospheres \( \gamma \) may be taken (see ref. (4)) as 1.405, and the expression becomes

\[
\frac{p - p_0}{p_0} = 0.856 \cdot \frac{b^2 - a^2}{a^2}.
\]

Thus when the maximum pressure at a point is known, the velocity of the shock wave can be calculated. In figure 19 the variation of blast velocity with distance from the charge has been calculated for the T.N.T./C.E. charges, using the mean curve of maximum excess pressure (figure 12). For comparison with the observed mean velocities the mean velocity over

![Figure 19. Velocity of shock wave from cylindrical T.N.T./C.E. charges calculated from pressures observed at various distances.](http://rspa.royalsocietypublishing.org/)

Downloaded from http://rspa.royalsocietypublishing.org/ on June 15, 2017
the same intervals must be obtained from the calculated velocities at various distances. If $\tau$ is the time taken by the shock wave to travel from $r_0$ to $r$, then $\tau = \int_{r_0}^{r} \frac{dr}{b}$, and the mean velocity $b_m = (r - r_0)/\tau$. This may be evaluated graphically.

Table 3 gives a comparison between the calculated and observed values of the mean velocity for the T.N.T./C.E. charges. The agreement between the two sets of values is good.

<table>
<thead>
<tr>
<th>charge</th>
<th>distance from charge</th>
<th>mean velocity (ft./sec.)</th>
<th>observed</th>
<th>calculated from pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>2$\frac{1}{2}$ lb. (4 in.)</td>
<td>5–10</td>
<td>2140</td>
<td>2170</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10–15</td>
<td>1930</td>
<td>1830</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20–30</td>
<td>1200</td>
<td>1250</td>
<td></td>
</tr>
<tr>
<td>15 lb. (7 in.)</td>
<td>15–20</td>
<td>1830</td>
<td>1770</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30–50</td>
<td>1270</td>
<td>1270</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50–70</td>
<td>1210</td>
<td>1210</td>
<td></td>
</tr>
<tr>
<td>32 lb. (9 in.)</td>
<td>25–40</td>
<td>1440</td>
<td>1430</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40–60</td>
<td>1260</td>
<td>1270</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60–100</td>
<td>1220</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>44 lb. (10 in.)</td>
<td>41–50</td>
<td>1290</td>
<td>1300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50–70</td>
<td>1220</td>
<td>1270</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70–100</td>
<td>1160</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>41–100</td>
<td>1200</td>
<td>1260</td>
<td></td>
</tr>
<tr>
<td>76 lb. (12 in.)</td>
<td>25–40</td>
<td>1630</td>
<td>1610</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40–50</td>
<td>1430</td>
<td>1390</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50–70</td>
<td>1310</td>
<td>1310</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70–100</td>
<td>1150</td>
<td>1220</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40–100</td>
<td>1260</td>
<td>1280</td>
<td></td>
</tr>
</tbody>
</table>

When the velocity of the shock wave at any distance from the charge is known a calculation of the rate of increase of duration of the positive part of the blast wave with distance from the charge can be made, since the point behind the wave-front at which the excess pressure is zero travels with very approximately the velocity, $a$, of sound. Consequently, if the duration at any distance $r_0$ is known, the duration at any other distance $r$ can be determined.

If $t_0$ is the duration at a distance $r_0$, the duration $t_b$ at a distance $r$ is given by

$$ t_b = t_0 + \frac{r - r_0}{a} - \int_{r_0}^{r} \frac{1}{b} dr. $$

To make the calculation applicable to all sizes of charge, the duration is expressed in seconds/charge diameter, and the distances in units of charge diameter.
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The curve in figure 14 which is quite a good representation of the experimental observations was calculated in this way, the value of \( t_0/d \) being taken as \( 7.2 \times 10^{-3} \) at a distance of 30 charge diameters.

Calculations of the rate of decay of blast waves have been made by Taylor (see ref. (5)) and by Penney (see ref. (6)). In the Ministry of Home Security Note No. R.C. 39 on the Propagation and Decay of Blast Waves, Professor G. I. Taylor has shown that when the maximum pressure is not very high \([(p - p_0)/p_0 < 0.4]\) and if the decrease in pressure behind the shock wave is approximately linear the rate of decay of maximum pressure in a spherical shock wave can be expressed approximately by the equation

\[
\frac{dz}{dr} + \frac{z}{r} + \frac{\gamma + 1}{4\gamma} \frac{z^2}{L} = 0
\]

(1)

where

\[ z = \frac{p - p_0}{p_0}, \]

\[ r = \text{distance from charge}, \]

\[ L = \text{length of the positive phase of the blast wave}. \]

The formula applies to all sizes of charge if \( r \) and \( L \) are measured in units of charge diameter. If \( L \) can be regarded as constant, equation (1) can be integrated giving

\[
z = z_0 r_0 \frac{1}{r + \frac{\gamma + 1}{4\gamma} \frac{z_0 r_0}{L} \log_{10} \frac{r}{r_0}},
\]

where \( z_0 \) is the value of \( z \) at \( r = r_0 \).

Taking \( \gamma = 1.405 \), this can be written

\[
z = z_0 r_0 \left( 1 + 0.984 \frac{z_0 r_0}{L} \log_{10} \frac{r}{r_0} \right)^{-1}.
\]

(2)

\( L \) is not, in fact, constant but increases with distance from the explosion. Formula (2), however, can be used over any distance which is small enough for \( L \) not to increase appreciably over that distance. Therefore, if values of \( Z_0 \) and \( L \) at a distance \( r_0 \) are assumed, the value of \( z \) at a distance \( r \) can be calculated from equation (2), if \( r - r_0 \) is small. The value of \( L \) at \( r \) can then be found by using the Rankine-Hugoniot formula to calculate the mean velocity \( b_m \) of the shock wave between \( r_0 \) and \( r \), and deducing the increase in \( L \) while the shock wave is travelling from \( r_0 \) to \( r \) from the formula

\[
L - L_0 = (r - r_0) \left( 1 - \frac{a}{b_m} \right).
\]

(3)

Using these values of \( r, z \) and \( L \), equation (2) can then be employed again to calculate the value of \( z \) at another distance and so on.

The calculation has been carried out taking 55 charge diameters, where the maximum pressure is 5.9 lb./sq.in., as the starting point. The results are given in table 4. The calculated values are in fairly good agreement with
those derived from the mean curve of figure 12, but decrease rather less rapidly with distance than do the observed pressures.

<table>
<thead>
<tr>
<th>distance from charge in charge diameters</th>
<th>maximum pressure (lb./sq.in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>calculated</td>
</tr>
<tr>
<td>55</td>
<td>5.9</td>
</tr>
<tr>
<td>60</td>
<td>5.1</td>
</tr>
<tr>
<td>65</td>
<td>4.5</td>
</tr>
<tr>
<td>70</td>
<td>4.0</td>
</tr>
<tr>
<td>75</td>
<td>3.6</td>
</tr>
<tr>
<td>80</td>
<td>3.3</td>
</tr>
<tr>
<td>90</td>
<td>2.8</td>
</tr>
<tr>
<td>100</td>
<td>2.4</td>
</tr>
<tr>
<td>120</td>
<td>1.9</td>
</tr>
<tr>
<td>140</td>
<td>1.6</td>
</tr>
<tr>
<td>160</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The paper has been prepared by permission of the Department of Scientific and Industrial Research and the other Departments interested in the work. It was written following a suggestion by the Civil Defence Research Committee of the Ministry of Home Security that a paper giving a description of the apparatus used in work for them and some results of the work should be prepared. The subject-matter includes data obtained in the course of investigations made for the Ministry of Supply and Ministry of Home Security as well as for the Department of Scientific and Industrial Research itself. The authors wish to record their indebtedness to the Assistant Director, Road Research Laboratory (Dr A. H. Davis) under whose immediate supervision the work was conducted, and to Mr W. L. Cowley, who supervised the work in its early stages.*

REFERENCES

(2) A. R. Bryant, unpublished paper.
(5) Loc. cit.

* The paper is submitted by permission of the Director-General of Scientific Research and Development of the Ministry of Supply and the Chief Adviser of the Ministry of Home Security, Research and Experiments Department, and with the consent of the Director of the Road Research Laboratory, Department of Scientific and Industrial Research.
Figure 3. Piezo-electric blast pressure gauges.
**Figure 4a.** Triple oscillograph unit.

**Figure 4b.** Rotary switch.
Figure 9. Blast pressure records from a bare charge of 70 lb. 60/40 R.D.X./T.N.T.
Figure 10. Blast pressure records from a British 4000-lb. H.C. bomb filled 60/40 amatol—100 and 125 ft.

Figure 10 (cont.). Blast pressure records from a British 4000-lb. H.C. bomb filled 60/40 amatol—150 to 250 ft.