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BALLISTIC RESEARCH LABORATORIES

REPORT NO. 721

The Effect of Atmospheric Pressure and Temperature on Air Shock

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and
JOSEPH SPERRAZZA

ABERDEEN PROVING GROUND, MARYLAND

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May 1950

THE EFFECT OF ATMOSPHERIC PRESSURE AND TEMPERATURE ON AIR SHOCK

Jane Dewey

and

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Projects Nos. TB3-0112J and -5238 (Air) of the Research and Development Division, Ordnance Department

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JDewey/JSperrazza/med
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THE EFFECT OF ATMOSPHERIC PRESSURE AND TEMPERATURE ON AIR SHOCK

ABSTRACT

The side-on excess peak pressures and positive impulses of air shock waves from the detonations of spherically shaped explosive charges of 50/50 Pentolite have been measured under ambient atmospheric pressures and temperatures simulating altitudes up to 50,000 feet. The reduction in peak pressure and positive impulse attendant on decrease in ambient pressure for scaled distances $Zp_o^{1/3}$ ranging from approximately 2 to 30 can be expressed in the scaled variables of Sachs by the relations

Peak Pressure: $$\left(\frac{P}{p_o}\right) = \frac{37.95}{Z\,p_o^{1/3}} + \frac{154.9}{(Z\,p_o^{1/3})^2} + \frac{2034}{(Z\,p_o^{1/3})^3} + \frac{403.9}{(Z\,p_o^{1/3})^4}$$

Positive Impulse: $$\log_{10} \frac{I}{p_o^{2/3} W^{1/3}} = 1.374 - 0.695 \log_{10} (Z\,p_o^{1/3})$$

where P = peak pressure in psi

p_o = ambient atmospheric pressure in atmospheres (1 atmosphere = 14.7 psi)

$Z = R/W^{1/3}$

R = distance from explosive in feet

W = weight of explosive in pounds

I = positive impulse in psi milliseconds

Peak pressures are nearly independent of temperature. The impulse apparently increases more rapidly with falling temperature than as $T^{-1/2}$, although this conclusion is uncertain.

INTRODUCTION

The effect of altitude on blast parameters has been considered theoretically[1] and experimentally[2] by a number of authors. Except for the work of Sachs[1], the results apply only to relatively low altitudes. With the increase in high altitude flying, it appeared desirable to obtain experimental data over a wider range of pressures and temperatures. The installation at Aberdeen Proving Ground of a "Stratosphere Chamber" of adequate size for small scale blast experiments made this work possible.

EQUIPMENT USED

The stratosphere chamber consists of a metal cylinder, about 12 feet in diameter, divided into a firing and a concussion chamber. The latter, which is about 26 feet long, not including a sandtrap at one end, was used for these experiments. Pressures in the chamber can be varied from about 1/10 atmosphere to atmospheric and temperatures from about -60°C to + 25°C. Ports for the necessary lead wires, pressure measuring tubes, etc., are provided, as well as a number of glass windows for viewing the interior. Provision is made for regulating the pressure and holding it at any desired value. After closing the door, pressure equilibrium can be obtained in less than five minutes, so that the whole arrangement, in spite of its large size, is more convenient than the usual laboratory pressurized tank.

For blast measurements the chamber has many disadvantages. The cylindrical shape results in a focusing of the shock reflected from the walls along the axis of the chamber, so that the reflected shock is much stronger than the initially incident one and impairs the functioning of the equipment. All gages and blast switches must be placed near the axis to take full advantage of the size of the chamber in obtaining free air measurements. As the flooring was removed, the chamber may be regarded as an empty cylinder traversed in places by beams to support the flooring and by the supports of the gages. To reduce reflection, the inside of the cylinder and all beams were covered by hair felt. Two layers of the thickest grade (about 1/4 inch) of rug cushion were used during most of the work. At the start 3/4" felt was available. The felt was rapidly blown to fluff, especially by the larger charges, but the reduction in reflection was sufficient to make the very considerable labor of replacing it and cleaning fluff from the connecting pipes seem worth while. With the chamber lined, charges up to at least one pound of explosive can be fired. However, damage to felt was so rapid when one-half pound charges were used that it was decided not to extend the work to larger charges.

The support of the gages on the metal cylinder made it necessary to isolate them from vibrations transmitted through the metal, which would reach them in advance of the air shock. Ordinary commercial rubber shock mounts between the gages and the supports were found to accomplish this adequately. A vigorous kick on the supports themselves could be perceived on the recording equipment, but resounding blows on the sides of the

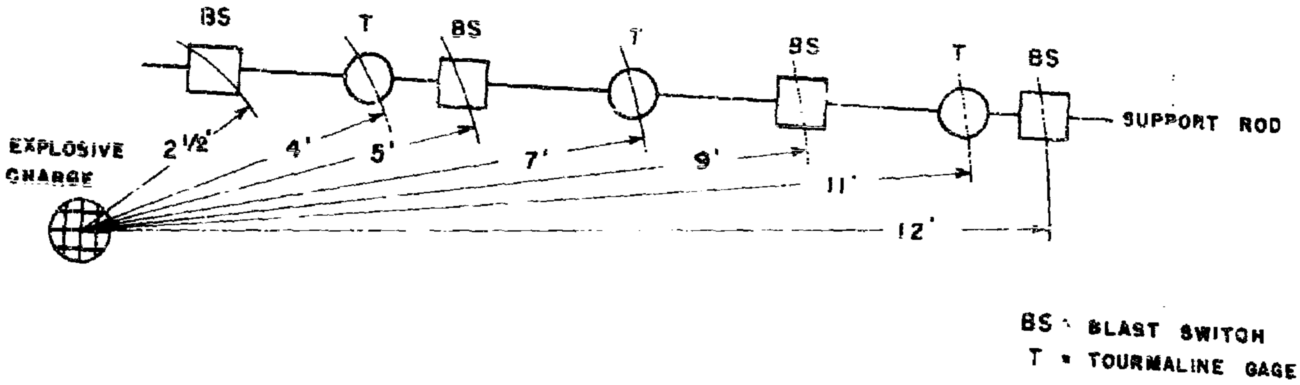
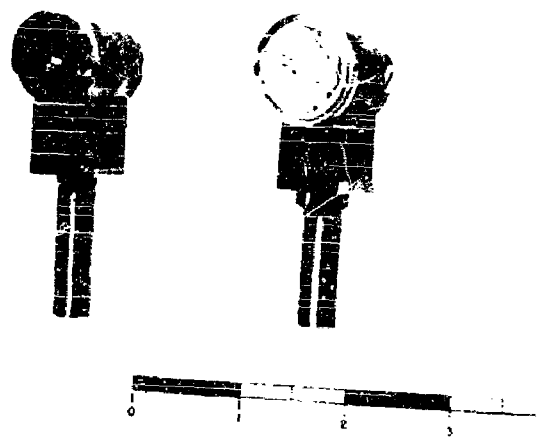


Figure 1. Schematic Diagram of Gage Set - Up
(Dimensions are approximate)

Tourmaline Gage with Vibration Mount



Without Foil With Foil

Blast Switch (Scale in inches)

Figure 2

chamber gave no visible effect. As the gages and necessary counterweights had a total mass of three pounds the displacement of the gage by the shock is small. The cables connecting the gages to the recording equipment apparently transmitted vibrations to the gages only imperceptibly. The blast switches were rigidly mounted as it was necessary to fix their positions accurately. Their setting was so adjusted that vibrations transmitted through the mounts did not operate them. The arrangement of gages and blast switches is shown in Figure 1. A photograph of the mount for the tourmaline gage is shown in Figure 2.

The instrumentation used was designed for large scale work, [3,4] primarily with bombs and could be given only hurried alterations for this work. The BRL tourmaline gage, [5] with its $2\frac{1}{2}$" diameter and unfortunate aerodynamic properties (aspect ratio about 4 and square corners presented to the blast) was used, except close to the charge, because it was all that was available. One gage designed for the measurement of ground shock, [6] diameter approximately 1-3/8", thickness at the middle about 3/8", was used at the position closest to the charge. The BRL gage is so large that approximately 0.2 milliseconds is required for a weak shock to traverse it; even for the ground shock gage the traverse time of 0.1 milliseconds is undesirably long for small scale air work.

In order to check on systematic gage errors and in the interests of reliable results in general, dual instrumentation was used throughout the work, that is, peak pressures were measured by the velocity as well as the piezogage method. Four small blast switches were used. Their design, based on that tested on a larger scale, [3] is shown in Figure 2. 1 mil aluminum foil was found by experiment to give reliable results. A check on the response times of the switches was made by comparing them with tourmaline gages used face-on to the shock. Their reproducibility was found to be adequate to take advantage of the precision of timing given by the recording equipment.

The "White" four channel trailer, operated by the Ballistic Measurement Laboratory, was used for the recording. This trailer contains four nine-inch DuMont K1002 tubes with P11 screens, with the necessary DC amplifiers, calibration circuits, etc. The amplifiers have a flat response from DC to 80 kilocycles and gains of 1,000 to 100,000. The built-in camera uses paper at a speed up to 480 inches per second. Two major improvements were made in the recording for this work. A 10 KC sine was used as the base of the timing record. Closing a blast switch put a DC shift on this record. As the sine wave base line is longer, times can be read with greater accuracy than on a straight line record. Also a General Radio camera taking records on 35mm film at about 300 inches per second was installed. Film records are clearer and can be read at a higher magnification than paper. Hence many records missing on the paper, due to poor focus or a weak record toward the end of the life of a tube, were readable on the film. As the results of film records were found to be more reproducible, the paper records were utilized largely for rapid examination to determine whether results of a round were usable, or when the film record was missing.

Pressure in the chamber was measured on an open-end mercury manometer combined with an aneroid barometer, which was calibrated against a Fortin barometer daily. As accurate measurement and uniformity of pressure are of more importance at lower pressures than at higher (since a given error produces a larger variation in the peak pressure ratio), measurements were also made on two closed-end manometers when firings took place at about 1/10 atmosphere pressure. The three manometers measured pressures at three points at which it was believed, from the pumping arrangements in the chamber, that maximum variations in pressure would occur. No variations with position were observable. As measurements were made to the nearest millimeter, it was concluded that variations in pressure with position larger than this value did not occur and only the closed-end manometer readings of low pressures were used. Temperature measurements were made on copper-constantan thermocouples and ordinary thermometers, mercury and bimetallic, at various locations in the chamber. No significant temperature variations were found and only the thermocouple measurements are reported.

EXPERIMENTAL PROCEDURE

Cast hemispheres of Pentolite with wells to fit the M-36 detonator were weighed in pairs, and assembled with cellophane "Scotch" tape. The nominal weights of the spheres fired were 1/16, 1/8, 1/4 and 1/2 pound. In the preliminary firings blasting gelatine in glass spheres was also used because of the possibility that the effect of altitude on oxygen rich nitroglycerine might differ from that on the oxygen deficient Pentolite. So much trouble was experienced in obtaining reproducible high order detonation of the blasting gelatine that this portion of the project was abandoned. As far as could be judged from a few firings, blasting gelatine gives about the same result as Pentolite, except for a much higher variability.[2]

The procedure for calibrating tourmaline gages at room temperature has been described elsewhere[3] and is straightforward. Some of the gages were calibrated at the ambient pressures used, by placing the calibration tank in the stratosphere chamber. Calibrations were also conducted by evacuating the calibration tank and admitting atmospheric pressure. As would be expected, since the gages have a linear response, the gage constant was independent of the exact conditions of calibration at room temperature. It was, therefore, not thought necessary to calibrate every gage at reduced pressure. All gages were, however, calibrated before and, when they did not fail during the firings, again after the whole series of firings, either at 20 and 35 psi or at 5, 15 and 30 psi excess pressures. All gages used were calibrated at least three times, with five measurements at each pressure each time. Because of the relative inaccuracy of paper records, calibrations obtained from film records, taken on the 24 channel trailer, were averaged to obtain the gage constant. The standard deviation of the mean of a set of calibrations did not exceed 2%.

Both the BRL and the earth shock gage were calibrated also at reduced temperatures. This work was done by enclosing the calibration tank in a controlled temperature cold box. With both gages a high value of the charge per unit pressure was obtained at low temperatures; at -67°C, for instance, 30% higher than at +29°C. Records were taken on two earth shock gages under the erroneous impression that their gage constants were independent of temperature. As subsequent calibration showed this not to be the case, the calibration constant was plotted against temperature and an interpolated value used. See Figure 3. As the change in constant between -4°C and -67°C, the low temperatures at which calibrations were made, is small, a linear interpolation was used.

As the piezoelectric constant of tourmaline is reliably reported to vary less than 2% in a much wider temperature range than used here,[7] there is no obvious explanation of the change in gage constant. Probably the crystallization of the material in which the tourmaline is imbedded causes a rise, but it is difficult to account for its large magnitude, approximately the same in the two gages, on this basis. While the agreement of the tourmaline gage peak pressures with those calculated from shock velocities indicates that the low temperature gage constants used were approximately correct, it did not appear worth while to make more than a limited number of low temperature impulse measurements with gages of anomalous response to temperature changes.

The distance between blast switches was measured along the straight line connecting them, by the Physical Measurement Section, Development and Proof Services, using steel scales graduated in hundredths of an inch. The difference in distance between charge and gage was computed for each gage, using the differences in distance between the support of the charges and two of the switches to determine the angle. Repeated determinations of the distances usually checked to two or three tenths of an inch. As the times of arrival of shocks were determined to about 20 microseconds, the uncertainty in the velocity due to the distance measurements is about the same as that due to the velocity measurements.

Room temperature firings of three weights of charges were conducted in regular rotation, atmospheric pressure, 2/3 atmosphere, 1/3 atmosphere, 1/10 atmosphere, pressures corresponding approximately to those at altitudes of 0, 10,000, 30,000, and 50,000 feet. Firings at 2/3 and 1/3 atmosphere were carried out after equilibrium had been reached in the chamber with the pumps shut off. At 1/10 atmosphere the pumps were kept running as more reproducible pressures were obtained in this way. An attempt was made to obtain five good records by the piezo and the velocity method at each of the distances under each condition. This necessitated a considerable number of "fill-in" firings, which were conducted in any order convenient to the firing crew. Since many partial records were obtained, all of which were read, it also resulted in a variable number of measurements. A large number of firings of 1/16 pound charges was made to reduce the large variability observed in the initial firings. In other cases, however, determinations in excess of five result from attempts to complete a set of five readings for each position. Usually all firings of a given weight of charge were made consecutively, to avoid resetting the gains of the recording equipment. The low temperature firings were made after completion of the others. Firings

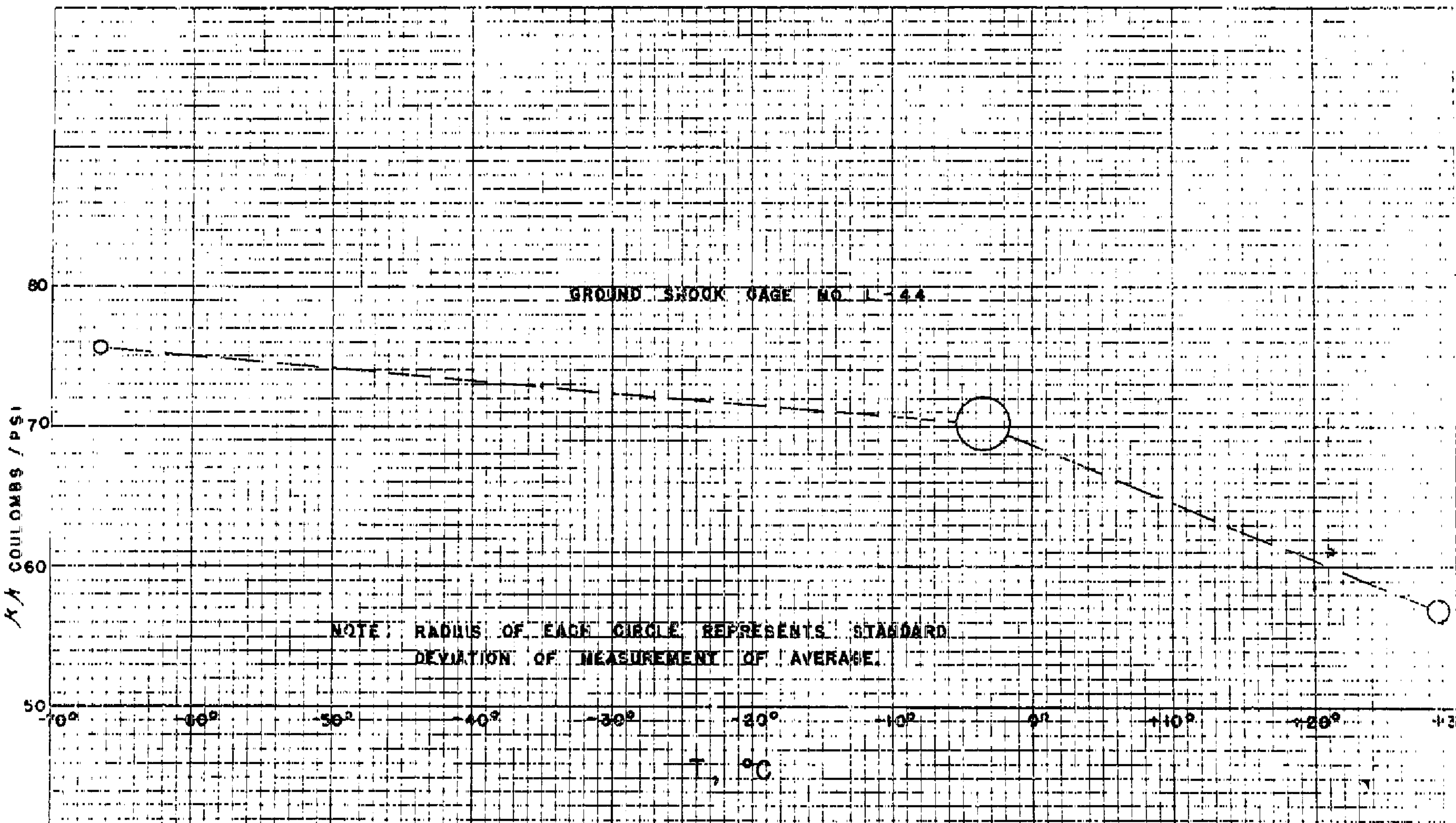


FIGURE 5.

GAGE CONSTANT, MICROMICROCOULOMBS / PSI VS. TEMPERATURE, °C of 1/8 pound charges and most of the low temperature firings were carried out at 1 atmosphere and 1/10 atmosphere only.

Film records were read on a Bausch and Lomb Contour Projector, usually at a magnification of 10. After considerable experimentation, it appeared that projection of the paper records did not improve the accuracy with which they could be read. They were therefore read through a glass grid to reduce labor.

REDUCTION OF DATA

The method of reduction of peak pressure data from tourmaline records is described in BRL Report No. 681[3].

Velocity records were reduced to pressure by the use of the Hugoniot relations for a perfect gas. The velocity of sound in the undisturbed air in front of the shock was taken to be $a = 1088\sqrt{1 + {}^{o}C/273}$,

a = velocity of sound in ft/sec

^{o}C = temperature of air in degrees Centigrade

To a first approximation the scaled distance, $Z = R/W^{1/3}$,

R = distance from explosive to shock front, in feet

W = weight of explosive, in lbs.

at which the pressure was determined was taken to be the midpoint, Z_m, of the particular values of Z over which the velocity was measured. A first order correction (which was quite small and hence sufficient) to this distance was obtained as follows:

Both the peak pressures calculated from the shock velocities and those recorded by the tourmaline gages were plotted against Z on log-log paper and curves fitted by eye to these data. These curves were transformed to velocity-scaled distance curves by means of the Rankine-Hugoniot relations. The final correction was obtained by graphical integration.

The positive impulse was estimated by drawing, from the peak of the pressure-time curve to the base line, the straight line which appeared to enclose the same area as the actual curve. The duration reported is the base of the triangle formed by the start of the pressure rise to the peak, this line, and the base line. Impulse was calculated from this duration. The labor of attempting to obtain more precise measurements of impulse appeared to be unwarranted in view of the uncertainties introduced by irregularities in the records and by the response times of the gages.

RESULTS

The peak pressures from tourmaline and velocity measurements are plotted as a function of scaled distance in Figure 4 for each pressure at which measurements were made. The data are reported in detail in Appendix I and summarized in Table I. Points on the plot represent averages of firings of varying numbers of charges of a given nominal weight at a given nominal ambient pressure. Pressure measurements averaged together were not always made without moving the gages. Measurements at distances differing by less than 5% of the distance were averaged together. Standard deviations of the Z's are not reported as they are in all cases negligible compared to other uncertainties. Points at about the same scaled distance represent differing charge weights or methods of measurement. The radius of the circles gives the standard deviation of the average of the pressure measurements. The variations in weight in charges of a given nominal weight are obviously not significant. The effect of the variations in ambient pressure from the average value on the peak pressure is below the standard deviation of the measurements and was, therefore, also disregarded in averaging.

All readable records of reasonable form are reported in the Appendix I. Seven measurements of the 716 made at room temperature were discarded as outlying on the basis of a t-test, as were 2 of the 250 made at low temperatures. Appendix II shows examples of acceptable records and of an oscillatory one discarded as "No good". At one-tenth atmosphere all piezogage measurements at $Z = 5.3$ ft/lb$^{1/3}$ were discarded, as they show oscillations superposed on the shock.

The data were scaled by the dimensional analysis of Sachs[1]. Figure 5 is a plot of the data of Figure 4 scaled in this way, with the units so chosen that the curve represents atmospheric pressure data in the usual units. The dotted line given by the Kirkwood and Brinkley[8] calculations for sea-level shows no large deviations from the measurements but is clearly not the best line through the points. The solid line is the least square line (weighted) fit to a quartic in $1/Z$. Its equation in terms of the numerical values of P in psi, p_o in atmospheres and Z in ft/lb^3, is

$$1)\quad P/p_o = \frac{37.95}{Z\,p_o^{1/3}} + \frac{154.9}{(Z\,p_o^{1/3})^2} + \frac{2034}{(Z\,p_o^{1/3})^3} + \frac{403.9}{(Z\,p_o^{1/3})^4}\,,\quad 30 > Z\,p_o^{1/3} > 2$$

This equation has purely empirical validity, and appears to be adequate for representation of these data except at the largest values of $Z\,p_o^{1/3}$.

It is not possible to obtain a good fit with a three term equation of the form used by Stoner and Bleakney[9]

$$2)\quad P/p_o = a/Z + b/Z^2 + c/Z^3$$

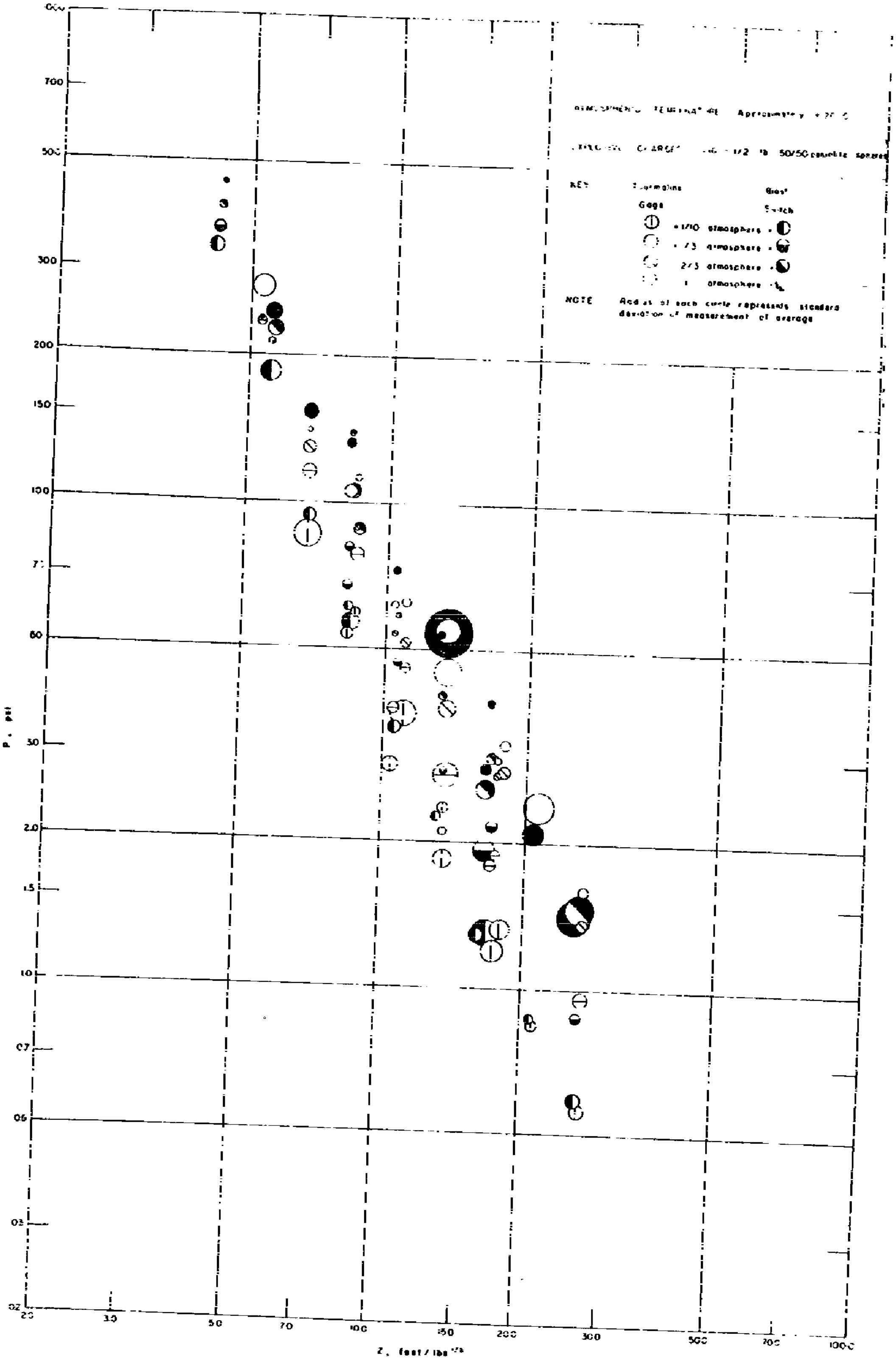


FIGURE 4

PEAK PRESSURE, PSI vs Z = DISTANCE / (CHARGE WEIGHT)$^{1/3}$

at

DIFFERENT ATMOSPHERIC PRESSURES

Table I

Peak Pressures and Impulses at Normal Temperatures

P_o psi	T_o °C	Z ft/lb$^{1/3}$	W lb	Tourm. or Blast Switch	Peak Pressure Avg. psi	σ %	$\bar{\sigma}$ psi	Positive Impulse Avg. psi ms	σ %	$\bar{\sigma}$ psi ms
14.9	19.8	4.36	0.542	B	45.4	2.1	0.47			
14.9	19.8	5.29	0.542	T	27.7	14	1.50	6.12	6.9	0.17
14.7	19.9	5.95	0.262	B	24.6	10	0.94			
14.8	21.1	6.74	0.141	B	15.3	8.9	0.51			
14.7	19.9	6.76	0.262	T	14.2	4.2	0.21	4.00	3.0	0.04
14.9	19.8	8.28	0.542	B	13.3	3.6	0.28			
14.8	21.1	8.29	0.141	T	10.5	7.0	0.28	2.84	4.9	0.06
14.7	18.4	8.31	0.070	B	10.4	23	0.09			
14.9	19.8	8.61	0.542	T	11.2	5.2	0.22	5.44	4.6	0.09
14.7	18.4	10.4	0.070	T	6.11	3.4	0.06	2.14	6.5	0.05
14.7	19.9	10.4	0.262	B	7.23	4.7	0.13			
14.7	19.9	11.0	0.262	T	6.22	4.3	0.10	3.21	5.6	0.06
14.8	21.1	13.1	0.141	B	5.35	4.3	0.09			
14.9	19.8	13.5	0.542	B	5.43	19	0.58			
14.8	21.1	13.5	0.141	T	5.47	15	0.31	2.64	16	0.18
14.9	19.8	13.6	0.542	T	4.48	15	0.29	2.63	4.6	0.06
14.8	18.7	16.6	0.072	B	2.84	6.0	0.06			
14.7	19.9	16.8	0.262	B	3.89	4.6	0.07			
14.7	18.4	17.0	0.070	T	3.19	8.8	0.10	1.37	14	0.05
14.7	19.9	17.4	0.262	T	2.95	3.4	0.04	1.85	13	0.11
14.8	21.1	21.0	0.141	B	2.09	14	0.11			
14.8	21.1	21.3	0.141	T	2.36	19	0.17	1.35	15	0.09
14.8	18.7	25.7	0.072	B	1.40	23	0.12			
14.7	18.4	26.7	0.070	T	1.59	6.3	0.04	0.78	13	0.04
9.78	20.2	4.30	0.544	B	40.3	4.6	0.76			
9.78	20.2	5.29	0.544	T	23.9	1.5	0.12	4.40	9.3	0.16
9.90	19.9	5.66	0.262	B	22.6	9.8	0.90			
9.90	19.9	6.76	0.262	T	13.0	5.4	0.31	3.26	4.3	0.06
9.78	20.2	8.41	0.544	B	10.5	8.9	0.38			
9.78	20.2	8.61	0.544	T	8.83	3.6	0.12	3.96	6.1	0.09
9.89	20.7	8.72	0.072	B	8.81	12	0.26			
9.89	20.7	10.4	0.072	T	5.33	5.1	0.07	1.81	6.6	0.03
9.90	19.9	10.7	0.262	B	5.83	3.3	0.08			
9.90	19.9	11.0	0.262	T	5.14	5.1	0.12	2.28	6.1	0.06
9.78	20.2	13.4	0.544	B	4.00	5.2	0.09			
9.78	20.2	13.6	0.544	T	3.67	10	0.16	2.52	13	0.13
9.89	20.7	16.5	0.072	B	2.56	22	0.14			
9.89	20.7	17.0	0.072	T	2.79	12	0.09	1.19	7.6	0.03
9.90	19.9	17.0	0.262	B	2.99	7.4	0.09			
9.90	19.9	17.4	0.262	T	2.74	2.2	0.04	1.61	6.2	0.07
9.89	20.7	26.4	0.072	B	1.46	23	0.09			
9.89	20.7	26.7	0.072	T	1.36	8.1	0.03	0.77	6.5	0.02

Table I

Peak Pressures and Impulses at Normal Temperatures

P_o psi	T_o °C	Z ft/lb$^{1/3}$	W lb	Tourm. or Blast Switch	Peak Pressure Avg. psi	σ %	$\bar{\sigma}$ psi	Positive Impulse Avg. psi ms	σ %	$\bar{\sigma}$ psi ms
4.85	20.5	4.25	0.543	B	36.5	6.2	0.84			
4.85	20.5	5.29	0.543	T	23.7	6.1	0.59	4.01	8.2	0.13
4.86	19.9	5.54	0.262	B	21.4	3.3	0.25			
4.86	19.9	6.76	0.262	T	11.5	8.9	0.39	2.32	12	0.12
4.85	20.5	8.29	0.543	B	8.09	5.4	0.17			
4.92	21.1	8.37	0.070	B	6.73	7.7	0.15			
4.85	20.5	8.61	0.543	T	7.82	8.7	0.28	2.82	6.0	0.08
4.92	21.1	10.4	0.070	T	3.77	9.0	0.10	1.03	9.7	0.03
4.86	19.9	10.6	0.262	B	4.67	5.4	0.08			
4.86	19.9	11.0	0.264	T	4.56	7.9	0.12	2.05	14	0.12
4.85	20.5	13.5	0.543	B	2.80	4.3	0.04			
4.85	20.5	13.6	0.543	T	2.75	16	0.16	1.86	17	0.12
4.92	21.1	16.5	0.070	B	1.93	22	0.11			
4.92	21.1	17.0	0.070	T	1.79	10	0.05	0.82	11	0.03
4.86	19.9	17.1	0.262	B	2.16	8.3	0.07			
4.86	19.9	17.4	0.262	T	1.89	4.2	0.03	1.27	5.5	0.03
4.92	21.1	26.3	0.070	B	0.87	5.8	0.02			
4.92	21.1	26.7	0.070	T	0.95	7.4	0.03	0.63	6.3	0.02
1.66	19.2	4.20	0.542	B	33.5	13	1.57			
1.48	17.7	5.55	0.262	B	18.5	15	0.95			
1.48	17.7	6.76	0.262	T	8.54	18	0.55	1.73	21	0.13
1.66	20.8	6.79	0.141	B	9.41	11	0.33			
1.66	20.8	8.29	0.141	T	5.34	10	0.15	0.94	13	0.04
1.66	19.2	8.31	0.542	B	6.11	7.5	0.18			
1.68	21.4	8.40	0.071	B	5.67	18	0.24			
1.66	19.2	8.61	0.542	T	5.94	4.7	0.13	1.63	10	0.08
1.68	21.4	10.4	0.071	T	2.88	12	0.09	0.78	15	0.03
1.48	17.7	10.6	0.262	B	3.45	7.8	0.10			
1.48	17.7	11.0	0.262	T	3.69	24	0.27	1.18	21	0.08
1.66	20.8	13.1	0.141	B	2.26	6.6	0.05			
1.66	20.8	13.5	0.141	T	2.36	8.9	0.06	0.66	9.1	0.02
1.66	19.2	13.5	0.542	B	2.11	4.7	0.04			
1.66	19.2	13.6	0.542	T	1.84	8.2	0.08	0.96	4.2	0.02
1.68	21.4	16.3	0.071	B	1.28	12	0.04			
1.48	17.7	16.8	0.262	B	1.30	18	0.08			
1.68	21.4	17.0	0.071	T	1.32	37	0.07	0.54	9.3	0.01
1.48	17.7	17.4	0.262	T	1.19	18	0.07	0.79	22	0.06
1.66	20.8	21.0	0.141	B	0.87	5.6	0.02			
1.66	20.8	21.3	0.141	T	0.84	8.3	0.02	0.40	10	0.01
1.68	21.4	26.3	0.071	B	0.59	12	0.02			
1.68	21.4	26.7	0.071	T	0.56	11	0.02	0.38	13	0.02

over the range of pressures measured in this work. The best values of the constants, computed by a least square fit, are

$$a = 55.34 \text{ psi lb}^{-1/3}\text{ ft}, \quad b = -150.0 \text{ psi lb}^{-2/3}\text{ ft}^2, \quad c = 3196 \text{ psi lb}^{-1}\text{ ft}^3$$

as compared to

$$a = 31.96 \text{ psi lb}^{-1/3}\text{ ft}, \quad b = 275.5 \text{ psi lb}^{-2/3}\text{ ft}^2, \quad c = 1837 \text{ psi lb}^{-1}\text{ ft}^3$$

obtained by Stoner and Bleakney.

The difference between the constants results of course from the fact that the coefficients of neither polynomial, in $1/Z$, are precisely and uniquely determined from the data. The coefficients are correlated within the least squares solutions. Provided that simultaneous variations are permitted in all three coefficients, each set of data is represented almost equally well by any of the triplets in an infinite set of triplets of coefficients. Stoner and Bleakney also obtained widely differing constants in this form of equation for the different charges they used, although the peak pressures differed only slightly.

Figures 6 and 7 show impulse, scaled in the usual way and scaled taking ambient pressure into account, following Sachs's analysis. The original data are given in Appendix I and summarized in Table I. The lines of Figure 6 are least squars fits of straight lines to the data at each pressure. The line of Figure 7 is fitted to the scaled data in the same way.

Figure 8 gives the scaled peak pressure measurements at low temperatures. The lines are the Kirkwood-Brinkley and least square lines for room temperature of Figure 5. Figure 9 gives the reduced temperature impulse data, scaled for both ambient pressure and temperature. The solid line is fitted to these data. The dotted line is fitted to the room temperature data of Figure 7. The original data are included in Appendix I and summarized in Table II.

The room temperature impulse measurements are represented by

$$3) \quad \log_{10}\left(\frac{I}{p_o^{2/3}W^{1/3}}\right) = 1.374 - 0.695 \log_{10}(Z\, p_o^{1/3})$$

The equation of the line representing the low temperature data on Figure 9 is

$$4) \quad \log_{10}\left(\frac{I\sqrt{\frac{T_o}{T_n}}}{p_o^{2/3}W^{1/3}}\right) = 1.339 - 0.451 \log_{10}(Z\, p_o^{1/3})$$

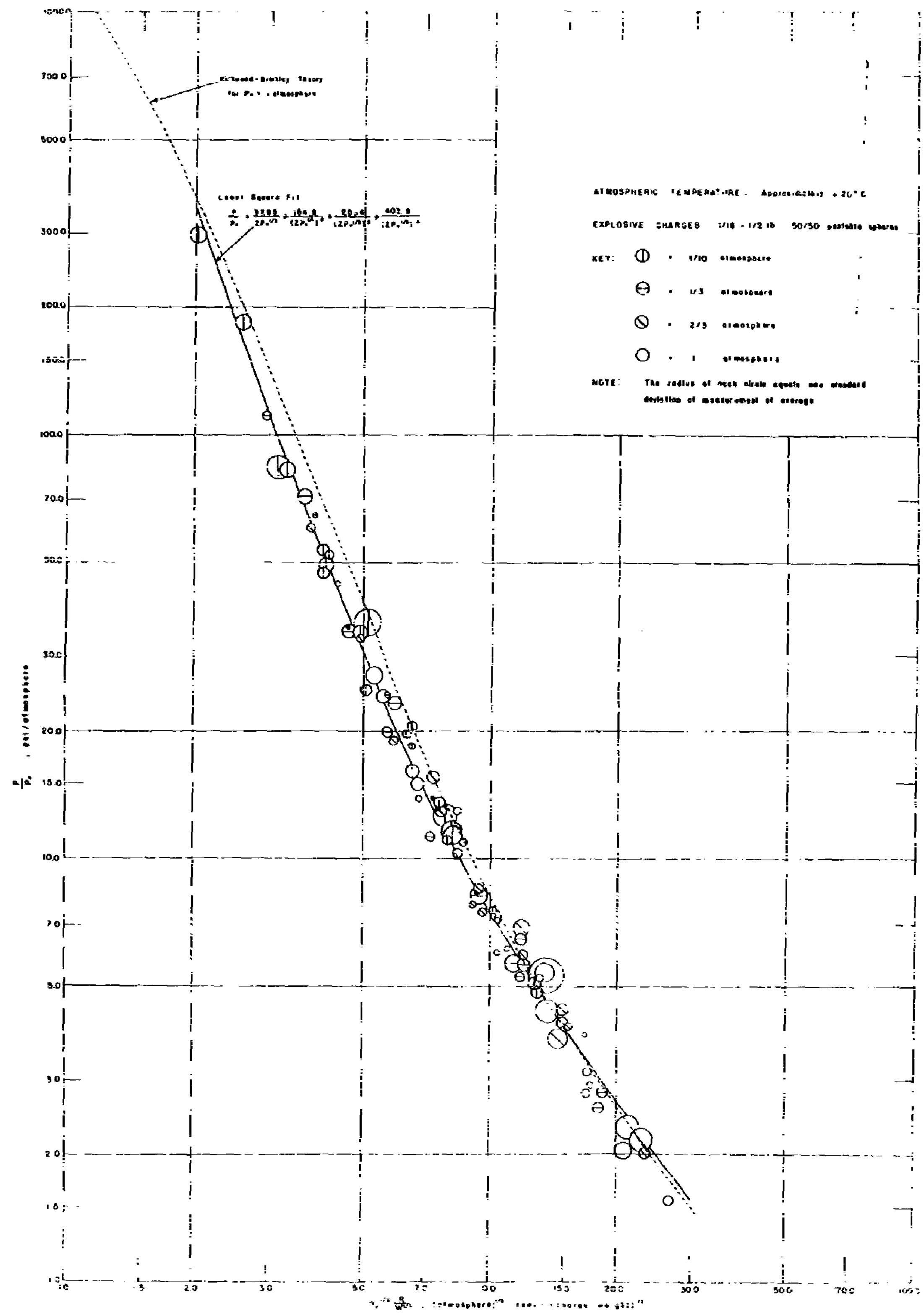


FIGURE 5

PEAK PRESSURE PSI/ATMOSPHERE VS SCALED DISTANCE, (ATMOSPHERES)$^{1/3}$ FEET/(CHARGE WT.)$^{1/3}$
AT
DIFFERENT ATMOSPHERIC PRESSURES

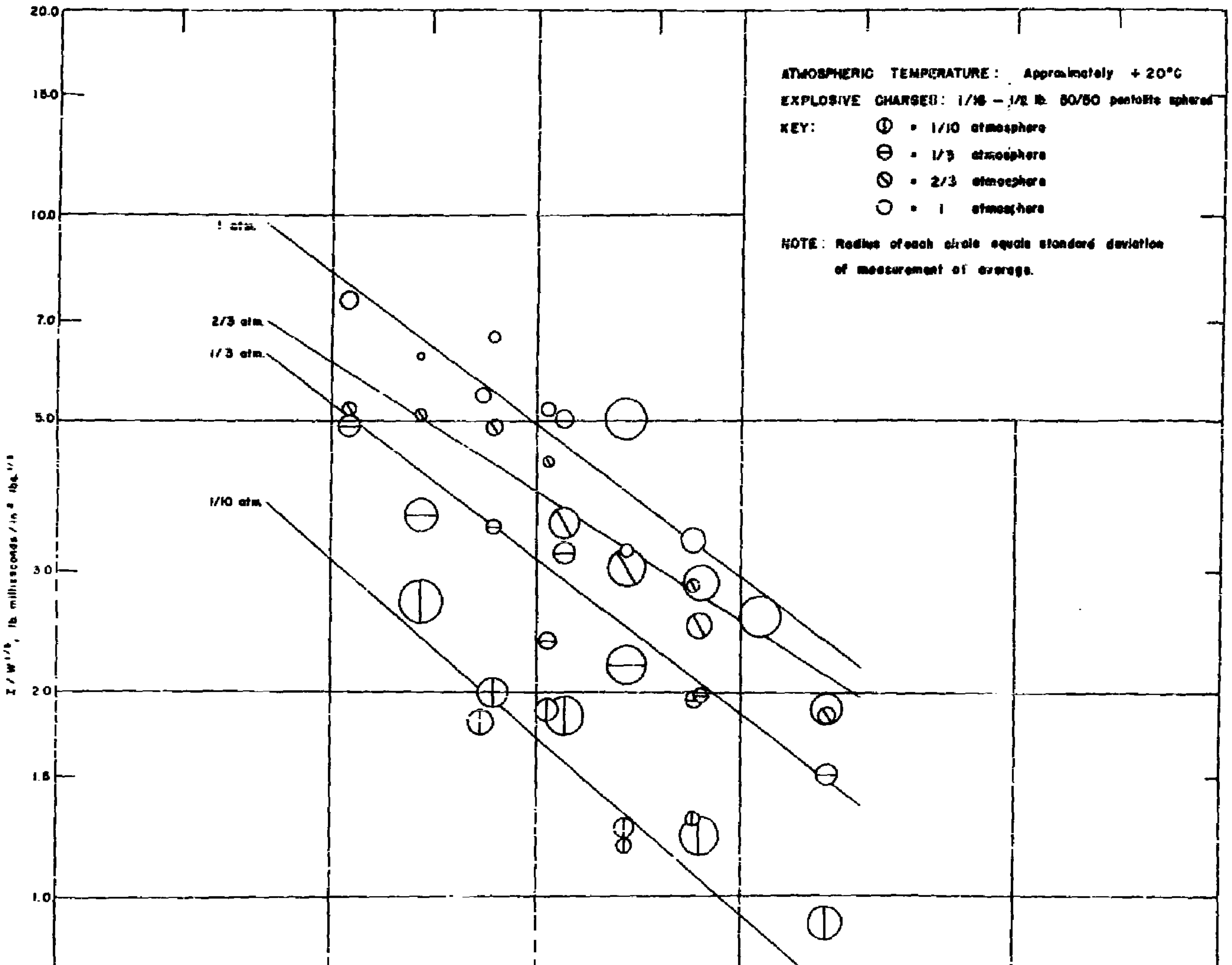


FIGURE 6

IMPULSE / (CHARGE WEIGHT)$^{1/3}$ vs Z = DISTANCE / (CHARGE WEIGHT)$^{1/3}$

at

DIFFERENT ATMOSPHERIC PRESSURES

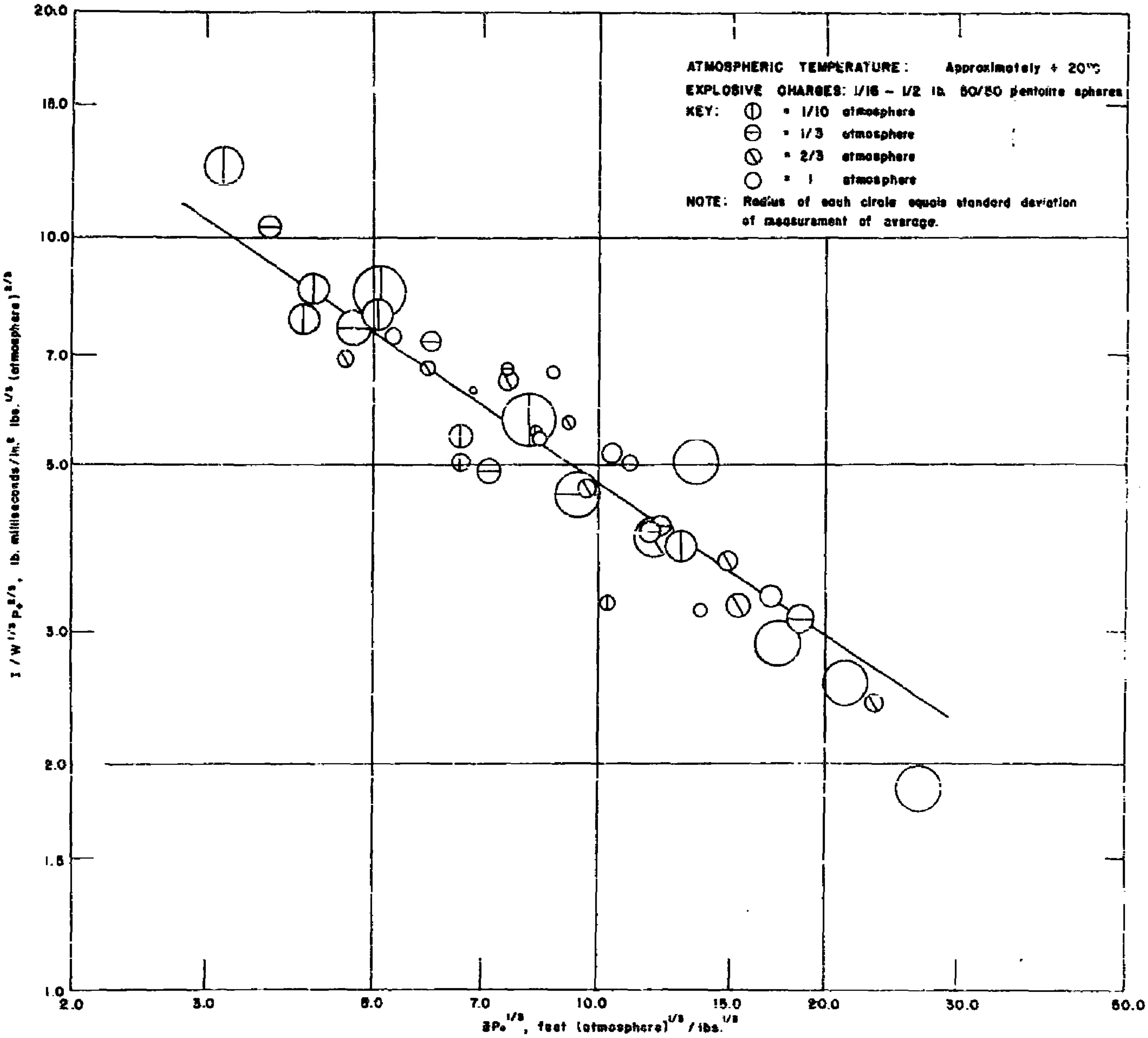


FIGURE 7
SCALED IMPULSE vs. SCALED DISTANCE
at
DIFFERENT ATMOSPHERIC PRESSURES

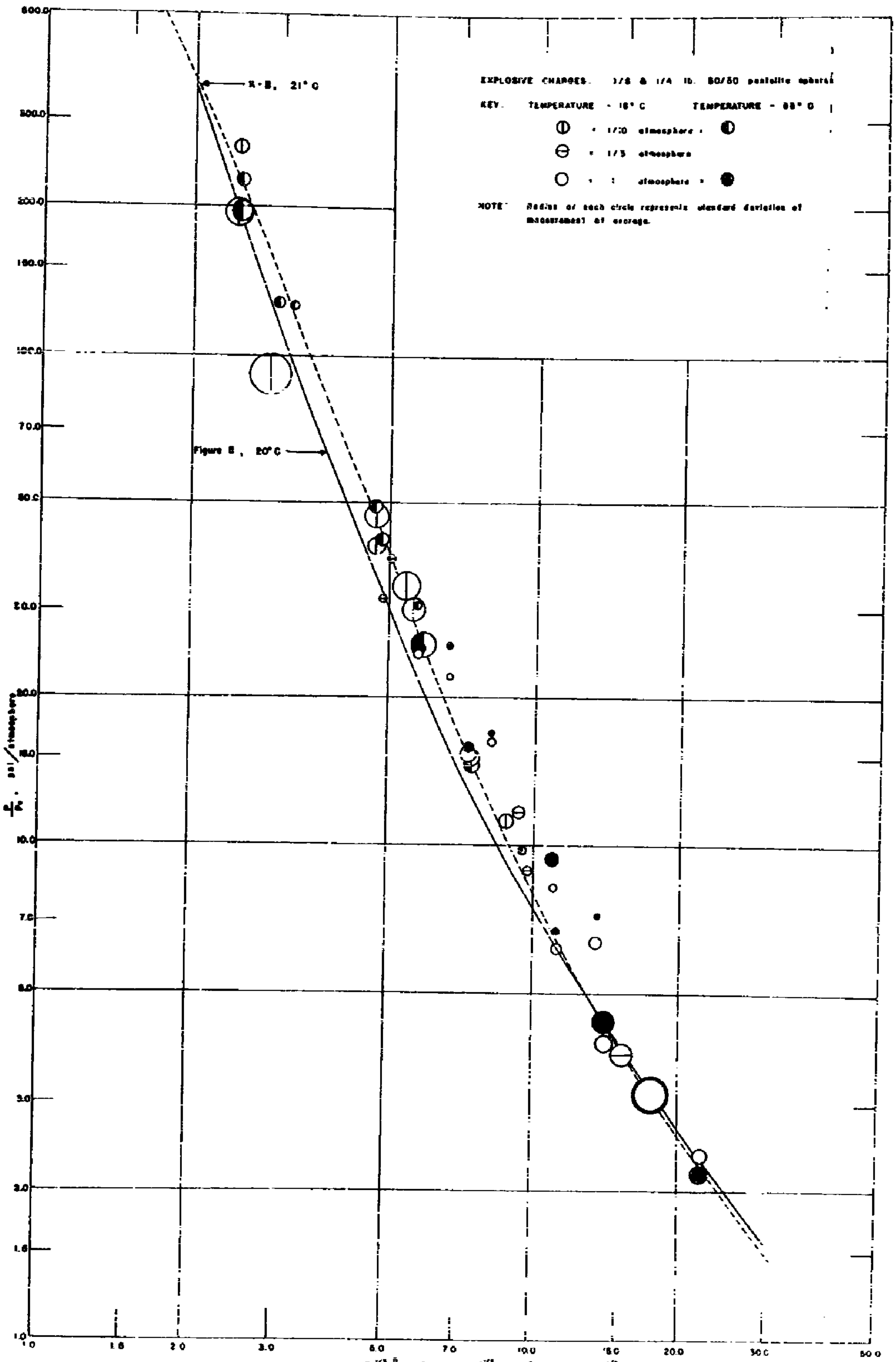


FIGURE 8

PEAK PRESSURE, PSI/ATMOSPHERE VS SCALED DISTANCE
AT
DIFFERENT ATMOSPHERIC PRESSURES & TEMPERATURES

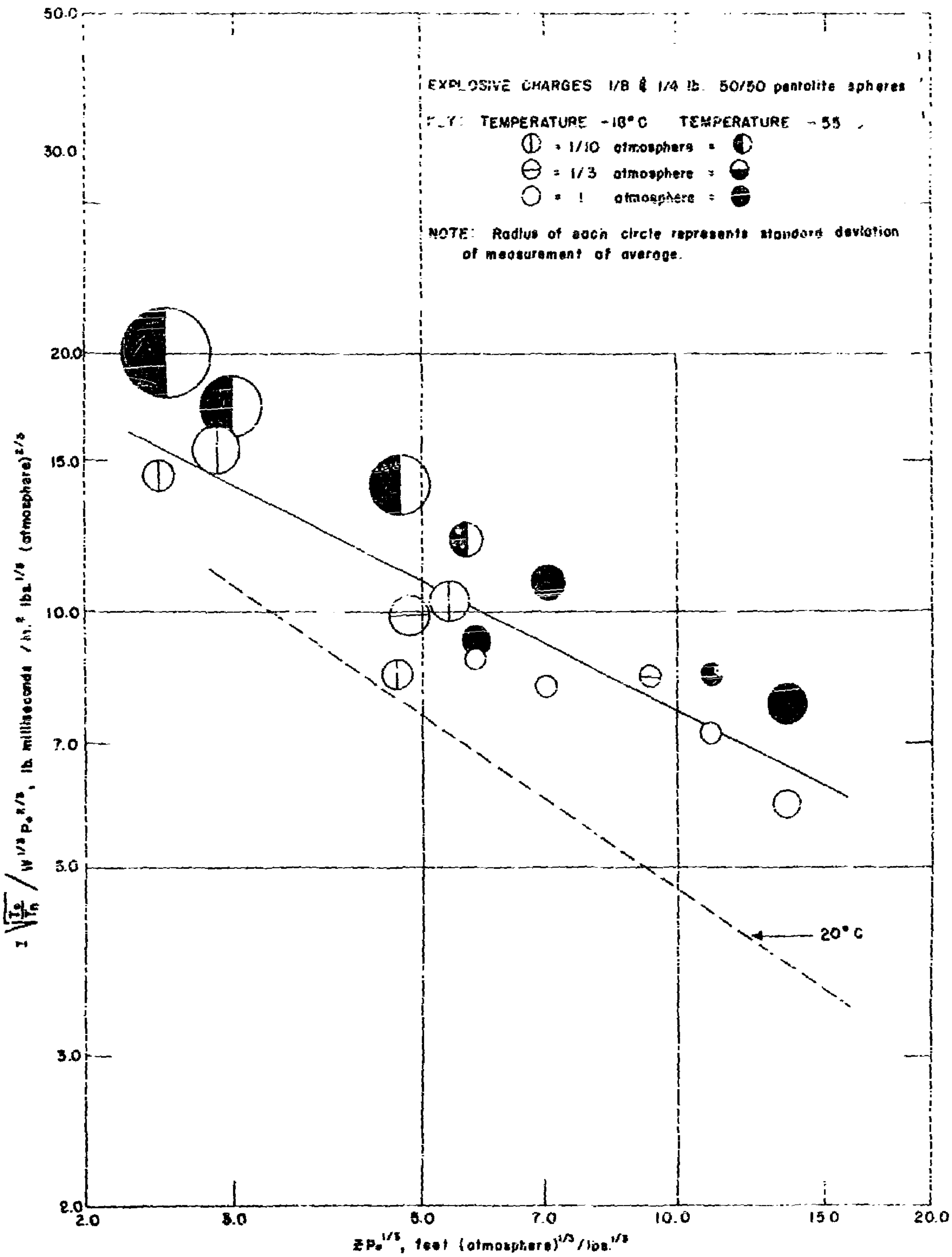


FIGURE 9

SCALED IMPULSE vs. SCALED DISTANCE

at

DIFFERENT ATMOSPHERIC PRESSURES AND TEMPERATURES

Table II

Peak Pressures and Impulses at Reduced Temperatures

P_o psi	T_o °C	Z ft/lb$^{1/3}$	W lb	Tourm. or Blast Switch	Peak Pressure Avg. psi	Peak Pressure σ %	Peak Pressure $\bar{\sigma}$ psi	Positive Impulse Avg. psi ms	Positive Impulse σ %	Positive Impulse $\bar{\sigma}$ psi ms
14.8	-18.3	5.87	0.262	B	24.4	3.2	0.35			
14.8	-18.3	6.76	0.262	T	21.9	2.1	0.21	6.10	6.4	0.17
14.7	-18.3	7.40	0.140	B	15.1	4.0	0.25			
14.7	-18.3	8.29	0.140	T	16.1	3.1	0.14	4.52	8.0	0.12
14.8	-18.3	11.0	0.262	T	8.25	2.2	0.08	4.96	5.3	0.12
14.8	-18.3	11.2	0.262	B	6.12	7.2	0.20			
14.7	-18.3	13.5	0.140	T	6.34	6.0	0.12	3.32	10	0.11
14.7	-18.3	14.1	0.140	B	3.98	11	0.15			
14.8	-18.3	17.6	0.262	B	3.08	17	0.24			
14.7	-18.3	22.2	0.140	B	2.35	6.4	0.06			
14.9	-52.7	5.87	0.263	B	25.0	5.0	0.56			
14.9	-52.7	6.76	0.263	T	25.5	3.2	0.36	6.90	6.0	0.19
14.9	-53.1	7.40	0.140	B	15.9	4.4	0.26			
14.9	-53.1	8.29	0.140	T	17.0	1.9	0.12	6.58	2.2	0.08
14.9	-52.7	11.0	0.263	T	9.47	7.2	0.29	6.38	5.4	0.15
14.9	-52.7	11.2	0.263	B	6.47	3.7	0.11			
14.9	-53.1	13.5	0.140	T	7.27	2.6	0.07	4.76	2.9	0.06
14.9	-53.1	14.1	0.140	B	4.46	3.1	0.05			
14.9	-52.7	17.6	0.263	B	3.10	18	0.27			
14.9	-53.1	22.2	0.140	B	2.19	5.0	0.04			
4.84	-17.0	7.12	0.140	T	10.3	1.8	0.08	2.67	10	0.14
4.84	-17.0	7.40	0.140	B	12.4	1.7	0.15			
4.84	-17.0	13.6	0.140	T	3.85	5.5	0.09	2.23	6.5	0.06
4.84	-17.0	14.1	0.140	B	2.91	2.1	0.03			
4.84	-17.0	22.2	0.140	B	1.24	8.1	0.06			
1.13	-18.2	5.81	0.263	T	14.5	14	0.91	1.80	6.7	0.05
1.13	-18.2	5.87	0.263	B	19.4	23	2.23			
0.97	-18.0	7.12	0.139	T	5.84	27	0.58	1.45	12	0.08
1.13	-18.2	11.1	0.263	T	3.54	10	0.19	1.01	7.9	0.04
1.13	-18.2	11.2	0.263	B	3.08	6.5	0.07			
0.97	-18.0	13.6	0.139	T	2.19	21	0.15	0.95	12	0.04
0.97	-18.0	14.1	0.139	B	1.74	17	0.09			
1.13	-18.2	17.6	0.263	B	1.15	5.2	0.03			
0.97	-18.0	22.2	0.139	B	0.74	8.1	0.03			

Table II

Peak Pressures and Impulsese at Reduced Temperatures

P_o psi	T_o °C	Z ft/lb$^{1/3}$	W lb	Tourm. or Blast Switch	Peak Pressure Avg. psi	σ %	σ psi	Positive Impulse Avg. psi ms	σ %	σ psi ms
1.17	-54.5	5.81	0.263	T	15.0	8.8	0.59	2.77	24	0.30
1.17	-54.5	5.87	0.263	B	16.8	7.1	0.54			
1.10	-57.5	7.12	0.140	T	8.54	3.6	0.13	1.88	16	0.13
1.10	-57.5	7.40	0.140	B	9.08	1.6	0.08			
1.17	-54.5	11.1	0.263	T	3.83	7.5	0.13	1.94	15	0.15
1.17	-57.5	11.2	0.263	B	3.27	7.6	0.11			
1.10	-57.5	13.6	0.140	T	2.26	6.7	0.06	1.33	9.3	0.05
1.10	-57.5	14.1	0.140	B	1.87	12	0.10			
1.17	-54.5	17.6	0.263	B	1.15	8.7	0.04			
1.10	-57.5	22.2	0.140	B	0.73	2.7	0.01			

DISCUSSION OF ERRORS

It is hoped to prepare a separate report on variability and systematic errors in blast measurements, including a statistical analysis of these data. Only the more obvious measurement phenomena will be discussed here. No systematic differences between piezogage and velocity determinations of pressure appear in the data, as can be seen in Figure 4. As these methods are completely independent, the random error probably gives a reliable estimate of the accuracy of the measurements. It is rather surprising that the standard deviations do not vary more rapidly with pressure, as the velocity method gives a 25% error in peak pressure for a 1% error in velocity at the lowest peak pressures and 1 atmosphere ambient pressure, and only a 3% error in peak pressure at the highest peak pressures.

Standard deviations, σ, of the individual pressure measurements about the least square curve for the normal temperature data are tabulated in Table III. Dr. Stoner was kind enough to furnish us with his original observations. Standard deviations of these measurements from his least square curve, equation 2) are included for comparison. The BRL measurements show approximately twice the standard deviation; at the lower pressures the larger error is due in large part to the poor fit of the quartic.

Included also in Table III for the BRL data are the ranges of standard deviations, σ, of the average pressures for a given charge weight at given point, taken from Table I.

TABLE III

Comparison of Standard Deviation of Pressure Measurements with those of Stoner and Bleakney

Range of Z ft/lb$^{1/3}$	Range of P/p$_0$ psi/atm	σ in psi from Appropriate Curve: Stoner & Bleakney	σ in psi from Appropriate Curve: BRL	σ in %* from Appropriate Curve: Stoner & Bleakney	σ in %* from Appropriate Curve: BRL	Range of* σ in % from Avg. Measurement
2 - 3	350-115		36.7		15.8	1.1-6.8
3 - 4	115- 53		11.8		14.1	0.9-6.5
4 - 5	53- 32	5.7	7.1	13.6	16.9	1.1-4.9
5 - 6	32- 20	1.8	5.7	6.2	21.9	1.7-10.4
6 - 9	20- 9	1.6	1.9	11.0	13.1	1.0-5.1
9 -14	9-4.5	0.37	0.77	5.5	11.4	0.9-8.7
14 -30	4.5-1.5	0.19	0.49	6.4	16.3	1.5-4.9

* In % of the average pressure over the range of Z.

One-eighth and one-sixteenth pound charges gave much more variable results than one-quarter and one-half pound charges at the same scaled distance. This probably results partly from initiation variations, which would give larger variabilities with small charges, and partly from the short duration of the shocks from small charges.

The magnitude of the aerodynamic error is less than would be expected. At a peak pressure of 9 psi and 1/10 atmosphere ambient pressure ($P/p_0 \sim 6$) the Mach number of air flow immediately behind the shock relative to the velocity of sound at this point is 1.1. Nevertheless the piezogage measurement of peak pressure is in good agreement with the peak pressure computed from shock velocity at the same point. The earth shock gage fails to record properly at a higher peak pressure ratio. (See top trace of Record No. 194, Appendix II). The oscillations observed in these records are probably due to formation and breakdown of secondary shocks at the gage. With the BRL gage oscillations of even greater amplitude were observed at high peak pressure ratios. Both gages gave readings in agreement with velocity measurements except when oscillations were observed. The better performance of the earth shock gage is probably due as much to its rough surface as to a higher aspect ratio. When there is a considerable disturbance of the flow, as is the case with both these gages, turbulence would be expected to lead to a smaller gage error than laminar flow. As both the rate of flow and the rate of change of pressure on the gage drop off rapidly behind the shock front, the maximum aerodynamic error occurs at the peak of the shock, so that impulse measurements should be reasonably reliable if peak pressure measurements are. The Mach number of the air flow also drops off rapidly and it is undoubtedly for this reason that no gage error was observed at Mach number 1.1. When the shock has reached the sensitive portion of the gage the flow at the edge of the gage is subsonic. and flow at the sensitive portion has adjusted itself to some extent to the presence of the gage.

DISCUSSION OF RESULTS

The variation of excess peak pressure with ambient pressure increases rapidly with distance for the measurements reported. This result is correctly predicted by the theory of Kirkwood and Brinkley[1]. However, there are significant, though not large, differences between the observed peak pressures and those predicted by this theory. The computations of these authors have been extended over the pressure range of these experiments by R. Makino. It is hoped to present his results in a separate report, now in preparation. As the agreement with Sachs's much simpler theory is better than with the Kirkwood-Brinkley calculations, only the dimensional analysis will be discussed here.

The effect of temperature on peak pressure, seen in Figure 8, is of the order of the error of measurement. The data suggest a slight increase in peak pressure with falling temperature but are not of sufficient precision to distinguish between the Kirkwood-Brinkley theory, which predicts a small increase, and Sachs's, which predicts none.

The Kirkwood-Brinkley theory predicts a smaller dependence of impulse on ambient pressure than was observed. Sachs's theory (Figure 7) is in agreement with the data within the large experimental error.

From the impulse data of Figure 9 it appears that the increase of impulse with falling temperature is greater than is predicted by Sachs's scaling law. The Student's t-test shows that the slopes of the lines representing room temperature and reduced temperature data [equations 3) and 4)] differ significantly at the 5% level. Figure 9 shows also that scaled impulses measured at the lowest temperature are larger than those measured at the intermediate temperature. As piezogage peak pressure measurements, determined from the gage constant for the appropriate temperature, agree with derminations of peak pressure by the velocity method, there is no obvious reason for attributing this difference to gage error. These impulse measurements are not of sufficient reliability, however, to establish a new scaling law. However, taken with the apparent slight dependence of pressure on temperature, they do suggest that the scaling used is only approximately correct. Better impulse measurements are needed and should be possible with smaller gages of better aerodynamic form.

As the agreement of the data with Sachs's scaling law is of considerable theoretical interest, his assumptions are restated here.

Stating the principle of similitude in the usual way, that a relation expressed in terms of all relevant dimensionless variables must be invariant to changes in dimensional variables, we find that no conclusions can be drawn from it. In order to obtain a definite scaling law, Sachs assumes also:

1. The only charge parameter necessary to a description of a shock at a distance from a charge large compared to the charge diameter is its total energy (presumably of detonation). The total energy of the shock is assumed to be proportional to this charge energy, WE_d.

2. Scaling of the time is independent of pressure. The time scaling must then be related to the distance scaling in such a way as to give the correct velocity of sound in the undisturbed air. The obvious dimensionless variable describing peak pressure is then the peak pressure ratio, P/p_o and the only dimensionless variable describing distance and not containing P is $R(p_o/WE_d)^{1/3}$. Subject to the restriction of the second assumption, the dimensionless variable describing the time is $ta_n(T_o/T_n)^{1/2}(p_o/WE_d)^{1/3}$ giving for the impulse variable $Ia_n(T_o/T_n)^{1/2}/(p_o WE_d)^{1/3}$. The detonation energy, E_d is assumed to be constant for a given explosive and has, therefore, been dropped from the coordinates of the graph. The blast is assumed to be in air, and the speed, a_n, of sound in air under standard conditions has also been dropped from the coordinates. T_n is some standard air temperature.

The difficulty with this argument is that there is no apparent reason for excluding other dimensionless variables from consideration. The variable R/R_e, where R_e is the radius of the charge, or the ratio of undisturbed air density to explosive density, would be expected to enter into the description of the shock. The assumptions made by Sachs exclude loading density as a factor in determining shock parameters. Nor is there any apparent physical basis for the assumption that the time scale of sound velocity in undisturbed air will determine the form of strong shocks, although this assumption is as reasonable as any that can be made in the present state of knowledge.

For practical purposes, the scaling laws of Sachs give the most reliable estimates of peak pressures and impulses as functions of ambient pressure now available. Their extrapolation to large distances should be entirely reliable. At smaller values of the distance (scaled for pressure and charge size) than those at which measurements were made, the data justify some extrapolation. Fortunately a rather small extrapolation covers the range of greatest interest in damage work. The use of equations 1) and 3) to calculate peak pressures and impulses is undoubtedly more reliable than the use of data obtained at a few points. Equation 4) probably gives as reliable an estimate of impulse at high altitude as is presently available, although the factor in the temperature is not consistent with the difference between equations 3) and 4).

These equations give excellent agreement with reliable pressure measurements at atmospheric pressure from other Laboratories, such as those of Stoner and Bleakney[9]. Possibly an estimate of blast parameters about spherical charges of other explosives can be obtained by multiplying the charge weight of the explosive, wherever it occurs, by the ratio of the detonation energy of the explosive to that of Pentolite. In view of the small number of reliable measurements available for any other explosives than Pentolite and TNT, for which data are of lower reproducibility than for Pentolite, this method should give better results than the use of a few shock measurements on a particular explosive.

FUTURE WORK PLANNED

Extension of peak pressure measurements to much smaller distances from the charge, using the velocity method, is planned for the immediate future. This work will be conducted electronically in a small chamber, which has been constructed from the casing of a 4000 pound bomb, and photographically. At the same time, measurements of the increase in static pressure in the chamber will be extended over a much longer time than is possible with piezogage recording. To investigate the effect of afterburning, it is planned to make such measurements on a number of explosives detonated in air and in inert gases and to obtain analyses of the gas in the chamber after the detonation.

It is hoped to obtain greatly improved measurements of impulse and of the form of the pressure-time curve behind a shock, but such results must await the development of measuring equipment of much shorter response times and greater reliability than that used in this work.

ACKNOWLEDGMENTS

The contributions of T. E. Sterne to this work, especially in considering possible applications of theory to the problems presented by low altitude blast are gratefully acknowledged. The improvements in timing and in clarity of recording made by Channing Adams and the assistance of R. W. Grubbs in carrying out the numberless minor changes in instrumentation required in the course of the work were alike essential to completing these measurements.

Jane Dewey

Joseph Sperrazza

APPENDIX I

TABLES OF INDIVIDUAL PEAK PRESSURE AND IMPULSE MEASUREMENTS

Rd. No.	Ambient Pressure psi	Ambient Temp. °C	Charge Weight lbs	"Tourmaline" Peak Pressure, psi			"Velocity" Peak Pressure, psi			Duration of Positive Phase in milliseconds			Impulse of Positive Phase in lb. millisec/in²			Z for "Tourmaline" measurements			Z for "Velocity" measurements		
				Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
83	14.8	18.0	(0.070)	5.81	3.12	1.51	Failed to function			0.74	0.83	1.04	2.15	1.29	0.78	10.4	17.0	26.7	8.31	16.6	25.7
87	14.9	19.5	(0.070)	6.15	3.29	1.46	10.1	2.97	1.06	0.74	0.91	1.09	2.23	1.50	0.82	10.4	17.0	26.7	8.31	16.6	25.7
91	14.8	19.5	(0.070)	5.98	3.46	No trace	10.2	2.57	1.41	0.73	0.86	No trace	2.18	1.49	No trace	10.4	17.0	26.7	8.31	16.6	25.7
95	14.8	20.5	(0.070)	6.32	3.63	1.62	10.3	2.80	1.27	0.70	Lost	1.04	2.21	Lost	0.84	10.4	17.0	26.7	8.31	16.6	25.7
99	14.6	15.5	(0.070)	6.09	3.12	1.61	10.6	2.65	1.09	0.73	0.95	1.14	2.22	1.48	0.92	10.4	17.0	26.7	8.31	16.6	25.7
107	14.8	18.5	(0.070)	6.08	3.16	1.64	10.3	2.92	1.61	0.62	1.00	1.00	1.86	1.61	0.79	10.4	17.0	26.7	8.31	16.6	25.7
111	14.6	16.0	(0.070)	6.04	2.96	1.78	10.7	3.08	1.93	0.67	0.82	0.67	1.99	1.16	0.60	10.4	17.0	26.7	8.31	16.6	25.7
117	14.6	19.5	(0.070)	6.38	2.74	1.52	Failed to function			0.72	0.86	1.05	2.21	1.08	0.72	10.4	17.0	26.7	8.31	16.6	25.7
Av.	14.7	18.4		6.16	3.19	1.59	10.4	2.84	1.40				2.14	1.37	0.78	10.4	17.0	26.7	8.31	16.6	25.7
σ	0.12	1.78		0.20	0.25	0.10	0.24	0.17	0.32				0.14	0.20	0.10						
σ̄	0.04	0.63		0.06	0.08	0.04	0.09	0.06	0.12				0.05	0.08	0.04						
181	14.8	18.9	0.147	11.8	No Kick	2.99	Failed to function			No Kick	No Kick	No Kick	No Kick	No Kick	No Kick	8.29	13.5	21.3	6.69	13.1	21.0
182	14.8	19.2	0.139	No trace	6.23	1.55	13.2	5.38	2.28	No trace	1.02	1.24	No trace	3.37	1.02	8.29	13.5	21.3	6.69	13.1	21.0
183	14.8	19.4	0.141	10.5	5.06	No trace	15.1	5.69	1.58	0.52	1.00	No trace	2.74	2.53	No trace	8.29	13.5	21.3	6.69	13.1	21.0
186	14.8	20.3	0.140	10.0	4.91	2.42	14.2	5.41	2.20	0.52	1.00	1.20	2.61	2.46	1.45	8.29	13.5	21.3	6.69	13.1	21.0
188	14.9	18.1	0.141	11.1	5.00	2.63	14.9	5.55	2.04	0.52	1.00	1.19	2.91	2.49	1.54	8.29	13.5	21.3	6.69	13.1	21.0
204	14.8	25.6	0.140	10.3	6.99	2.34	16.1	5.03	2.24	0.56	Lost	1.16	2.94	Lost	1.35	8.29	13.5	21.3	6.78	13.1	20.9
205	14.7	25.6	0.140	9.52	4.98	2.36	17.1	5.26	1.80	0.62	0.95	1.19	2.90	2.38	1.44	8.29	13.5	21.3	6.78	13.1	20.9
214	15.0	21.7	0.140	10.3	5.19	2.26	16.6	5.15	2.46	0.58	Lost	Lost	2.99	Lost	Lost	8.29	13.5	21.3	6.78	13.1	20.9
Av.	14.8	21.1	0.141	10.5	5.47	2.36	15.3	5.35	2.09				2.84	2.64	1.35	8.29	13.5	21.3	6.74	13.1	21.0
σ	0.07	2.96	0.002	0.73	0.82	0.44	1.36	0.23	0.30				0.14	0.41	0.20						
σ̄	0.02	1.04	0.0009	0.28	0.31	0.17	0.51	0.09	0.11				0.06	0.18	0.09						
221	14.7	-16.1	0.140	14.7	5.81		16.0	4.33	Lost	0.57	1.07		4.08	3.17		8.29	13.5		7.40	14.1	22.2
223	14.7	-15.6	0.140	15.2	6.75		Failed to function			0.53	1.07		4.04	3.60		8.29	13.5		7.40	14.1	22.2
222	14.7	-15.0	0.139	15.4	6.56		15.4	4.65	2.56	0.59	1.05		4.54	3.39		8.29	13.5		7.40	14.1	22.2
226	14.7	-19.4	0.140	14.5	5.89		Lost	4.13	2.44	0.67	1.00		4.80	2.90		8.29	13.5		7.40	14.1	22.2
225	14.7	-19.2	0.139	14.5	6.15		Lost	4.00	2.45	0.60	1.07		4.36	3.27		8.29	13.5		7.40	14.1	22.2
224	14.7	-16.7	0.139	14.8	5.94		Failed to function			0.64	1.07		4.76	3.22		8.29	13.5		7.40	14.1	22.2
234	14.8	-19.4	0.139	15.5	5.97		14.2	3.73	2.20	0.58	1.07		4.41	3.19		8.29	13.5		7.40	14.1	22.2
275	14.9	-18.9	0.141	15.3	7.76		15.2	3.80	2.22	0.67	1.05		5.22	4.08		8.29	13.5		7.40	14.1	22.2
276	14.1	-19.4	0.140	15.0	5.85		15.1	3.95	2.22	0.60	1.07		4.43	3.06		8.29	13.5		7.40	14.1	22.2
274	14.9	-22.9	0.140	15.9	6.67		14.7	3.21	*1.31	Lost	Lost		Lost	Lost		8.29	13.5		7.40	14.1	22.2
Av.	14.7	-18.3	0.140	15.1	6.34		15.1	3.98	2.35				4.52	3.32		8.29	13.5		7.40	14.1	22.2
σ	0.02	2.40	0.0008	0.47	0.38		0.61	0.42	0.15				0.36	0.34							
σ̄	0.006	0.76	0.0002	0.14	0.12		0.25	0.15	0.06				0.12	0.11							

* Omitted in computation of the mean and standard deviation.

Rd. No.	Ambient Pressure psi	Ambient Temp. oC	Charge Weight lbs.	"Tourmaline" Peak Pressure, psi			"Velocity" Peak Pressure, psi			Duration of Positive Phase in milliseconds			Impulse of Positive Phase in lb. millisec/in^2			Z for "Tourmaline" measurements			Z for "Velocity" measurements		
				Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
259	14.9	-42.8	0.139	16.9	6.97		15.2	4.30	Lost	0.86	1.24		7.03	4.28		8.29	13.5		7.40	14.1	22.2
261	14.9	-55.6	0.139	16.6	7.09		15.4	4.57	2.03	0.76	1.34		6.31	4.88		8.29	13.5		7.40	14.1	22.2
262	14.9	-52.8	0.140	17.0	7.43		16.0	4.45	2.22	0.70	1.31		5.83	4.88		8.29	13.5		7.40	14.1	22.2
263	14.9	-52.8	0.140	17.0	7.45		15.7	4.53	2.18	0.74	0.95		6.40	3.48		8.29	13.5		7.40	14.1	22.2
264	14.9	-53.3	0.140	17.6	7.25		15.5	4.61	2.11	0.69	1.40		6.21	4.96		8.29	13.5		7.40	14.1	22.2
265	14.9	-57.3	0.141	17.4	7.28		16.9	4.53	2.33	0.73	1.28		6.74	4.57		8.29	13.5		7.40	14.1	22.2
267	14.9	-56.7	0.141	17.0	7.43		16.8	4.26	2.26	0.79	1.33		6.82	4.98		8.29	13.5		7.40	14.1	22.2
Av.	14.9	-53.1	0.140	17.0	7.27		15.9	4.46	2.19				6.58	4.76		8.29	13.5		7.40	14.1	22.2
σ		4.95	0.0008	0.32	0.19		0.69	0.14	0.11				0.15	0.14							
σ̄		1.87	0.0003	0.12	0.07		0.26	0.05	0.04				0.08	0.06							
101	14.6	21.5	(0.262)	14.8	6.58	2.84	26.3	7.51	3.55	0.52	1.00	1.36	3.95	3.36	1.96	6.76	11.0	17.4	5.59	10.4	16.8
106	14.8	18.0	(0.262)	14.2	6.38	Lost	23.4	7.33	3.87	0.59	1.05	Lost	3.95	3.49	Lost	6.76	11.0	17.4	5.59	10.4	16.8
107	14.8	17.5	(0.262)	13.6	6.34	2.86	23.0	7.35	3.79	0.59	1.05	1.45	4.22	3.18	2.16	6.76	11.0	17.4	5.59	10.4	16.8
120	14.6	20.0	(0.262)	13.7	5.72	2.95	26.8	6.58	3.93	0.55	1.05	1.00	3.85	3.08	1.50	6.76	11.0	17.4	5.59	10.4	16.8
128	14.5	20.0	0.263	13.8	5.96	3.00	24.3	7.10	4.11	0.56	0.98	1.18	3.95	2.90	1.80	6.76	11.0	17.4	5.59	10.4	16.8
132	14.7	21.0	0.262	13.3	6.12	Lost	No good	No good	4.00	0.59	1.05	Lost	3.95	3.32	Lost	6.76	11.0	17.4	5.59	10.4	16.8
136	14.8	20.5	0.262	14.8	6.35	Lost	20.8	7.10	3.84	0.56	1.00	Lost	4.14	3.23	Lost	6.75	11.0	17.4	5.59	10.4	16.8
140	14.8	21.0	0.263	14.8	6.29	3.06	27.9	7.62	4.06	0.53	1.00	1.21	3.92	3.14	1.85	6.76	11.0	17.4	5.59	10.4	16.8
Av.	14.7	19.[illegible]	0.262	14.2	6.22	2.95	24.6	7.23	3.89				4.00	3.21	1.85	6.76	11.0	17.4	5.59	10.4	16.8
σ	0.12	1.3[illegible]	0.007	0.60	0.27	0.10	2.49	0.34	0.18				0.12	0.18	0.24						
σ̄	0.04	0.49	0.003	0.21	0.10	0.04	0.94	0.13	0.07				0.04	0.06	0.11						
239	14.7	-18.9	0.263	21.6	8.30		23.3	6.46	3.23	0.51	1.17		5.92	4.86		6.76	11.0		5.87	11.2	17.6
240	14.8	-19.4	0.262	21.3	8.12		25.2	6.02	3.78	0.55	1.23		6.33	5.71		6.76	11.0		5.87	11.2	17.6
241	14.8	-16.7	0.262	21.4	7.99		24.4	6.06	2.80	0.59	1.17		6.24	4.65		6.75	11.0		5.87	11.2	17.6
242	14.9	-15.6	0.262	21.7	8.21		25.2	5.46	3.26	0.56	1.16		6.50	4.84		6.76	11.0		5.87	11.2	17.6
243	14.8	-21.1	0.262	21.0	8.16		24.2	6.59	2.36	0.53	1.21		5.94	5.33		6.76	11.0		5.87	11.2	17.6
Av.	14.8	-18.3	0.262	21.9	8.25		24.4	6.12	3.08				6.10	4.96		6.76	11.0		5.87	11.2	17.6
σ	0.04	2.20	0.0005	0.47	0.19		0.78	0.44	0.53				0.39	0.26							
σ̄	0.02	0.98	0.0002	0.21	0.08		0.35	0.20	0.24				0.17	0.12							
249	14.9	-55.0	0.263	25.5	9.65		22.9	6.28	3.18	0.50	1.23		6.42	6.07		6.76	11.0		5.87	11.2	17.6
250	14.9	-51.0	0.263	25.5	9.56		25.6	6.72	3.64	0.51	1.21		6.58	5.87		6.76	11.0		5.87	11.2	17.6
251	14.9	-55.0	0.262	26.3	11.0		26.2	6.73	3.15	0.52	1.24		6.98	6.77		6.76	11.0		5.87	11.2	17.6
252	14.9	-49.4	0.263	23.2	9.21		24.8	6.32	2.56	0.56	1.35		7.10	6.55		6.76	11.0		5.87	11.2	17.6
253	14.9	-52.8	0.264	24.8	9.60		25.4	6.28	2.96	0.56	1.53		7.44	6.64		6.76	11.0		5.87	11.2	17.6
Av.	14.9	-52.7	0.263	25.5	9.47		25.0	6.47	3.10				6.90	6.38		6.76	11.0		5.87	11.2	17.6
σ		2.45	0.0007	0.82	0.69		1.26	0.24	0.56				0.42	0.34							
σ̄		1.05	0.0003	0.36	0.29		0.56	0.11	0.27				0.19	0.15							

Rd No.	Ambient Pressure psi	Ambient Temp. °C	Charge Weight lbs	"Tourmaline" Peak Pressure, psi			"Velocity" Peak Pressure, psi			Duration of Positive Phase in milliseconds			Impulse of Positive Phase in lb. millisec/in²			Z for "Tourmaline" measurements			Z for "Velocity" measurements		
				Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
150	15.0	19.7	0.539	24.7	10.1	No trace	Not readable			0.45	1.00	No trace	5.56	5.04	Lost	5.29	8.61	13.6	4.34	8.28	13.5
154	15.0	[illegible]	0.541	26.6	10.9	No trace	45.8	13.8	4.64	0.45	1.05	No trace	6.03	5.76	Lost	5.29	8.61	13.6	4.34	8.26	13.5
158	14.8	17.8	0.545	23.2	11.6	5.38	44.1	13.1	6.57	0.50	0.98	No good	5.85	5.71	No good	5.29	8.61	13.6	4.34	8.28	13.5
162	14.9	19.7	0.543	25.2	11.1	4.91	46.3	12.9	5.07	0.48	0.96	1.09	6.10	5.50	2.80	5.29	8.61	13.6	4.34	8.28	13.5
205	14.9	22.8	0.542	34.3	11.9	4.32	No record			No good	0.93	1.31	No good	5.42	2.59	5.29	8.61	13.6	4.34	8.28	13.5
201	14.9	20.6	0.543	29.8	11.4	4.02	No record			0.45	0.93	1.32	6.70	5.28	2.65	5.29	8.61	13.6	4.38	8.26	13.5
195	15.0	21.4	0.542	30.2	11.2	3.78	45.4	No record		0.45	0.95	1.36	6.50	5.42	2.50	5.29	8.61	13.6	4.38	8.26	13.5
Av.	14.9	19.8	0.542	27.7	11.2	4.48	45.4	13.3	5.43				6.12	5.44	2.63	5.29	8.61	13.6	4.36	8.28	13.5
σ	0.04	2.08	0.002	3.90	0.58	0.66	0.94	0.49	1.01				0.42	0.25	0.12						
$\bar{\sigma}$	0.017	0.78	0.0007	1.50	0.22	0.29	0.47	0.28	0.58				0.17	0.09	0.06						
76	10.1	19.5	(0.070)	5.16	2.47	Lost	Failed to function			0.70	0.88	Lost	1.91	1.09	Lost	10.4	17.0	26.7	8.72	16.5	26.4
81	9.92	17.5	(0.070)	4.83	2.66	1.26	9.64	3.52	Lost	0.68	0.91	1.16	1.64	1.21	0.73	10.4	17.0	26.7	8.72	16.5	26.4
84	10.1	18.5	(0.070)	5.56	2.86	1.29	8.75	1.96	1.11	0.73	0.80	1.18	2.02	1.14	0.76	10.4	17.0	26.7	8.72	16.5	26.4
88	8.92	19.0	(0.070)	4.88	2.47	1.26	8.03	1.55	0.98	Wavy baseline		1.13	Wavy baseline		0.74	10.4	17.0	26.7	8.72	16.5	26.4
92	9.89	18.0	(0.070)	5.47	2.53	1.29	6.90	1.89	1.27	0.82	Lost	1.19	1.70	Lost	0.77	10.4	17.0	26.7	8.72	16.5	26.4
96	9.90	21.5	(0.070)	5.06	2.66	1.30	7.14	1.65	1.18	Wavy baseline		1.14	Wavy baseline		0.72	10.4	17.0	26.7	8.72	16.5	26.4
100	9.84	17.0	(0.070)	5.16	2.52	1.32	8.49	2.66	1.69	0.73	0.96	1.18	1.89	1.20	0.77	10.4	17.0	26.7	8.72	16.5	26.4
110	9.90	18.5	(0.070)	5.46	2.73	Lost	9.31	2.81	1.85	0.59	0.95	1.16	1.63	1.28	Lost	10.4	17.0	26.7	8.72	16.5	26.4
114	9.89	20.5	(0.070)	5.64	2.71	1.40	9.62	2.88	1.95	0.68	0.88	1.17	1.93	1.16	0.80	10.4	17.0	26.7	8.72	16.5	26.4
118	9.94	20.0	(0.070)	5.47	2.62	1.57	9.50	2.42	1.78	0.62	0.86	No good	1.71	1.01	No good	10.4	17.0	26.7	8.72	16.5	26.4
122	9.94	19.5	0.072	5.31	Lost	Lost	8.30	2.72	1.85	0.68	0.82	Lost	1.80	Lost	Lost	10.4	17.0	26.7	8.72	16.5	26.4
124	9.93	19.5	0.071	5.79	2.94	1.56	10.7	2.84	2.02	0.68	0.82	1.13	1.97	1.16	0.89	10.4	17.0	26.7	8.72	16.5	26.4
219	9.86	25.0	0.072	5.28	3.06	1.27	Lost	Lost	Lost	0.68	0.88	1.12	1.76	1.29	0.68	10.4	17.0	26.7	8.72	16.5	26.4
220	9.89	27.5	0.072	5.20	3.35	1.36	8.55	2.88	1.13	0.70	0.79	1.16	1.77	1.28	0.75	10.4	17.0	26.7	8.72	16.5	26.4
215	9.97	23.1	0.072	5.39	Lost	Lost	8.76	2.86	1.24	0.68	Lost	Lost	1.80	Lost	Lost	10.4	17.0	26.7	8.72	16.5	26.4
216	10.1	23.6	0.071	5.29	3.50	1.33	8.38	2.68	1.13	Lost	0.73	1.18	Lost	1.28	0.76	10.4	17.0	26.7	8.72	16.5	26.4
217	10.1	23.9	0.072	5.66	Lost	1.47	10.3	3.04	1.30	0.68	Lost	1.14	1.90	Lost	0.82	10.4	17.0	26.7	8.72	16.5	26.4
Av.	9.89	20.7	0.072	5.33	2.79	1.36	8.81	2.56	1.46				1.81	1.19	0.77	10.4	17.0	26.7	8.72	16.5	26.4
σ	0.26	2.94	0.0003	0.27	0.32	0.11	1.02	0.55	0.34				0.12	0.09	0.05						
$\bar{\sigma}$	0.06	0.71	0.0001	0.07	0.09	0.03	0.26	0.14	0.09				0.03	0.03	0.02						
104	9.96	21.5	(0.262)	13.6	5.48	Lost	23.6	5.76	2.81	0.52	0.91	Lost	3.46	2.51	Lost	6.76	11.0	17.4	5.66	10.7	17.0
121	9.96	19.5	(0.262)	12.8	5.18	2.70	20.0	5.73	3.14	0.50	0.86	1.14	3.20	2.23	1.54	6.76	11.0	17.4	5.66	10.7	17.0
129	9.86	19.5	0.263	12.7	5.05	2.78	23.6	5.67	2.67	0.50	0.91	1.23	3.15	2.24	1.68	6.76	11.0	17.4	5.66	10.7	17.0
133	9.77	21.0	0.251	Not readable			19.7	*5.78	3.34	Not readable		1.14	Not readable			6.76	11.0	17.4	5.66	10.7	17.0
137	9.67	20.0	0.262	12.0	5.07	No good	23.8	6.17	2.90	0.53	0.93	No good	3.15	2.32	No good	6.76	11.0	17.4	5.66	10.7	17.0
141	9.68	18.0	0.262	13.8	4.95	Lost	25.0	5.82	3.10	0.50	0.86	No trace	3.35	2.12	No trace	6.76	11.0	17.4	5.66	10.7	17.0
Av.	9.90	19.9	0.262	13.0	5.14	2.74	22.6	5.83	2.99				3.26	2.28	1.61	6.76	11.0	17.4	5.66	10.7	17.0
σ	0.24	1.03	0.0008	0.70	0.26	0.06	2.21	0.19	0.22				0.14	0.14	0.10						
$\bar{\sigma}$	0.10	0.42	0.0004	0.31	0.12	0.04	0.90	0.08	0.09				0.06	0.06	0.07						

* Omitted in computation of the mean and [illegible] ... in computation of the mean and standard deviation.

Rd. No.	Ambient Pressure psi	Ambient Temp. °C	Charge Weight lbs.	"Tourmaline" Peak Pressure, psi			"Velocity" Peak Pressure, psi			Duration of Positive Phase in milliseconds			Impulse of Positive Phase in lb. millisec/in^2			Z for "Tourmaline" measurements			Z for "Velocity" measurements		
				Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
151	9.87	20.3	0.544	23.4	8.88	4.05	37.8	12.1	3.87	0.36	0.86	1.45	4.21	4.00	2.88	5.29	8.61	13.6	4.30	8.41	13.4
155	9.83	16.9	0.547	24.0	9.04	Lost	Failed to function			0.36	0.90	No good	4.43	4.12	No good	5.29	8.61	13.6	4.30	8.41	13.4
159	9.76	20.0	0.542	24.4	8.66	3.94	41.5	10.6	3.88	0.36	0.91	1.41	4.41	4.00	2.86	5.29	8.61	13.6	4.30	8.41	13.4
163	9.70	20.0	0.542	23.8	8.70	4.02	38.9	10.8	3.96	0.44	0.85	1.31	5.24	3.70	2.63	5.29	8.61	13.6	4.30	8.41	13.4
200	9.74	23.3	0.545	23.7	8.42	3.49	41.4	9.50	3.77	0.37	0.83	1.30	4.30	3.62	2.38	5.29	8.61	13.6	4.30	8.41	13.4
197	9.83	20.6	0.544	23.7	8.72	3.25	39.4	10.3	4.28	0.36	0.86	1.35	4.31	3.98	2.20	5.29	8.61	13.6	4.30	8.41	13.4
196	9.76	20.6	0.542	24.3	9.42	3.20	42.6	9.73	4.23	0.32	0.88	1.34	3.90	4.32	2.16	5.29	8.61	13.6	4.30	8.41	13.4
Av.	9.78	20.2	0.544	23.9	8.83	3.67	40.3	10.5	4.00				4.40	3.96	2.52	5.29	8.61	13.6	4.30	8.41	13.4
σ	0.06	1.86	0.002	0.35	0.32	0.38	1.86	0.93	0.21				0.41	0.24	0.33						
$\bar{\sigma}$	0.02	0.70	0.0007	0.12	0.12	0.16	0.76	0.38	0.09				0.16	0.09	0.13						
85	4.65	20.0	(0.070)	No calibration steps			5.99	1.44	0.98	0.50	0.84	Lost	No calibration steps			10.4	17.0	26.7	8.52	16.4	26.4
89	5.04	19.0	(0.070)	3.38	1.82	0.92	6.36	1.32	0.85	0.66	0.98	1.49	1.06	0.90	0.71	10.4	17.0	26.7	8.52	16.4	26.4
93	5.12	17.5	(0.070)	3.24	1.40	Lost	*8.60	1.36	1.03	No good	0.98	Lost	No good	0.70	Lost	10.4	17.0	26.7	8.52	16.4	26.4
97	4.96	19.0	(0.070)	Lost	1.82	Lost	6.78	1.63	1.04	Lost	0.82	Lost	Lost	0.75	Lost	10.4	17.0	26.7	8.52	16.4	26.4
101	4.92	19.0	(0.070)	3.78	1.81	Lost	7.41	1.84	1.02	0.56	0.81	Lost	1.11	0.74	Lost	10.4	17.0	26.7	8.52	16.4	26.4
111	4.88	18.6	(0.070)	3.82	1.89	1.03	6.77	1.77	1.03	0.52	0.90	1.19	0.99	0.85	0.61	10.4	17.0	26.7	8.52	16.4	26.4
115	4.90	22.0	(0.070)	3.97	1.68	Lost	6.16	1.67	1.05	0.51	0.93	Lost	1.02	0.92	Lost	10.4	17.0	26.7	8.52	16.4	26.4
119	4.96	20.0	(0.070)	3.47	1.79	0.99	6.57	2.07	1.04	0.50	0.96	1.23	0.87	0.89	0.63	10.4	17.0	26.7	8.52	16.4	26.4
168	4.92	23.3	0.070	3.94	1.96	Lost	6.47	2.54	0.84	0.48	0.82	Lost	0.96	0.79	Lost	10.4	17.0	26.7	8.32	16.5	26.3
170	4.89	25.0	0.071	No calibration steps			6.50	2.14	0.83	Lost	Lost	Lost	Lost	Lost	Lost	10.4	17.0	26.7	8.32	16.5	26.3
172	4.88	25.3	0.070	4.04	1.96	Lost	7.01	2.35	0.90	0.50	0.86	Lost	1.03	0.86	Lost	10.4	17.0	26.7	8.32	16.5	26.3
172	4.90	25.4	0.070	3.85	1.95	0.98	6.78	2.54	0.69	0.50	0.82	1.34	0.98	0.85	0.60	10.4	17.0	26.7	8.32	16.5	26.3
169	4.92	23.3	0.071	3.77	1.92	0.93	Lost	2.16	0.60	0.66	0.99	1.32	1.24	0.95	0.61	10.4	17.0	26.7	8.32	16.5	26.3
173	4.88	21.9	0.070	Lost	1.48	Lost	7.96	2.23	0.54	Lost	0.89	Lost	Lost	0.66	Lost	10.4	17.0	26.7	8.32	16.5	26.3
Av.	4.92	21.1	0.070	3.77	1.79	0.95	6.75	1.93	0.87				1.03	0.82	0.63	10.4	17.0	26.7	8.37	16.5	26.3
σ	0.10	2.65	0.001	0.34	0.18	0.07	0.52	0.42	0.05				0.10	0.09	0.04						
$\bar{\sigma}$	0.02	0.66	0.0004	0.10	0.05	0.03	0.15	0.11	0.02				0.03	0.03	0.02						
130	4.90	18.0	0.261	10.8	4.58	1.88	21.9	4.87	2.04	0.45	0.92	1.27	2.59	2.02	1.18	6.76	11.0	17.4	5.54	10.6	17.1
134	4.75	20.5	0.262	11.6	5.46	1.89	21.2	4.69	2.07	0.45	0.77	1.36	2.66	2.01	1.22	6.76	11.0	17.4	5.54	10.6	17.1
138	4.91	19.0	0.262	13.0	4.46	1.86	22.1	4.76	2.25	0.32	0.95	1.41	1.94	2.10	1.28	6.76	11.0	17.4	5.54	10.6	17.1
142	4.84	18.3	0.262	11.7	4.46	No trace	21.6	4.90	2.28	0.36	0.91	No trace	2.11	1.96	No trace	6.76	11.0	17.4	5.54	10.6	17.1
143	4.83	20.6	0.261	10.2	4.24	No trace	21.6	4.44	2.09	0.39	0.98	No trace	2.03	2.06	No trace	6.76	11.0	17.4	5.54	10.6	17.1
144	4.85	24.2	0.262	No good	4.21	1.93	21.4	4.71	1.96	No good	0.95	1.36	No good	1.96	1.31	6.76	11.0	17.4	5.54	10.6	17.1
145	4.84	19.7	0.262	10.5	4.45	2.01	21.7	4.96	2.14	0.46	0.98	1.40	2.46	2.23	1.37	6.76	11.0	17.4	5.54	10.6	17.1
105	4.94	20.0	0.262	No good	4.71	1.76	19.8	4.20	No good	0.45	0.84	No good	No good	1.98	No good	6.76	11.0	17.4	5.54	10.6	17.1
122	4.85	19.0	0.262	12.5	4.42	No trace	*18.0	4.50	2.44	0.45	0.95	No trace	2.47	2.17	No trace	6.76	11.0	17.4	5.54	10.6	17.1
Av.	4.86	19.9	0.262	11.5	4.56	1.89	21.4	4.67	2.16				2.32	2.05	1.27	6.76	11.0	17.4	5.54	10.6	17.1
σ	0.06	1.84	0.0006	1.02	0.36	0.08	0.71	0.25	0.18				0.29	0.09	0.07						
$\bar{\sigma}$	0.02	0.61	0.0002	0.39	0.12	0.03	0.25	0.08	0.07				0.12	0.03	0.03						

* Omitted in computation of the mean and standard deviation

Rd. No.	Ambient Pressure psi	Ambient Temp. °C	Charge Weight lbs.	"Tourmaline" Peak Pressure, psi			"Velocity" Peak Pressure, psi			Duration of Positive Phase in milliseconds			Impulse of Positive Phase in lb. millisec/in²			Z for "Tourmaline" measurements			Z for "Velocity" measurements		
				Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
156	4.63	19.7	0.542	22.9	7.35	No good	Lost	Lost	Lost	0.39	0.75	No good	4.47	2.76	No good	5.29	8.61	13.6	4.20	8.27	13.5
160	4.85	18.6	0.541	22.4	7.46	2.19	35.9	8.45	3.00	0.32	0.73	1.23	3.58	2.85	1.65	5.29	8.61	13.6	4.20	8.27	13.5
164	4.84	20.0	0.546	22.4	8.00	3.13	37.2	8.61	2.71	0.36	0.68	1.45	4.03	2.75	2.26	5.29	8.61	13.6	4.20	8.27	13.5
165	4.91	20.8	0.549	No good	9.20	3.22	40.2	8.21	2.71	No good	0.68	1.23	No good	3.13	1.98	5.29	8.61	13.6	4.20	8.27	13.5
201	4.83	23.3	0.542	25.7	No good	2.43	36.8	7.43	2.68	0.32	0.77	1.23	4.11	No good	1.43	5.29	8.61	13.6	4.33	8.34	13.4
193	4.93	21.1	0.541	25.2	No good	2.53	32.6	7.59	2.84	0.32	0.77	1.45	3.68	No good	1.65	5.29	8.61	13.6	4.23	8.27	13.4
197	4.96	22.2	0.540	23.7	7.98	2.51	36.0	8.05	2.94	0.36	0.73	1.41	4.19	2.77	1.73	5.29	8.61	13.6	4.33	8.34	13.4
152	4.84	18.3	0.543	No good	6.92	3.21	37.1	8.32	2.76	0.35	0.76	1.41	No good	2.63	2.26	5.29	8.61	13.6	4.20	8.27	13.5
Av.	4.85	20.5	0.543	23.7	7.82	2.75	36.5	8.09	2.80				4.01	2.82	1.36	5.29	8.61	13.6	4.25	8.29	13.5
σ	0.10	1.60	0.003	1.44	0.68	0.43	2.25	0.44	0.12				0.33	0.17	0.32						
$\bar{\sigma}$	0.04	0.60	0.001	0.59	0.28	0.16	0.84	0.17	0.04				0.13	0.08	0.12						
277	4.81	-18.3	0.140	10.2	4.01		12.5	2.96	1.25	0.59	1.18		3.01	2.36		7.12	13.6		7.40	14.1	22.2
278	5.05	-16.1	0.141	10.2	4.02		12.2	2.83	Lost	0.50	1.14		2.62	2.32		7.12	13.6		7.40	14.1	22.2
279	4.72	-17.8	0.140	10.4	3.51		Lost	2.95	1.14	0.46	1.14		2.35	1.98		7.12	13.6		7.40	14.1	22.2
280	4.85	-15.6	0.140	10.6	3.92		Lost	2.94	1.34	0.50	1.18		2.72	2.27		7.12	13.6		7.40	14.1	22.2
281	4.77	-17.2	0.140	10.2	3.77		Lost	Lost	Lost	No good	1.18		No good	2.22		7.12	13.6		7.40	14.1	22.2
Av.	4.84	-17.0	0.140	10.3	3.85		12.4	2.91	1.24				2.67	2.23		7.12	13.6		7.40	14.1	22.2
σ	0.13	1.15	0.0005	0.18	0.21		0.21	0.06	0.10				0.27	0.14							
$\bar{\sigma}$	0.05	0.51	0.0002	0.08	0.09		0.15	0.03	0.06				0.14	0.06							
78	1.67	20.0	(0.070)	3.02	1.25	0.55	Lost	1.42	Lost	0.60	0.84	1.40	0.91	0.52	0.39	10.4	17.0	26.7	8.52	16.2	26.3
82	1.58	18.0	(0.070)	2.46	1.47	0.56	7.40	1.35	Lost	0.51	0.81	1.42	0.63	0.59	0.40	10.4	17.0	26.7	8.52	16.2	26.3
86	1.73	20.0	(0.070)	3.12	1.33	0.58	4.99	1.04	Lost	0.43	0.87	1.40	0.67	0.59	0.39	10.4	17.0	26.7	8.52	16.2	26.3
90	1.72	19.5	(0.070)	No calibration steps			5.24	1.16	0.58	Lost	0.84	No trace	Lost	0.52	No trace	10.4	17.0	26.7	8.52	16.2	26.3
94	1.75	22.5	(0.070)	No calibration steps			5.12	0.95	0.66	No calibration steps			No calibration steps			10.4	17.0	26.7	8.52	16.2	26.3
94A	1.63	22.0	(0.070)	3.12	No trace	No trace	7.95	1.04	0.43	0.56	No trace	No trace	0.87	No trace	No trace	10.4	17.0	26.7	8.52	16.2	26.3
98	1.63	19.5	(0.070)	2.78	1.36	Lost	6.15	1.52	0.69	0.48	0.83	Lost	0.67	0.56	Lost	10.4	17.0	26.7	8.52	16.2	26.3
102	1.82	20.5	(0.070)	3.51	1.31	0.54	5.06	1.26	0.69	0.50	0.79	1.38	0.63	0.51	0.37	10.4	17.0	26.7	8.52	16.2	26.3
112	1.72	22.0	(0.070)	No good	1.21	0.55	4.44	1.30	0.55	0.44	0.93	1.39	No good	0.54	0.37	10.4	17.0	26.7	8.52	16.2	26.3
123	1.64	19.5	0.072	4.17	No trace	No trace	6.44	1.35	0.70	0.45	No trace	No trace	0.94	No trace	No trace	10.4	17.0	26.7	8.52	16.2	26.3
126	1.68	18.0	0.072	3.02	1.12	Lost	6.07	1.32	0.61	0.48	0.86	Lost	0.72	0.48	Lost	10.4	17.0	26.7	8.52	16.2	26.3
116	1.68	16.5	0.071	No good	1.18	0.58	5.10	1.31	0.56	No good	0.90	1.43	No good	0.52	0.41	10.4	17.0	26.7	8.52	16.2	26.3
174	1.70	22.2	0.070	2.28	1.04	Lost	Not readable			[illegible]	Lost	Lost	0.67	Lost	Lost	10.4	17.0	26.7	8.52	16.2	26.3
175	1.63	23.3	0.070	2.84	1.48	Lost	4.99	1.36	0.56	[illegible]	0.91	No trace	0.87	0.66	Lost	10.4	17.0	26.7	8.31	16.3	26.3
176	1.67	25.3	0.070	3.16	1.56	Lost	5.35	1.40	0.59	0.61	0.77	Lost	0.96	0.59	Lost	10.4	17.0	26.7	8.31	16.3	26.3
177	1.67	25.4	0.071	2.97	1.38	Lost	7.45	1.15	0.54	0.56	Lost	Lost	0.83	Lost	Lost	10.4	17.0	26.7	8.31	16.3	26.3
178	1.64	22.5	0.070	No good	1.28	0.63	4.55	1.31	0.55	No good	0.79	1.40	No good	0.51	0.49	10.4	17.0	26.7	8.31	16.3	26.3
179	1.68	22.5	0.071	No good	1.42	0.66	5.52	1.51	0.52	No good	0.71	0.98	No good	0.49	0.32	10.4	17.0	26.7	8.31	16.3	26.3
180	1.66	22.2	0.071	2.60	1.29	0.57	5.25	1.27	0.53	0.61	0.91	1.28	0.74	0.57	0.36	10.4	17.0	26.7	8.31	16.3	26.3
221	1.68	25.6	0.072	2.63	1.51	0.50	4.81	1.05	0.59	0.47	0.70	1.40	0.62	0.53	0.35	10.4	17.0	26.7	8.31	16.3	26.3
218	1.68	22.5	0.072	2.88	Lost	0.56	4.76	1.50	0.62	0.47	Lost	1.16	0.66	Lost	0.29	10.4	17.0	26.7	8.31	16.3	26.3
Av.	1.68	21.4	0.07	2.88	1.32	0.56	5.67	1.28	0.59				0.78	0.54	0.38	10.4	17.0	26.7	8.42	16.3	26.3
σ	0.05	1.33	0.007	0.34	0.49	0.06	1.03	0.16	0.07				0.12	0.05	0.05						
$\bar{\sigma}$	0.02	0.29	0.002	0.09	0.07	0.02	0.24	0.04	0.02				0.03	0.01	0.02						

Rd. No.	Ambient Pressure psi	Ambient Temp. °C	Charge Weight lbs.	"Tourmaline" Peak Pressure, psi			"Velocity" Peak Pressure, psi			Duration of Positive Phase in milliseconds			Impulse of Positive Phase in lb. millisec/in²			Z for "Tourmaline" measurements			Z for "Velocity" measurements		
				Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
184	1.66	19.7	0.140	5.70	2.12	Lost	Lost	2.18	0.83	Lost	0.57	Lost	Lost	0.57	Lost	8.29	13.5	21.3	6.79	13.1	21.0
185	1.64	20.0	0.139	6.06	Lost	Lost		No record		Lost	Lost	Lost	Lost	Lost	Lost	8.29	13.5	21.3	6.79	13.1	21.0
187	1.57	20.3	0.140	5.28	2.27	Lost		No record		0.33	0.57	Lost	0.87	0.65	Lost	8.29	13.5	21.3	6.79	13.1	21.0
189	1.67	18.1	0.140	6.13	2.21	0.97	8.80	2.38	0.84	0.32	0.58	0.82	0.95	0.60	0.40	8.29	13.5	21.3	6.79	13.1	21.0
190	1.67	20.8	0.142	5.93	*1.54	0.94	9.19	2.26	0.81	0.32	0.59	0.82	0.93	No good	0.39	8.29	13.5	21.3	6.79	13.1	21.0
203	1.68	24.2	0.142	5.32	2.20	0.76	10.99	2.40	0.83	0.34	0.54	0.86	1.04	No good	0.32	8.29	13.5	21.3	6.79	13.1	21.0
206	1.66	21.7	0.140	5.27	2.46	0.78	8.69	2.26	0.88	0.37	0.64	1.10	0.94	0.79	0.43	8.29	13.5	21.3	6.79	13.1	21.0
207	1.65	24.7	0.143	5.25	2.14	0.80		No record		0.35	0.59	0.86	0.92	0.63	0.34	8.29	13.5	21.3	6.79	13.1	21.0
208	1.69	18.6	0.142	5.64	2.80	0.84	10.2	2.34	0.98	0.31	0.69	1.04	0.88	No good	0.42	8.29	13.5	21.3	6.79	13.1	21.0
209	1.67	19.7	0.140	5.66	2.70	0.85	9.61	2.39	0.86	0.31	0.52	1.09	0.78	0.67	0.44	8.29	13.5	21.3	6.79	13.1	21.0
210	1.64	21.1	0.139	4.55	2.34	0.80	7.31	Lost	Lost	0.33	0.58	1.12	0.75	0.68	0.43	8.29	13.5	21.3	6.79	13.1	21.0
211	1.64	20.8	0.142	4.30	2.34	No trace	9.47	Lost	Lost	0.32	0.59	No trace	0.72	0.70	No trace	8.29	13.5	21.3	6.79	13.1	21.0
212	1.67	20.8	0.141	4.63	2.26	0.78	9.03	1.94	0.89	0.37	0.56	1.07	0.83	0.61	0.38	8.29	13.5	21.3	6.79	13.1	21.0
213	1.67	20.6	0.140	4.49	2.38	0.84	10.6	2.21	0.89	[illegible]	0.57	1.08	0.81	0.67	0.44	8.29	13.5	21.3	6.79	13.1	21.0
Av.	1.66	20.8	0.141	5.34	2.36	0.94	9.41	2.26	0.87				0.94	0.66	0.40	8.29	13.5	21.3	6.79	13.1	21.0
σ	0.02	1.81	0.0013	0.55	0.21	0.07	1.04	0.15	0.05				0.12	0.06	0.04						
$\bar{\sigma}$	0.005	0.48	0.0004	0.15	0.06	0.02	0.33	0.05	0.02				0.04	0.02	0.01						
228	0.87	-17.8	0.138	No good	2.77		Lost	1.79	0.71	No good	0.74		No good	1.00		7.12	13.6		7.40	14.1	22.2
229	1.08	-19.4	0.139	6.06	2.15		Lost	1.95	Lost	0.44	0.88		1.34	0.95		7.12	13.6		7.40	14.1	22.2
230	1.08	-21.1	0.139	4.89	1.81		Lost	1.91	Lost	0.52	1.00		1.27	0.90		7.12	13.6		7.40	14.1	22.2
232	0.76	-14.6	0.139	4.20	1.93		Lost	2.16	0.65	0.43	0.88		1.76	0.84		7.12	13.6		7.40	14.1	22.2
227	0.99	-22.2	0.137	4.65	2.16		Lost	1.73	0.79	0.56	0.93		1.30	1.00		7.12	13.6		7.40	14.1	22.2
231	0.99	-17.8	0.139	3.76	2.04		Lost	1.63	Lost	No good	No good		No good	No good		7.12	13.6		7.40	14.1	22.2
237	0.85	-16.1	0.140	5.[illegible]8	1.69		Lost	1.18	Lost	0.51	0.88		1.53	0.74		7.12	13.6		7.40	14.1	22.2
238	1.14	-20.6	0.139	7.37	2.08		Lost	1.65	0.77	0.41	0.98		1.50	1.02		7.12	13.6		7.40	14.1	22.2
233	0.99	-13.9	0.139	No good	3.17		Lost	2.03	Lost	No good	0.89		No good	1.10		7.12	13.6		7.40	14.1	22.2
236	0.85	-16.7	0.140	Lost	Lost		Lost	1.39	0.77	Lost	Lost		Lost	Lost		7.12	13.6		7.40	14.1	22.2
Av.	0.97	-18.0	0.139	5.84	2.19			1.74	0.74				1.45	0.95		7.12	13.6		7.40	14.1	22.2
σ	0.22	2.78	0.0006	1.56	0.46			0.30	0.06				0.18	0.12							
$\bar{\sigma}$	0.07	0.80	0.0002	0.58	0.15			0.09	0.03				0.08	0.04							
269	1.14	-57.8	0.139	9.26	2.40		9.01	1.58	0.72	0.45	1.18		1.80	1.26		7.12	13.6		7.40	14.1	22.2
270	1.14	-58.3	0.140	8.33	2.17		9.30	1.84	0.74	0.44	Lost		1.85	Lost		7.12	13.6		7.40	14.1	22.2
271	1.12	-57.8	0.140	8.70	2.15		9.03	1.74	0.73	0.50	1.09		1.93	1.18		7.12	13.6		7.40	14.1	22.2
268	1.12	-57.2	0.141	8.00	2.21		8.98	2.13	0.77	0.57	1.28		2.42	1.49		7.12	13.6		7.40	14.1	22.2
272	1.01	-57.8	0.140	9.30	2.10			Not readable		0.34	1.26		1.44	1.32		7.12	13.6		7.40	14.1	22.2
273	1.05	-56.1	0.140	9.15	2.52		*11.19	2.05	0.71	0.42	1.07		1.81	1.37		7.12	13.6		7.40	14.1	22.2
Av.	1.10	-57.5	0.140	8.54	2.26		9.08	1.67	0.73				1.88	1.33		7.12	13.6		7.40	14.1	22.2
σ	0.05	0.76	0.0006	0.31	0.16		0.15	0.22	0.02				0.31	0.12							
$\bar{\sigma}$	0.02	0.31	0.0003	0.13	0.06		0.08	0.10	0.01				0.13	0.05							

* Omitted in computation of the mean and standard deviation.

Rd. No.	Ambient Pressure psi	Ambient Temp. °F	Charge Weight lbs.	"Tourmaline" Peak Pressure, psi			"Velocity" Peak Pressure, psi			Duration of Positive Phase in milliseconds			Impulse of Positive Phase in lb. millisec/in²			Z for "Tourmaline" measurements			Z for "Velocity" measurements		
				Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
67	1.69	7.5*	0.260	No good	4.96	1.22	No record			0.46	0.52	No good	1.96	0.96	No good	6.76	11.0	17.4	5.55	10.6	16.8
71	1.70	9.5*	0.260	10.60	5.36	1.55	No record			0.42	0.55		2.23	1.47	No good	6.76	11.0	17.4	5.55	10.6	16.8
74	1.69	13.0*	0.260	14.30	4.30	0.93	No record			0.45	0.71	1.44	No good	1.58	0.67	6.76	11.0	17.4	5.55	10.6	16.8
108	1.75	18.9		No good	3.40	1.14	21.5	3.40	1.23	No good	0.64	1.41	No good	1.09	0.80	6.76	11.0	17.4	5.55	10.6	16.8
131	0.66	21.1	0.264	Lost	Lost	Lost	22.5	3.09	0.83	0.32	Lost	Lost	Lost	Lost	Lost	6.76	11.0	17.4	5.55	10.6	16.8
135	0.61	20.8	0.265	7.65	2.89	0.79	No record			0.41	0.59	1.27	1.57	0.85	0.50	6.76	11.0	17.4	5.55	10.6	16.8
139	1.63	22.2	0.261	8.63	4.05	1.22	18.7	3.57	1.21	0.41	0.72	1.45	1.77	1.46	0.89	6.76	11.0	17.4	5.55	10.6	16.8
146	1.68	19.1	0.262	7.14	3.40	1.44	15.7	3.66	1.55	No good	0.68	1.29	No good	1.16	0.93	6.76	11.0	17.4	5.55	10.6	16.8
147	1.65	19.4	0.260	9.70	3.20	1.23	17.9	3.50	1.55	0.32	0.77	1.27	1.55	1.23	0.78	6.76	11.0	17.4	5.55	10.6	16.8
148	1.65	19.7	0.262	7.68	3.51	1.17	20.2	3.91	1.38	0.33	0.66	1.27	1.27	1.16	0.74	6.76	11.0	17.4	5.55	10.6	16.8
149	1.65	19.4	0.261	10.4	3.20	1.37	16.8	3.32	1.46	0.42	0.74	1.58	2.19	1.18	1.08	6.76	11.0	17.4	5.55	10.6	16.8
127	1.17	21.7	0.263	6.49	2.32	1.04	14.9	3.16	1.22	0.41	0.72	1.32	1.13	0.94	0.67	6.76	11.0	17.4	5.55	10.6	16.8
Av.	1.48	17.7	0.262	8.54	3.69	1.19	18.5	3.45	1.30				1.73	1.18	0.79	6.76	11.0	17.4	5.55	10.6	16.8
σ	0.38	4.90	0.0018	1.55	0.90	0.22	2.72	0.27	0.24				0.37	0.25	0.17						
ε	0.11	1.42	0.0005	0.55	0.27	0.07	0.95	0.10	0.08				0.13	0.08	0.06						
244	0.99	-23.3	0.262	16.0	3.63		15.4	3.09	1.09	0.23	0.60		1.94	1.10		5.81	11.1		5.87	11.2	17.6
245	1.00	-18.9	0.263	13.6	3.74		15.9	3.14	1.11	0.27	0.50		1.90	0.95		5.81	11.1		5.87	11.2	17.6
246	1.14	-16.1	0.262	17.3	No good		Lost	3.38	Lost	0.18	No good		1.98	No good		5.81	11.1		5.87	11.2	17.6
247	1.24	-15.0	0.264	12.8	3.80		24.4	2.85	1.20	0.33	0.48		1.90	0.92		5.81	11.1		5.87	11.2	17.6
248	1.28	-17.8	0.262	13.0	3.00		22.0	2.95	1.20	0.27	0.68		1.80	1.06		5.81	11.1		5.87	11.2	17.6
Av.	1.13	-18.2	0.263	14.5	3.54		19.4	3.08	1.15				1.90	1.02		5.81	11.1		5.87	11.2	17.6
σ	0.13	3.22	0.001	2.04	0.37		4.46	0.20	0.06				0.12	0.08							
ε	0.06	1.44	0.0004	0.93	0.19		2.23	0.07	0.03				0.05	0.04							
254	1.24	-55.0	0.263	16.3	3.70		16.8	2.89	1.09	0.36	1.18		2.65	2.02		5.81	11.1		5.87	11.2	17.6
255	1.14	-56.1	0.263	15.7	4.10		16.5	3.17	1.18	0.28	1.09		2.17	2.21		5.81	11.1		5.87	11.2	17.6
256	1.14	-53.9	0.262	13.6	3.87		17.0	3.53	1.31	0.55	1.05		3.18	1.97		5.81	11.1		5.87	11.2	17.6
257	1.18	-49.4	0.263	13.4	4.04		15.1	3.33	1.11	0.45	0.77		2.75	1.54		5.81	11.1		5.87	11.2	17.6
258	1.14	-58.3	0.263	15.8	3.40		18.4	3.42	1.05	0.36	No good		2.63	No good		5.81	11.1		5.87	11.2	17.6
Av.	1.17	-54.5	0.263	15.0	3.83		16.8	3.27	1.15				2.77	1.94		5.81	11.1		5.87	11.2	17.6
σ	0.44	3.30	0.0005	1.33	0.29		1.20	0.25	0.10				0.66	0.29							
ε	0.20	1.47	0.0002	0.59	0.13		0.54	0.11	0.04				0.30	0.15							

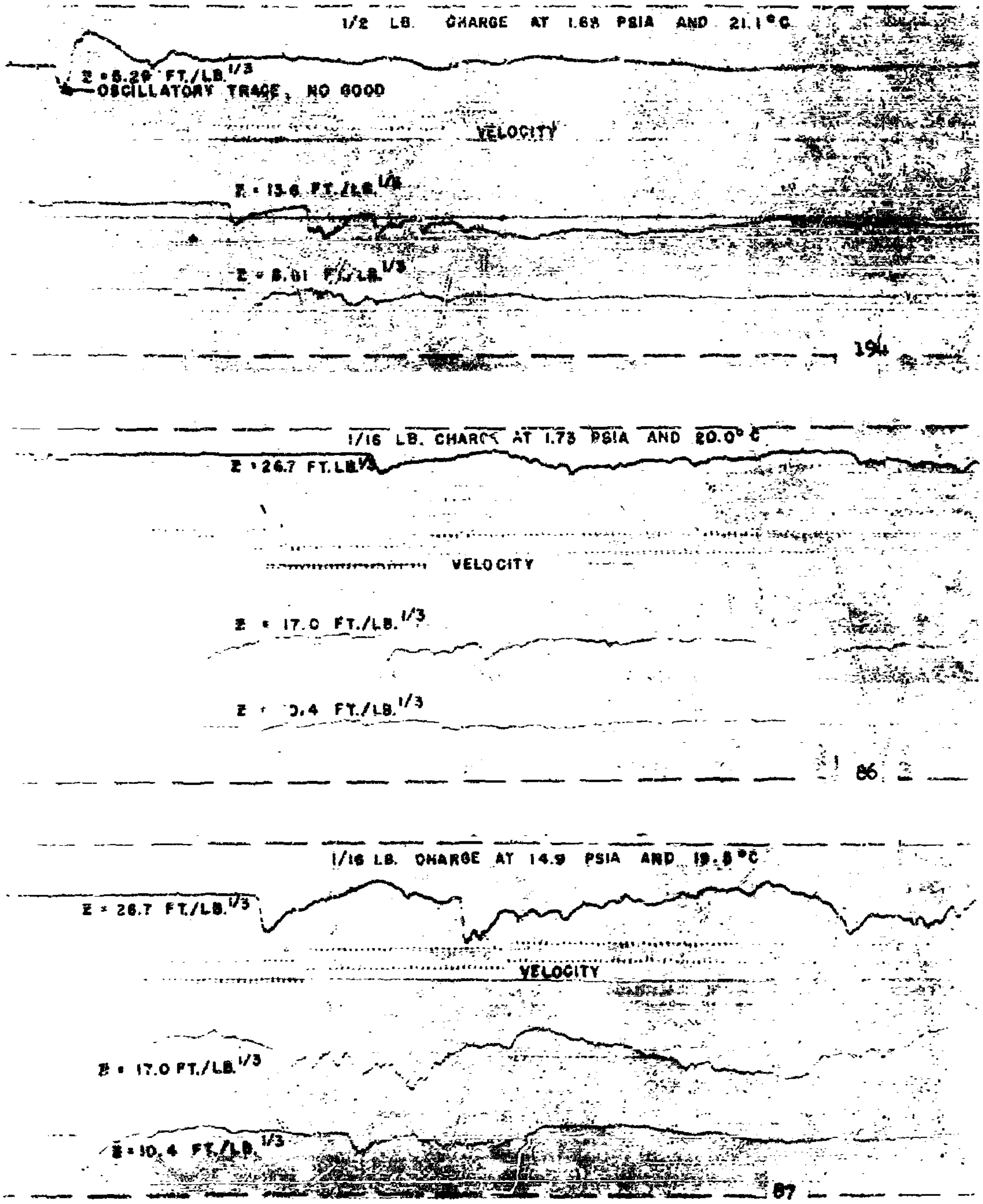
* The low ambient temperatures are due to cooling by expansion. The room temperature gage constant was used on the assumption that the gage would not be greatly cooled during pumping out. For subsequent firings at this low ambient pressure sufficient time was allowed to pass so that the walls of the chamber heated the air to a higher temperature.

Rd. No.	Ambient Pressure psi	Ambient Temp. °C	Charge Weight lbs.	"Tourmaline" Peak Pressure, psi			"Velocity" Peak Pressure, psi			Duration of Positive Phase in milliseconds			Impulse of Positive Phase in lb. millisec/in^2			Z for "Tourmaline" Measurements			Z for "Velocity" Measurements		
				Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
153	1.56	13.9	0.541	No good	No good	No good	35.2	6.94	*4.95	No good	0.77	No good	No good	No good	No good	5.29	8.61	13.6	4.20	8.31	13.5
161	1.69	16.7	0.540	No good	No good	No good	31.0	No good	No good	No good	No good	No good	No good	No good	No good	5.29	8.61	13.6	4.20	8.31	13.5
166	1.69	20.8	0.542	No good	6.33	1.94	31.0	*8.12	2.22	No good	0.58	0.98	No good	1.77	0.98	5.29	8.61	13.6	4.20	8.31	13.5
167	1.66	21.9	0.534	No good	6.02	1.99	30.2	5.94	2.10	No good	0.49	1.02	No good	1.44	0.96	5.29	8.61	13.6	4.20	8.31	13.5
202	1.68	22.3	0.540	No good	6.40	1.66	32.1	6.24	1.97	No good	0.47	1.09	No good	1.48	0.90	5.29	8.61	13.6	4.20	8.3[illegible]	13.5
194	1.68	21.3	0.550	No good	5.85	1.78	28.6	5.91	2.09	No good	0.58	1.07	No good	1.65	0.98	5.29	8.61	13.6	4.20	8.32	13.5
157	1.67	18.6	0.546	No good	5.09	No good	40.2	5.61	2.08	No good	Not readable		No good	Not readable		5.29	8.61	13.6	4.20	8.31	13.5
198	1.63	17.7	0.545	No good	No calibration steps		39.8	6.00	2.22	No good	No Calibration Steps		No good	No Calibration Steps		5.29	8.61	13.6	4.20	8.31	13.5
Av.	1.66	19.2	0.542		5.94	1.84	33.5	6.11	2.11					1.58	0.96	5.29	8.61	13.6	4.20	8.31	13.5
σ	0.04	3.01	0.0048		0.28	0.15	4.42	0.46	0.10					0.15	0.04						
$\bar{\sigma}$	0.016	1.06	0.0017		0.13	0.08	1.57	0.18	0.04					0.08	0.02						

* Omitted in computation of mean and standard deviation.

Notes:

Weights in parentheses are the average weights of similar charges.
"Not readable" and "lost" means that at this position the record was too faint to read or was off scale.
"No good," of a tourmaline record, means that the trace did not have a reasonable form. An example of an oscillatory record is shown in Appendix II. Occasionally rounded shock fronts were recorded. Usually "hash" was the cause of discarding a record as "No good."
"No good," of a velocity record means the position of the break could not be read.
"No record" or "no trace" means that the scope was not recording.



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ABSTRACT:

The side-on excess peak pressures and positive impulses of air shock waves from detonations of spherically shaped explosive charges of 50/50 pentolite were measured under ambient atmospheric pressures and temperatures simulating altitudes up to 50,000 ft. The peak pressures from tourmaline and velocity measurements are plotted as a function of scaled distance for each pressure at which measurements were made. Peak pressures were found to be nearly independent of temperature.

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