NAVY DEPARTMENT
DAVID TAYLOR MODEL BASIN
WASHINGTON, D.C.

DYNAMIC AND STATIC COMPRESSION TESTING OF 3/8-INCH COPPER BALLS

by

D.E. Abkowitz

July 1947

Report R-240

PERSONNEL

The work described was done by D.E. Abkowitz, who also wrote the report. Appreciation is expressed for the helpful suggestions offered by Dr. A. Borden and Dr. M.A. Greenfield under whose general supervision the work was done.

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DYNAMIC AND STATIC COMPRESSION TESTING OF 3/8-INCH COPPER BALLS

ABSTRACT

Copper balls, 3/8 inch in diameter, for use in ball-crusher gages, were calibrated statically and dynamically to investigate the relationship of speed effect to deformation. The falling-weight apparatus used in the dynamic calibrations is described, and the results are shown in energy-deformation curves.

The speed effect ranged from 1.19 to 1.17 when the deformation ranged from 0.03 inch to 0.12 inch. Since the sum of the random errors of the experiment has been calculated to be approximately plus or minus 7 per cent, and since the variation in speed effect is less than that, the speed effect can be assumed constant at about 1.18 for strain rates from 150 per second to 250 per second.

At a given deformation, the energies found for the dynamic and static calibrations of a second lot of balls, obtained from the Underwater Explosives Research Laboratory at Woods Hole, Massachusetts, were 5 per cent higher than those found for the original David Taylor Model Basin lot in the range of energies investigated.

The results of these calibrations are compared with the results of calibrations made by the Underwater Explosives Research Laboratory on their apparatus. With balls of the same lot the calibration on the Underwater Explosives Research Laboratory apparatus was 3 per cent or less higher than the calibration on the Taylor Model Basin apparatus. This difference of 3 per cent is well within the limits of the experimental error of each calibration.

INTRODUCTION

The David Taylor Model Basin was requested orally by the Bureau of Ordnance to calibrate dynamically a quantity of 3/8-inch copper balls by determining the relationship between the energy required to compress the balls and the amount of compression. These copper balls are used in ball-crusher gages (1),* which are mechanical gages for measuring underwater explosion pressures. Calibrations of this kind had been performed by groups elsewhere but a disagreement existed in the results.

The Bureau of Ordnance hoped that an independent investigation at the Taylor Model Basin would bring the results of these other groups into

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* Numbers in parentheses indicate references on page 22 of this report.

line. This report is a description of the experimental method used in the calibration at the Taylor Model Basin as well as a summary and discussion of the results obtained.

In determining the load-deformation relationship for copper balls, a ball is placed between two parallel plates and is deformed by applying a load to the plates. The change in diameter of the ball is measured after the load has been removed and is recorded with the load which produced it. To determine the static load-deformation relationship, the load is applied over a comparatively long period of time, to permit plastic flow to complete itself, whereas for the dynamic relationship, the loading is impulsive.

Static calibrations of copper balls have proved inadequate since the balls are used to measure dynamic loading in crusher gages; therefore it was necessary to develop a method of dynamic calibration. It has been found (2) that the dynamic load necessary to produce a given plastic deformation is greater than the static load necessary to produce the same deformation. In dynamic loading, the stress required to produce a given strain in a material becomes a function of the rate of strain.* As the rates of strain increase from approximately 10^{-3} per second under quasi-static conditions to more than 100 per second under dynamic conditions, the stress required to produce a given strain increases. This effect is known as the "speed effect"** and is appreciable for strain rates greater than 100 per second (2). It is because of this effect that a dynamic calibration of copper balls was necessary for the proper interpretation of records obtained with the crusher gage.

The dynamic calibration of the copper balls has been performed by investigators elsewhere, particularly by the Underwater Explosives Research Laboratory at Woods Hole, Massachusetts, which will sometimes be referred to herein as the UERL (3)(4)(5), and by investigators at the Carnegie Institute of Technology (6)(7)(8)(9)(10). At the Underwater Explosives Research Laboratory, 3/8-inch copper balls were calibrated with a ballistic-pendulum apparatus and with a falling-hammer apparatus (2). Complete agreement between the two methods was obtained. The strain rate used was approximately 200 per second, and the results obtained indicated that for the same energy there is less deformation of the balls at this strain rate than under quasi-static conditions.

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* "Rate of strain" is defined as the change in length per unit length per unit time. In this report the rate of strain is given in inches per inch per second.

** In this report "speed effect" is defined as the ratio of the energy required to deform a ball dynamically to the energy required to give the same deformation statically.

The final report by Winslow and Bessey of the Carnegie Institute (6) gives a summary of the results obtained on both a constant-velocity machine and a nonconstant-velocity falling-body apparatus. Using the constant-velocity machine, rates of strain from 400 per second to 2000 per second were possible. The relatively small amount of data obtained for the balls indicated a speed effect* of approximately 1.22, which was independent of the rate of strain but varied in an erratic way with the amount of the deformation.

The apparatus used to carry out the dynamic calibration at the Taylor Model Basin was of the falling-weight type and is described in this report. Since the rates of strain under which the ball-crusher gages are used range from 200 per second to 2000 per second, it is necessary to have a dynamic calibration which covers this range. The strain rates obtainable with the TMB apparatus ranged only from 150 per second to 250 per second.** Since this range covers only the lower strain rates, it is planned to continue the investigation by the use of an air gun, with which higher strain rates will be obtainable.

TEST APPARATUS

In the falling-weight apparatus for determining the dynamic calibration, a hammer is allowed to drop from a series of heights and to strike a copper ball. The calibration or energy-deformation relationship is given by the plot of the kinetic energy of the hammer against the deformation of the ball. To determine the kinetic energy of the hammer, it is necessary to know its velocity. Since the hammer is guided by a tube, there are frictional losses; therefore it is necessary to measure the velocity of the hammer just before it strikes the copper ball. This is done with electronic instruments and is checked photographically.

The apparatus is depicted and described in Figure 1. The ball held in place on top of an anvil with strips of scotch tape is deformed by being struck by a hammer which falls in a vertical guide tube. Since it is necessary to remove the tube each time a new ball is placed on the stand, the perpendicularity of the tube with respect to the stand is checked before each trial. The diameter of each ball is measured with a screw micrometer before the ball is mounted in place and again after it has been deformed by the falling hammer.

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* In Reference (6) "speed effect" was defined as the "ratio of dynamically applied force F to statically applied force F_0, each of which produces the same set."

** Strain rate is defined as the change in length per unit length per unit time. In this experiment, since the rate of strain is not constant, the time during which the strain occurs was calculated from the average value of the impact velocity during the deformation. The strain rate as defined here is only a first approximation and is the quotient of half the impact velocity and the diameter of the ball.

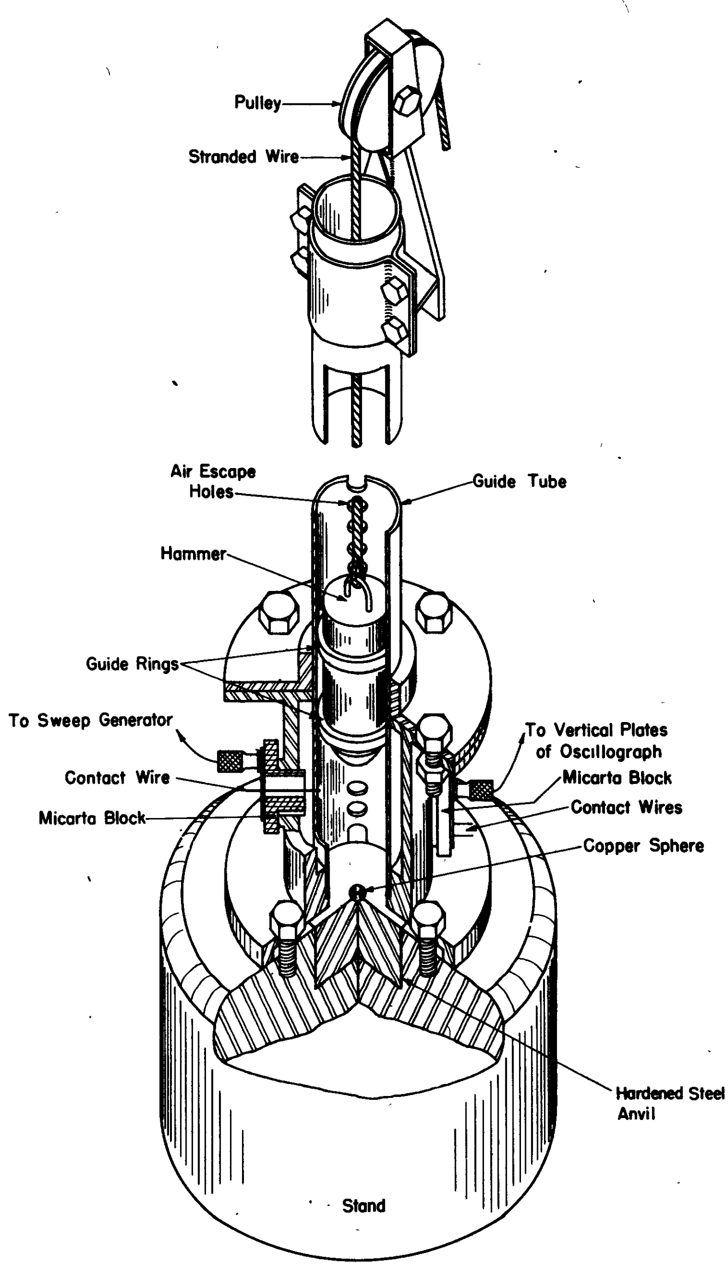

Figure 1 - Diagram of Falling-Weight Calibration Apparatus

The apparatus consists of a heavy stand, a guide tube, and a falling hammer. The stand is made of cast iron and weighs approximately 700 pounds. The copper ball is placed on an anvil of hardened steel which has been force-fitted into the top of the stand. The fit between the anvil and the stand is tight to make sure that none of the energy of the hammer is lost in vibrations. The guide tube is bolted to the stand and is lined up vertically with three leveling screws. The guide tube has perforations to allow the air beneath the falling hammer to escape. The copper ball is held in place on the anvil by three small strips of scotch tape which extend from the side of the ball to the top of the stand.

The hammer shown in this figure was made of a solid piece of tool steel and was hardened to Rockwell C55. The end which strikes the ball is flat over a surface 1/2 inch in diameter and is parallel to the stand to ensure that the ball will be deformed symmetrically. The hammer has two guide rings which fit closely in the tube and guide the hammer in its fall. The hammer is hoisted to the top of the tube by a stranded wire which passes over a pulley fixed at the top of the tube; it is dropped by releasing the wire.

The balls used were of copper, 3/8 inch in diameter, annealed for three hours at 950 degrees fahrenheit in an atmosphere of hydrogen, and then allowed to cool to room temperature.*

Hammers of three different sizes were used, weighing approximately 0.9 pound, 3 pounds, and 5 pounds, in order to obtain different energies.

MEASUREMENT OF HAMMER VELOCITY

The velocity of the hammer is measured electronically about 1.5 inch above the point where it hits the ball, by determining the time required for the hammer to traverse a distance of 0.5 inch. When friction was neglected, it was calculated that the velocity of the hammer at the point of impact was greater than the velocity measured 1.5 inch above by no more than 1 per cent in the range of velocities used.

As the hammer slides down the tube, it completes an electrical circuit used in the velocity measurement. Since it was found necessary to ground the hammer more positively than was possible through its sliding contact with the walls of the tube, the hoist wire was soldered to the hammer and connected to ground externally. The hammer is dropped and the lower guide ring of the hammer hits an electrical contact wire which is placed in the guide tube about two inches above the copper ball; see Figure 1. This completes an electrical circuit which supplies the tripping voltage to a sweep generator as shown in Figure 2. The sweep generator in turn supplies the voltage which produces a single sweep of the electron beam across the screen of the cathode-ray oscillograph. The electrical contact, shown in Figure 1, consists of a piece of 24-gauge wire which is passed through a hole into a cylindrical sleeve. The contact and the sleeve are mounted in a micarta block which fits into a hole in the side of the guide tube. The contact wire protrudes about 1/8 inch from the end of the sleeve into the guide tube and depends upon a fairly snug fit in the cylindrical sleeve to remain horizontal. When the hammer falls, it bends the contact wire and completes the electrical circuit which initiates the sweep. After each trial, it is necessary to remove the micarta block in order to pull fresh wire out and to cut off the bent end.

Another micarta block is located about 0.5 inch below the first one and on the opposite side of the guide tube; see Figure 1. Mounted in this block are a pair of electrical contacts, one 0.50 inch above the other. These contacts, like the one mentioned in the preceding paragraph, consist of sleeves through which copper wires are passed. Electrical contact is made

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* The balls were purchased from the Hartford Steel Company and were annealed at the Washington Naval Gun Factory by following the procedure described.

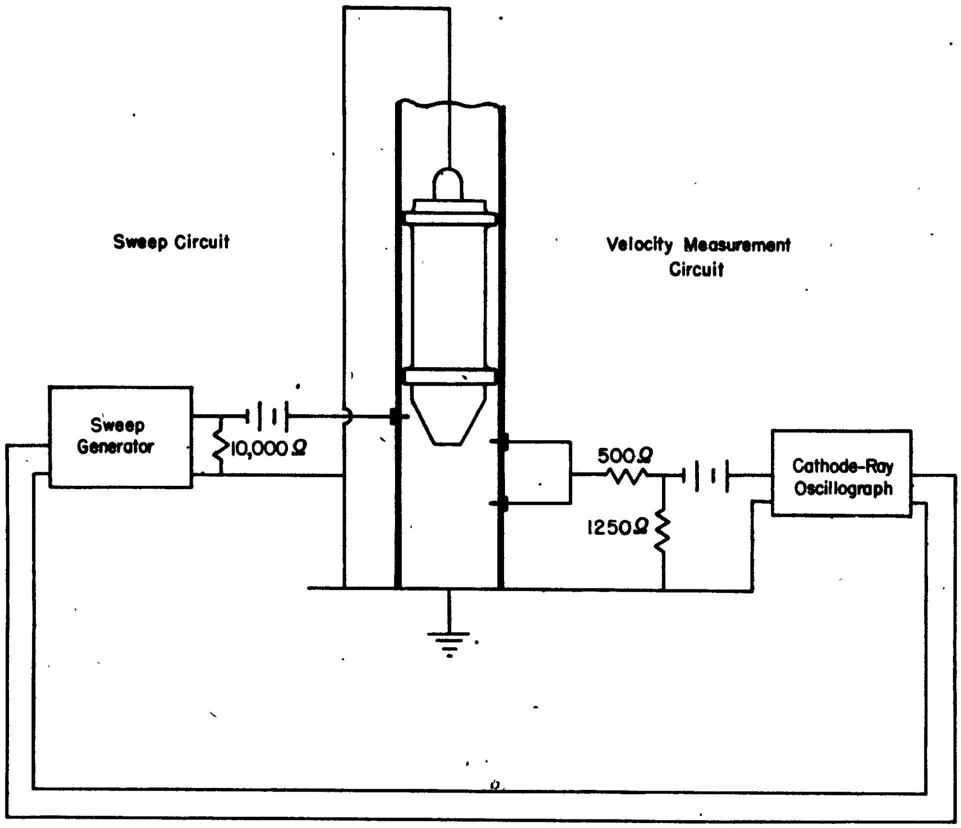

Figure 2 - Circuit Used in Measuring the Velocity of the Falling Hammer

The hammer is dropped and the lower guide ring of the grounded hammer strikes the first electrical contact which protrudes into the guide tube as shown in Figure 1. This completes an electrical circuit which supplies the tripping voltage to the sweep generator. The sweep generator in turn supplies the voltage which produces a single sweep of the electron beam across the screen of the cathode-ray oscillograph.

A pair of electrical contacts are located about 0.5 inch below the first one. These contacts, one 0.50 inch above the other, form part of the electronic circuit for measuring the velocity of the falling hammer. When the lower guide ring of the hammer strikes the first protruding contact of the pair, the resistance is changed in the velocity-measurement circuit and a voltage step is applied to the vertical deflection plates of the cathode-ray oscillograph. The voltage is applied for the length of time that the guide ring touches the electrical contact. Since there are two contacts, the velocity record consists of two such pulses as shown in Figure 3. These voltage pulses are resolved by the single sweep of the electron beam which was initiated by the first electrical contact.

with each wire in turn as the hammer strikes it in its fall. The distance between these protruding wires is adjusted to 0.50 inch and is checked before each trial with a pair of dividers and thus is made accurate to at least 2 per cent. These contacts form part of an electronic circuit for measuring the velocity of the falling hammer. When the lower guide ring of the falling hammer strikes the first protruding contact of the pair, the resistance is changed in the velocity-measurement circuit shown in Figure 2, and a voltage step is applied to the vertical deflection plates of the cathode-ray oscillograph. The voltage is applied for the length of time that the guide ring is in contact with the wire. Since there are two contacts, the velocity record consists of two such pulses as shown in Figure 3. The time between the initial rise in each of these two pulses is equal to the time required by the hammer to traverse the distance between the wire contacts.

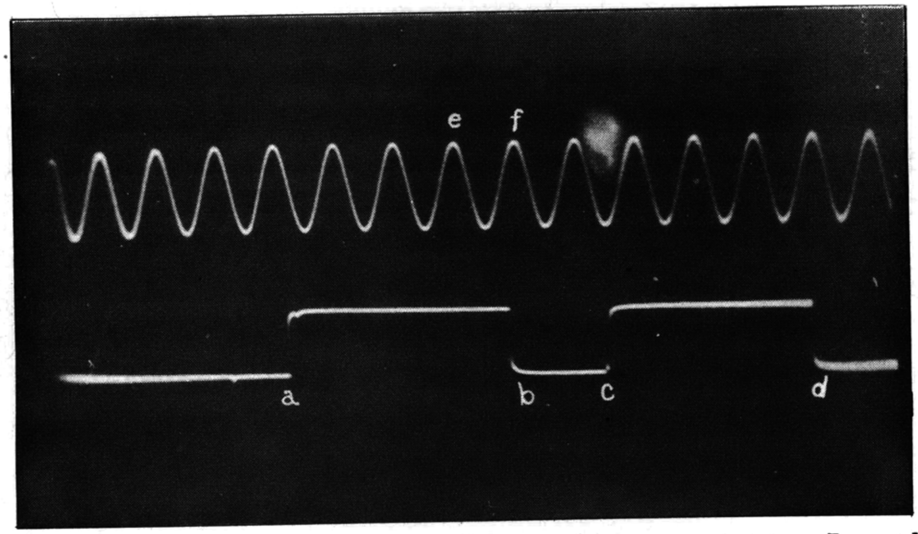

Figure 3 - Positive Enlargement of the Displacement-Time Record and Timing Wave Made by Oscillograph Trace

The record reads from left to right. On this record, *a* represents the time when the guide ring of the hammer strikes the first protruding contact and the voltage step is applied to the vertical plates of the oscillograph. The voltage is applied for the length of time that the guide ring is in contact with the wire, from *a* to *b*. Also, the distance from *c* to *d* represents the time of contact of the guide ring with the second protruding contact. The distance from *a* to *c* then represents the time for the hammer to fall 0.5 inch. The distance from *e* to *f* represents one cycle on the timing wave and is equivalent to 0.0005 second.

These voltage pulses are resolved by the single sweep of the electron beam which was initiated by the first electrical contact. The trace which is produced on the oscillograph screen is photographed on Super XX film with a Kodak Ektra camera using an f/1.9 lens. The camera is mounted at the end of a light-tight box about 1.5 foot from the oscillograph screen. The time scale for computing the velocity is furnished by a 2-kilocycle sine wave from a Boonton beat-frequency generator. The sine wave was obtained with a single sweep of the electronic beam at the same sweep speed as that used for the velocity record. The timing wave was photographed on the same frame as the velocity record. The beam was displaced vertically so that the two records would not overlap.

A typical oscillograph record is shown in Figure 3. The velocity of the hammer is obtained from the oscillograph record in the following way. Let X represent the time in seconds between the two pulses, or the time required for the hammer to traverse the distance between the two velocity contacts.

Then

$$X = \frac{0.0005\,ac}{ef} \text{ seconds}$$

Since the contacts are 0.50 inch apart, the velocity v of the hammer is

$$v = \frac{0.50}{X} \text{ inches per second}$$

The distances from a to c and between six peaks on the timing wave or approximately six times e to f shown in Figure 3 were measured from the film negative with the aid of a Gaertner traveling microscope. The portion of the timing wave measured was that which was on the same portion of the oscillograph screen as the velocity record. The film negative, which was held in a frame under the microscope by clips, could be aligned by proper manipulation of the adjusting screws. The frame with the film could be rotated about a vertical axis and could be moved transversely in two mutually perpendicular directions in the plane of the film. The zero line on the film, which is in line with points a and c, was aligned with the horizontal cross-hair in the eyepiece of the microscope, and the microscope was then made to travel along the zero line of the film. The distance traveled was measured by a vernier which could be read accurately to four significant figures. A reading of the vernier was taken when the vertical hair of the microscope reached point a of Figure 3 and then again at point c. Since the distance traveled represents a difference between two readings on the vernier, the distance was obtained to only three significant figures.

The distance between six peaks of the sine wave was measured by the method just described, and the mean of three readings was used in the final calculations. This mean reading was then divided by six to obtain the distance between two peaks. The readings of the sine wave agreed with one another and with the average to within plus or minus 0.2 per cent each time. The maximum variation obtained between any readings of the same velocity record was greater, however, because of the difficulty of aligning the zero line. Three readings of each velocity record were made and the mean value, agreeing with each of the readings to plus or minus 0.8 per cent, was used for the final calculations. The total error associated with the measurement of the velocity record then is plus or minus 1 per cent. Since the velocity is squared in the energy calculation, the error in terms of energy is plus or minus 2 per cent.

Velocities ranging from 110 inches per second to 190 inches per second were obtained by dropping the hammer from different heights in the guide tube.

CHECK OF HAMMER VELOCITY

To check the accuracy of the velocity obtained with the electronic circuit, an entirely different method of measuring the velocity of the hammer was used. The fall of the hammer was photographed with a General Radio camera provided with a Zeiss f/1.5 lens, set up to operate as a "streak" camera. This camera, which was originally designed as a cathode-ray oscillograph recorder, can run 100 feet of film through at a velocity of 600 inches per second. A timing spark, controlled by a Strobotac, makes small spots on the edge of the film at intervals of 1/60 second.

To determine the velocity of fall photographically, a slit 1 inch long and approximately 1/8 inch wide was made in the bottom of the guide tube at the same level as the contacts used in the method previously described. The hammer was painted black with a thin white line drawn around it about 1/2 inch from the bottom. When the hammer fell, a small white spot appeared to move down the opening. Since the film moved across the slit at a known rate

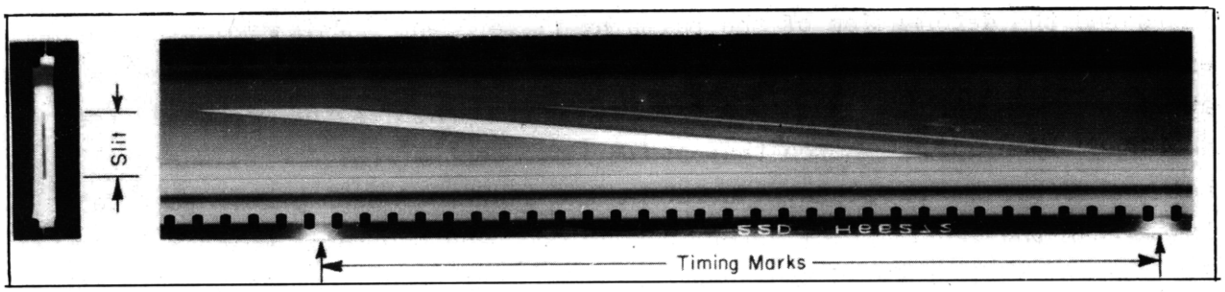

Figure 4 - Streak Displacement-Time Picture of Hammer and Slit of Known Height

The wide white band on the displacement-time record was made when the lower guide ring of the hammer passed by the slit, and could be used in the velocity measurement. It is more convenient, however, to use the thin white line above it which was produced by the white spot passing the slit opening. Two timing marks can be seen on the edge of the film.

in a direction perpendicular to the fall of the hammer, the velocity of the hammer could be calculated from the slope of the line on the film, which actually represents a displacement-time plot of the motion of the hammer. A typical record is shown in Figure 4. A still photograph of the slit made at the beginning of the run furnished the vertical scale for computing the distance, while the timing spark provided the horizontal scale for computing the time.

When both methods for measuring the velocity were used simultaneously, the results agreed within approximately 2 per cent each time. Since this is well within the accuracy of the photographic method, the velocity as obtained from the electronic measurement is assumed correct.

DISCUSSION OF ENERGY LOSSES

In the earlier measurements it was suspected that all the energy in the falling hammer was not going into the deformation of the copper ball. An investigation of some of the sources of energy loss in the apparatus was therefore made. These included vibrational losses in the apparatus and hammer, loss of energy to the stand due to its finite mass, and loss of energy due to the rebound of the hammer.

INERTIAL LOSS IN STAND

The first stand used, which was later discarded, consisted of a piece of pipe with a flat plate of steel welded to the top; the total weight was about 50 pounds. Comparison of the results obtained on this stand with those obtained by other investigators indicated that considerable energy was being lost. To investigate energy losses in this stand due to its low inertia, the hollow steel pipe was filled with cement, which increased its weight to 100 pounds. For a given energy in the falling hammer, this added weight increased the deformation of the balls by 11 per cent. This indicated that energy was being transferred from the hammer to the stand by imparting an appreciable velocity to the stand. Although the mass of the stand had been doubled, calculations showed that about 5 per cent of the energy was still being absorbed by the stand. To reduce the amount of energy lost to a value lower than the experimental error, a heavier stand was built which weighed 700 pounds. This reduced the energy loss to less than 1 per cent. All measurements presented in this report were made on this heavy stand, which is described earlier in this report.

VIBRATION OF THE HAMMER

Since the hammer is set into vibration by its impact with the copper ball, it was necessary to find the energy that was lost in causing this vibration. To do this an SR-4 strain gage was cemented to the side of the hammer near its bottom. This gage was then connected in series to a dummy gage and a battery and was connected in parallel with the vertical amplifier of the oscillograph, as shown in Figure 5. Since the strain gage responded to the strains in the hammer by a change in its resistance, this resistance change was in turn recorded on the oscillograph screen as a change in voltage. A single sweep of the oscillograph beam was initiated by the same method as was used in measuring the hammer velocity, and the records were photographed with a Kodak Ektra camera as before. Eight records were obtained, and the maximum strains were computed from each one. The energy required to produce

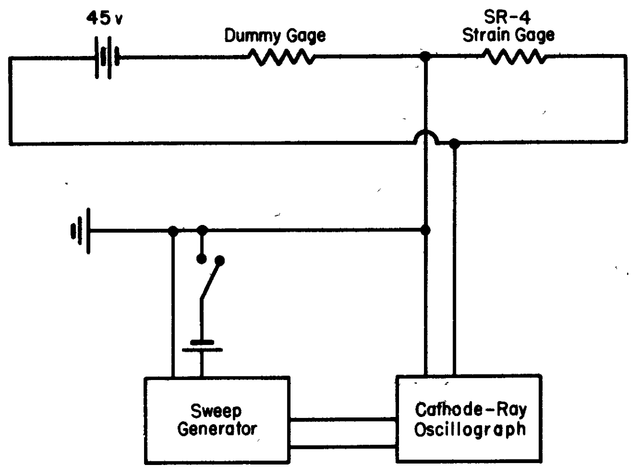

Figure 5 - Strain-Gage Setup for Measuring the Energy in the Vibrations of the Hammer

When the lower guide ring of the hammer touches the electrical sweep contact, the switch is closed and a single sweep of the beam across the oscillograph screen is initiated. The strain gage responds to the strains in the hammer by a change in resistance and this resistance change is in turn recorded on the oscillograph screen as a change in voltage.

the worst possible condition, in which the whole hammer was uniformly stressed at the same time, was calculated from these strains and was found to be less than 1 per cent of the total energy.

EFFECT OF MOUNTING BALLS IN BALL-CRUSHER GAGES

In a special set of experiments, in order to simulate test conditions as closely as possible in the calibration, the copper balls were mounted in a ball-crusher gage, one type of which is shown in Reference (1), which in turn was screwed to the top of the stand. The falling hammer applied the load to the hammer plug in the gage. It was found that the balls deformed asymmetrically owing to the cocking of the hammer plug and to the use of the rubber washer in positioning the ball. In an attempt to correct for this the dimensions of the hammer plug and the gage top were altered so that the plug would have more guided length. The top of the hammer plug was made slightly convex to ensure central contact between the plug and the flat-bottomed hammer. As the use of the rubber washer was found to give a further scatter of experimental points on the plot of energy against deformation, the balls were positioned with three pieces of scotch tape instead of the washer.

When the gage thus altered was used, the results plotted on an energy-deformation curve showed a large scatter of experimental points. The curve drawn through these points was also shifted in a direction which indicated an average loss of approximately 2 per cent of the hammer's energy. Therefore, it was decided to do away with the gage as a mount since it was introducing other variables.

REBOUND OF HAMMER

Since energy was also being lost in the rebound of the hammer, it was necessary to find the magnitude of the bounce and to correct for it. The bounce of the hammer was photographed with the General Radio streak camera at the same time as the photographic check on the velocity of the hammer was made. The same method was used but with the spot located farther up on the hammer so that the path of the spot in the vertical direction during the bounce could be completely observed. A diagram representing a typical record of the bounce

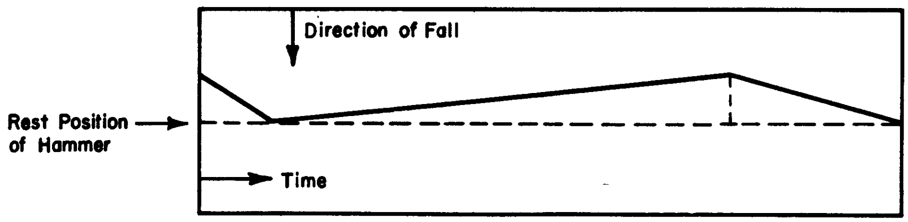

Figure 6 - Diagrammatic Streak Record of Bounce of Hammer

The vertical broken line represents the height of bounce. The vertical scale for computing this height was obtained by photographing a slit of known length such as the one shown in Figure 5. The actual bounce photograph was too long to be included here.

is shown in Figure 6. The height of the bounce is obtained by measuring from the lowest point on the record, which corresponds to the lowest position of the hammer, to the highest point on the record. The vertical scale is again obtained from a still picture of the slit which is of a known length.

The results indicated that 3 per cent of the energy of the 0.9-pound hammer was lost in the bounce, 2 per cent for the 3-pound hammer, and 3.5 per cent for the 5-pound hammer. All these values were independent of the velocities used.

All the points on the energy-deformation curve presented later in this report have been corrected for the bounce. The total energy that would go into deforming the balls, correcting for the bounce, is obtained from the equation

$$\text{Energy} = \frac{1}{2}M(V^2 - 2gB) \qquad [1]$$

where M is the mass of the hammer,

V is the velocity of the hammer,

g is the acceleration due to gravity, and

B is the height of bounce of the hammer.

There was some question as to whether the true bounce had been determined because the frictional forces inside the tube may have decreased the upward distance traveled by the hammer. A hammer was weighed with a spring balance and, still suspended from the balance, was allowed to accelerate slowly up and down the tube. The difference in weight of the 5-pound hammer due to the opposing frictional force was found in this manner to be approximately 0.1 pound. Even if a large error was made in the determination, this effect would be negligible in the final calculation of the bounce.

STATIC CALIBRATION

A static calibration of the 3/8-inch copper balls was carried out with a 30,000-pound Southwark-Emery testing machine in the range from 50 pounds to 3400 pounds. The error of the machine as obtained from a recent proving-ring calibration was 0.2 per cent. The amount of the compressive load applied was indicated in pounds on a dial which could be read accurately to the nearest pound, and therefore the maximum error, which occurred at the lower loads, was plus or minus 1 per cent. The load was completely released after each compression.

The balls were mounted with three pieces of scotch tape which extended from the side of the ball to the top of a hardened piece of steel placed on the table of the machine. The original and the final diameters of the balls were measured with a screw micrometer.

Two methods were used in this calibration. In the first a different ball was used for each load, whereas in the second successive loads were applied to the same ball and the deformation was measured after each load application. Since it was found that the second method gave results that were comparable to the first, the second method was used with two loads applied to each ball.

Approximately 75 balls were used in this calibration with a strain rate of approximately 10^{-3} per second. The results were plotted as load on a basis of deformation, and the best curve was drawn through the points. The curve was then integrated with an integraph to obtain energy as a function of deformation.

RESULTS

The results obtained in the dynamic and static calibrations are shown on the energy-deformation plot of Figure 7. The energy in the dynamic calibration curve is the kinetic energy of the hammer obtained by multiplying the square of the velocity of the hammer by half its mass. All points on the dynamic curve were corrected for the bounce of the hammer, which amounted to approximately two per cent or three per cent, depending upon the weight of the hammer used. The range in energy for the dynamic curve was obtained by varying the height from which the hammer was dropped and by using hammers of different weights.

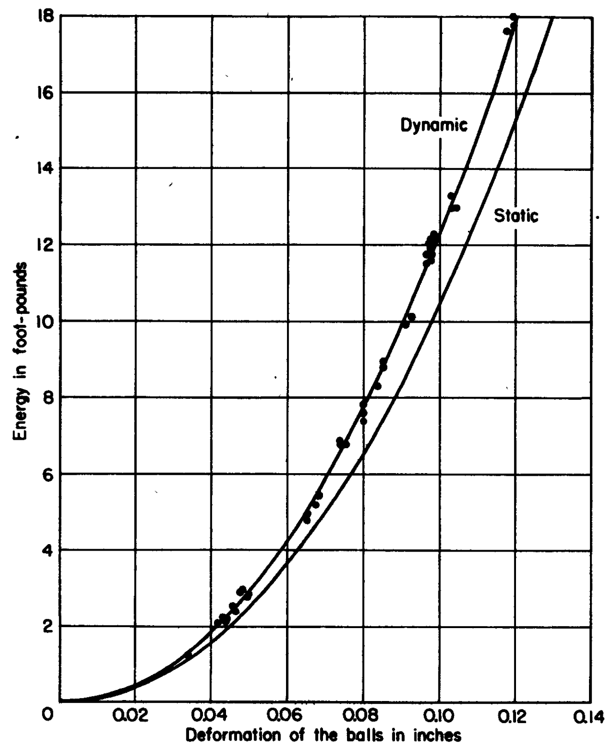

Figure 7 - Comparison of Static and Dynamic Curves for TMB 3/8-Inch Copper Balls of Lot 9/13/44

The curves drawn were obtained from the experimental data by the method of least squares. The equation of the curve for the dynamic calibration obtained by this method is

$$Y_D = 0.1070\ (10^2\ X)^{2.061} \qquad [2]$$

where Y_D is the energy in foot-pounds required to deform the ball X inch. The equation of the curve for the static calibration is

$$Y_S = 0.0883\ (10^2\ X)^{2.074} \qquad [3]$$

where Y_S is the energy in foot-pounds required to deform the ball X inch. The dynamic calibration curve was based on about fifty data points, while the static calibration curve was based on about one hundred data points.

Data for the dynamic and static calibrations are recorded in Tables 1 and 2 respectively. The average deviation of the data points from the least-square curve for the dynamic calibration is plus or minus 0.179, whereas the standard deviation is 0.218. The average deviation of the data points from the least-square curve for the static calibration is plus or minus 0.0391, whereas the standard deviation is 0.0524. These static-data points were obtained from the integrated load-deformation curve, as explained in the section "Static Calibration."

TABLE 1

Complete Data for the Dynamic-Calibration Curve and the Evaluation of Deviation from the Least-Square Curve

Deformation *X* inches	Energy *Y* (Least Square) ft-lb	Energy *Y* (Data) ft-lb	Deviation	Deviation^2	Percentage Deviation
0.0335	1.292	1.366	-0.074	+0.0055	-5.73
0.0412	1.978	2.070	-0.092	+0.0085	-4.65
0.0427	2.130	2.209	-0.079	+0.0062	-3.71
0.0441	2.276	2.147	+0.129	+0.0166	+5.67
0.0452	2.394	2.488	-0.094	+0.0088	-3.93
0.0454	2.417	2.384	+0.033	+0.0011	+1.37
0.0463	2.517	2.337	+0.180	+0.0324	+7.15
0.0466	2.550	2.513	+0.037	+0.0014	+1.45
0.0476	2.664	2.893	-0.229	+0.0524	-8.60
0.0480	2.710	2.956	-0.246	+0.0605	-9.08
0.0494	2.875	2.727	+0.148	+0.0219	+5.15
0.0499	2.936	2.811	+0.125	+0.0156	+4.26
0.0507	3.034	3.026	+0.008	+0.0001	+0.26
0.0651	5.079	4.742	+0.337	+0.1136	+6.45
0.0653	5.111	5.037	+0.074	+0.0055	+1.45
0.0655	5.142	4.910	+0.232	+0.0538	+4.51
0.0670	5.389	5.170	+0.219	+0.0480	+4.06
0.0679	5.540	5.455	+0.085	+0.0072	+1.53
0.0737	6.560	6.820	-0.260	+0.0676	-3.96
0.0738	6.578	6.735	-0.157	+0.0246	-2.39
0.0751	6.816	6.754	+0.062	+0.0038	+0.91
0.0760	6.987	6.906	+0.081	+0.0066	+1.15
0.0798	7.727	7.398	+0.329	+0.1082	+4.26
0.0799	7.745	7.797	-0.052	+0.0027	-0.67
0.0800	7.766	7.562	+0.204	+0.0416	+2.63
0.0835	8.842	8.269	+0.213	+0.0454	+2.51
0.0851	8.819	8.950	-0.131	+0.0172	-1.49
0.0852	8.841	8.779	+0.062	+0.0038	+0.70
0.0912	10.17	9.940	+0.230	+0.0053	+0.80
0.0925	10.47	10.12	+0.350	+0.1225	+3.34
0.0930	10.59	10.57	+0.020	+0.0004	+0.19
0.0963	11.38	11.45	-0.070	+0.0049	-0.62
0.0964	11.41	11.70	-0.290	+0.0841	-2.54
0.0969	11.53	11.56	-0.030	+0.0009	-0.26
0.0973	11.63	11.87	-0.240	+0.0576	-2.06
0.0976	11.70	11.53	+0.170	+0.0289	+1.45
0.0976	11.70	11.87	-0.170	+0.0289	-1.45
0.0977	11.73	12.01	-0.280	+0.0784	-2.39
0.0978	11.75	12.10	-0.350	+0.1225	-2.98
0.0980	11.80	12.23	-0.430	+0.1849	-3.64
0.0981	11.83	12.08	-0.250	+0.0625	-2.11
0.0988	12.00	12.08	-0.080	+0.0064	-0.67
0.1032	13.13	12.92	+0.210	+0.0441	+1.60
0.1040	13.33	12.92	+0.410	+0.1681	+3.08
0.1172	17.06	17.57	-0.510	+0.2601	-2.99
0.1173	17.09	17.10	-0.010	+0.0001	-0.06
0.1189	17.58	17.75	-0.170	+0.0289	-0.97
0.1190	17.61	17.65	-0.040	+0.0016	-0.23
0.1191	17.63	18.13	-0.500	+0.2500	-2.84

Average Deviation ± 0.179

Standard Deviation 0.218

Average Percentage Deviation ± 2.77

TABLE 2

Complete Data for the Static-Calibration Curve and the Evaluation of Deviations from the Least-Square Curve

Deformation *X* inches	Energy *Y* (Least Square) ft-lb	Energy *Y* (Data) ft-lb	Deviation	Deviation^2	Percentage Deviation
0.0330	1.050	1.042	+0.008	+0.000064	+0.76
0.0358	1.243	1.250	-0.007	+0.000049	-0.56
0.0385	1.446	1.458	-0.012	+0.000144	-0.83
0.0410	1.647	1.667	-0.020	+0.000400	-1.21
0.0434	1.853	1.875	-0.022	+0.000484	-1.19
0.0457	2.063	2.083	-0.020	+0.000400	-0.97
0.0503	2.517	2.500	+0.017	+0.000289	+0.68
0.0542	2.938	2.917	+0.021	+0.000441	+0.71
0.0577	3.345	3.333	+0.012	+0.000144	+0.36
0.0613	3.792	3.750	+0.042	+0.001764	+1.11
0.0642	4.174	4.167	+0.007	+0.000049	+0.17
0.0671	4.574	4.583	-0.009	+0.000081	-0.20
0.0701	5.008	5.000	+0.008	+0.000064	+0.16
0.0730	5.448	5.417	+0.031	+0.000961	+0.57
0.0756	5.857	5.833	+0.024	+0.000576	+0.41
0.0783	6.300	6.250	+0.050	+0.002500	+0.79
0.0807	6.707	6.667	+0.040	+0.001600	+0.60
0.0831	7.127	7.083	+0.044	+0.001936	+0.62
0.0855	7.560	7.500	+0.060	+0.003600	+0.79
0.0876	7.951	7.917	+0.034	+0.001156	+0.43
0.0898	8.370	8.333	+0.037	+0.001369	+0.44
0.0919	8.780	8.750	+0.030	+0.000900	+0.34
0.0940	9.202	9.167	+0.035	+0.001225	+0.38
0.0960	9.612	9.583	+0.029	+0.000841	+0.30
0.0979	10.012	10.000	+0.012	+0.000144	+0.12
0.1015	10.790	10.833	-0.043	+0.001849	-0.40
0.1052	11.623	11.667	-0.044	+0.001936	-0.38
0.1085	12.391	12.500	-0.109	+0.011881	-0.88
0.1122	13.283	13.333	-0.050	+0.002500	-0.38
0.1156	14.129	14.167	-0.038	+0.001444	-0.27
0.1187	14.928	15.000	-0.072	+0.005184	-0.48
0.1216	15.693	15.833	-0.140	+0.019600	-0.89
0.1246	16.508	16.667	-0.159	+0.025281	-0.96

Average Deviation	± 0.0391
Standard Deviation	0.0524
Average Percentage Deviation	± 0.586

The speed effect, defined in this report as the ratio of the energy Y_D required to deform a ball dynamically to the energy Y_S required to produce the same deformation statically, is from Equations [2] and [3]

$$\frac{Y_D}{Y_S} = \frac{1.211}{(10^2 X)^{0.013}} \qquad [4]$$

Thus it may be computed from this empirical equation that the speed effect ranges from 1.19 to 1.17 when the deformation ranges from 0.03 inch to 0.12 inch in the range of strain rates used in this experiment. Since this is within the random errors of the experiment (see "Evaluation of Errors in the Dynamic Calibration"), the speed effect can be assumed to be constant in the range of strain rates used.

No evidence was found to substantiate the results obtained by the Carnegie investigators indicating that the speed effect varied in an erratic way with the amount of deformation at a given strain rate. No definite conclusions can be drawn about the dependency of speed effect on strain rate in the Taylor Model Basin calibration since the strain rates investigated ranged only from 150 per second to 250 per second.

A comparison was made between the dynamic calibrations results obtained at the Taylor Model Basin with those obtained at the Underwater Explosives Research Laboratory. The essential difference between the two dynamic calibrations is the methods used, and therefore it was necessary to keep everything else constant. An exchange of balls was made between the two laboratories* since the balls used by the two different groups were not from the same lot and may therefore have been annealed differently. The Taylor Model Basin balls were then calibrated on the UERL apparatus, and the UERL balls on the Taylor Model Basin apparatus.

The energy absorbed by the UERL balls at a given deformation, as determined at the Taylor Model Basin was 3 per cent or less higher than that for the UERL balls at the Underwater Explosives Research Laboratory in the range of energy investigated, 3 foot-pounds to 13 foot-pounds. Also, the calibration of the TMB balls at the Taylor Model Basin and at the Underwater Explosives Research Laboratory agreed to 3 per cent or less in the range of energy investigated, 1 foot-pound to 16 foot-pounds. The results of these comparisons are plotted in Figure 8. This is probably as close agreement as

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* This exchange was made possible through the cooperation of Mr. P. Newmark of the Underwater Explosives Research Laboratory.

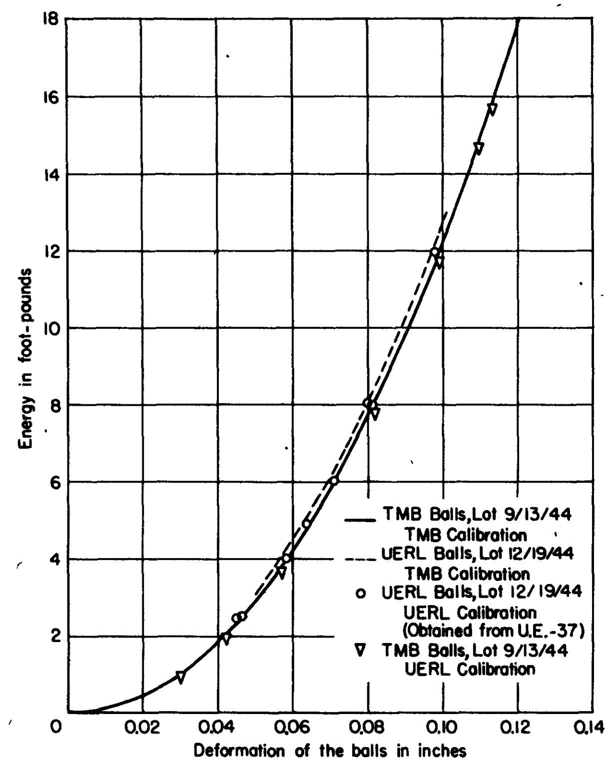

Figure 8 - Comparison of the Dynamic Calibration of UERL Balls at the Taylor Model Basin and at Underwater Explosives Research Laboratory and Also the Dynamic Calibration of TMB Balls at the Two Laboratories

can be expected between these two different experimental setups since the fluctuations are well within the limit of the experimental error of each calibration.

However, these results showed inherent differences between the two groups of balls. The experimental results as obtained for the two groups of balls on the TMB dynamic and static apparatus are compared in Figure 9. The curves for the UERL balls are less accurate since they are based on a very few points. On the basis of these results, the energies necessary to deform the UERL balls were as much as 5 per cent higher than the energies necessary to deform the TMB balls in the range of energies investigated, 3 foot-pounds to 12.5 foot-pounds. The final results plotted in Figure 7 of this report are not directly comparable to the results obtained by any other laboratory, since it was found that the calibrations or energy-deformation plots for two different groups of balls were not the same.

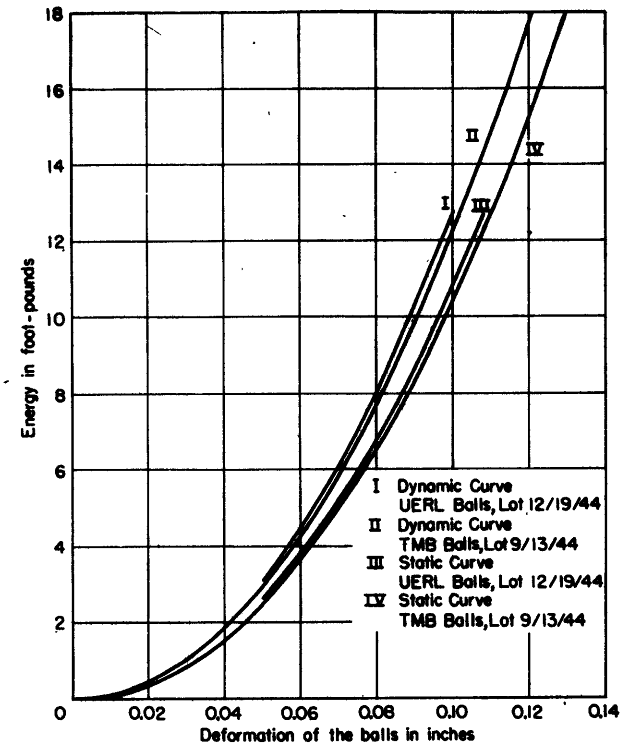

Figure 9 - Comparison of the Calibration of TMB and UERL Balls on the TMB Dynamic and Static Apparatus

EVALUATION OF ERRORS IN THE DYNAMIC CALIBRATION

SYSTEMATIC ERRORS

The systematic errors have already been discussed in previous sections and will simply be reviewed here. The error in the hammer-velocity measurement, discussed on page 5, due to measuring the velocity of the hammer 1.5 inch above the ball, is no more than 1 per cent. Since the velocity is squared in the energy calculation, the error in energy would be no more than 2 per cent. This error is considered a positive error since more energy is available in the calibration than is accounted for, while negative errors would be associated with a loss of energy.

Negative errors are introduced by the 1 per cent loss of energy due to the finite weight of the stand, which is discussed on page 10, and by the less than 1 per cent loss of energy due to stress in the hammer, discussed on page 10. These systematic errors are listed in Table 3 with an estimate of the percentage error they introduce in the energy calculation. In totaling the systematic errors, the positive and negative errors more or less cancel each other.

TABLE 3

Summary of Estimated Systematic Errors

Error	Magnitude of Error Affecting Energy Calculation per cent
Hammer-velocity measurement	plus 2 or less
Loss of energy to stand	minus 1 or less
Loss of energy in vibration of hammer	minus 1 or less
Total	plus or minus 2 or less

RANDOM ERRORS

Several measurements with the screw micrometer were necessary on the original diameter *O* of each ball, shown in Figure 10, to average out variations in the diameter. It was found that the measurements differed from each other by less than 0.3 per cent. An average diameter was used for the original diameter of the ball and this reading agreed with the individual readings to plus or minus 0.2 per cent. Table 4 shows measurements on five typical balls.

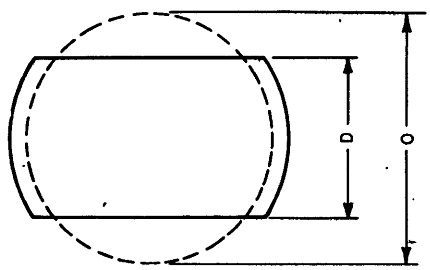

Figure 10 - Ball Showing Original Diameter *O* and Deformed Diameter *D*

The deformed diameter of the ball, *D* in Figure 10, is also measured at different points across the flats and the average is taken. It was found that the individual readings differed from the mean by no more than plus or minus 0.75 per cent. Therefore the total error associated with the deformation of the balls is at the most plus or minus 0.95 per cent.

The error associated with the spacing of the electrical contacts, which is discussed on page 6, is no more than plus or minus 2 per cent in the velocity measurement or plus or minus 4 per cent in the energy calculation.

The error associated with the measurement of the velocity record, discussed on page 8, is plus or minus 1.0 per cent in the velocity measurement or plus or minus 2.0 per cent in the energy calculation. The various random errors are listed in Table 5.

The scatter of the experimental points seen in Figure 7 was compared with the random errors. The average deviation of any of the data points from the least-square curve, plus or minus 2.77 per cent as shown in Table 1, was within the experimental errors of the calibration.

TABLE 4

Measurements of the Original Diameters of Five Balls

	Ball Diameter, inches				
	1	2	3	4	5
Measurements on ten different diameters	0.3759 0.3761 0.3758 0.3758 0.3752 0.3756 0.3761 0.3757 0.3760 0.3759	0.3765 0.3763 0.3761 0.3758 0.3759 0.3762 0.3761 0.3759 0.3768 0.3762	0.3762 0.3766 0.3762 0.3761 0.3759 0.3760 0.3758 0.3762 0.3762 0.3760	0.3759 0.3763 0.3762 0.3761 0.3759 0.3760 0.3761 0.3761 0.3762 0.3759	0.3762 0.3759 0.3758 0.3761 0.3758 0.3758 0.3757 0.3758 0.3756 0.3759
Average	0.3758	0.3762	0.3761	0.3761	0.3759

TABLE 5

Summary of Estimated Random Errors

Error	Magnitude of Error Affecting Energy Calculation per cent
Spacing of electrical contacts	plus or minus 4
Deformation of balls	plus or minus 0.95
Measurement of velocity record with microscope	plus or minus 2
Total	plus or minus 6.95

CONCLUSIONS

The static and dynamic calibrations of 3/8-inch copper balls when compared on an energy-deformation plot differed from each other by about 18 per cent when the deformation ranged from 0.03 inch to 0.12 inch and the strain rates were 10^{-3} per second for the static calibration and 150 per second to 250 per second for the dynamic calibration.

No evidence was found to substantiate the Carnegie investigators' results indicating an erratic dependency of speed effect on the amount of deformation at a given strain rate.

More work is necessary to investigate the effect of higher rates of strain on the speed effect.

The calibration results obtained with the TMB lot of balls differed from the results obtained with the UERL lot of balls by approximately 5 per cent; the UERL balls absorbed more energy for given deformations.

When balls from the same lot were used, the results obtained for the dynamic calibration at the Underwater Explosives Research Laboratory agreed with the results obtained at the Taylor Model Basin within approximately 3 per cent. The balls absorbed more energy in the TMB apparatus.

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