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C-682

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AFSWP 826

NAVY DEPARTMENT

THE DAVID W. TAYLOR MODEL BASIN

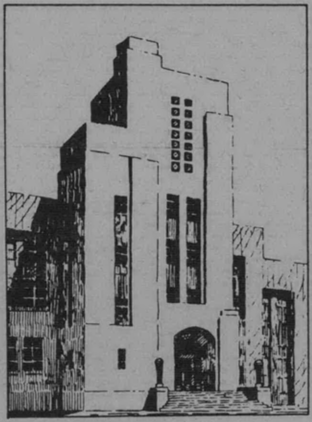
WASHINGTON 7, D.C.

MEASUREMENTS OF PEAK PRESSURE FROM 5350-POUND CYLINDRICAL CHARGES OF HBX-1 WITH BALL CRUSHER GAGES

by

Arthur E. Hirsch and
Carl D. Martin

[redacted]



23

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Report C-682

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MEASUREMENTS OF PEAK PRESSURE FROM 5350-POUND CYLINDRICAL CHARGES OF HBX-1 WITH BALL CRUSHER GAGES

by

Arthur E. Hirsch and Carl D. Martin

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ABSTRACT

Peak pressures from a 5350-lb cylindrical charge of HBX-1 with a length-diameter ratio of 1.6 have been measured with ball crusher gages. They agree within ± 10 percent with published data obtained from small spherical charges of HBX-1. However, there is some evidence that the pressure field was not spherically symmetric.

A formula is derived for the interpretation of ball deformation when an exponential shock wave is superposed on a hydrostatic pressure. Gage waterproofing techniques are also discussed.

INTRODUCTION

Existing similitude curves for HBX-1 are largely derived from tests involving rather small charges, about 50 lb.[1] There is a legitimate question as to whether these pressure-distance relations are true for much larger charges. The opportunity to check the relationships arose during tests at Gonave Bay, off Haiti, involving 5350-lb charges of HBX-1.[2] As extensively as facilities would permit, ball crusher gages were used to measure the peak pressure over a large range of $W^{1/3}/R$ where W is the charge weight in pounds and R is the charge-to-gage distance in feet. In some positions, piezoelectric and diaphragm gages were used alongside the ball crusher gages. The results from these other gages are included here but will be described in detail in a separate report.[3]

TEST GEOMETRY AND INSTRUMENTATION

Five tests were made with charges at depths from 100 to 1475 ft below the surface, and the pressures were measured at distances from about 200 to 2000 ft. The gage depths ranged from 3 to 1200 ft so that sometimes the hydrostatic pressure on the gage was comparable in magnitude with the shock-wave pressure. Table 1 gives gage and charge depths and gage standoffs for each test.

The charges had a ratio of length to diameter of 1.6 and were poured by the Naval Mine Depot, Yorktown, Virginia. They were housed in special cases designed and made by the Norfolk Naval Shipyard. A full charge case held 5350 lb of HBX-1. There were two boosters weighing 50 and 2.3 lb, respectively, for a total of 52.3 lb of pentolite. The main booster consisted of a metal can filled with pentolite which fitted snugly into a cavity in the charge. The main booster also had a cavity into which was placed the auxiliary booster. This was a small cylindrical charge containing holes for detonators. Two firing leads were used, one detonator across each lead.

---

[1] References are listed on page 12.

TABLE 1

Summary of Test Results

Test	Charge Depth ft	Gage Depth ft	Horizontal Standoff of Gage ft	Total Gage Standoff ft	Ball Size in.	Ball Deformation in.				Average Deformation in.	Percent Standard Deviation σ percent	Maximum Dynamic Pressure psi
1	580	387	0	191	3/8	(0.0046)	0.0199	0.0212	0.0208	0.0206	2.6	1466
		351	0	226	3/8	0.0175	0.0173	0.0182	0.0183	0.0178	2.3	1261
		331	0	247	3/8	0.0153	0.0153	0.0153	(0.0103)	0.0153	0	1074
		306	0	271	3/8	0.0136	0.0157	0.0135	0.0148	0.0144	6.3	1005
		291	0	286	3/8	0.0133	0.0135	(0.0017)	(0.0068)	0.0134	0.7	938
		271	0	306	3/8	0.0133	0.0133	0.0114	0.0138	0.0130	7.1	906
		251	0	326	3/8	0.0119	0.0114	0.0111	0.0114	0.0114	2.6	798
		241	0	336	3/8	0.0130	0.0133	0.0116	0.0121	0.0125	5.4	880
		196	0	382	3/8	0.0117	0.0116	0.0109	0.0113	0.0114	2.7	809
		151	0	427	5/32	0.0225	0.0223	0.0215	0.0196	0.0215	5.3	659
		90	0	487	5/32	0.0186	(0.0002)	0.0175	0.0189	0.0183	3.3	569
		25	0	552	5/32	0.0188	0.0170	0.0180	0.0199	0.0184	5.7	584
2	560	328	0	233	3/8	0.0175	0.0166	0.0159	0.0158	0.0165	4.1	1167
		268	0	290	3/8	0.0132	0.0139	0.0132	0.0121	0.0131	4.8	926
		233	0	325	3/8	0.0118	0.0124	0.0119	0.0124	0.0121	2.3	847
		210	0	348	3/8	0.0099	0.0097	0.0098	0.0089	0.0096	4.1	672
		168	0	394	5/32	0.0204	0.0212	0.0216	0.0211	0.0211	1.9	646
		83	0	479	5/32	0.0187	0.0170	0.0180	0.0188	0.0181	4.0	567
		100	1490	1560	5/32	0.0058	0.0056	0.0057	(0.0046)	0.0057	1.4	161
3B	1475	1175	0	308	3/8	0.0157	0.0157	0.0156	0.0157	0.0157	0.3	950
		1000	0	473	3/8	0.0112	0.0114	0.0105	0.0105	0.0109	3.7	617
		890	0	583	3/8	0.0095	0.0096	0.0084	0.0086	0.0090	5.9	494
		605	0	868	3/8	0.0065	0.0065	0.0061	0.0067	0.0064	3.5	354
		545	0	928	5/32	0.0138	0.0134	0.0130	0.0133	0.0134	2.1	320
		510	0	963	5/32	0.0134	0.0133	0.0127	0.0135	0.0130	2.9	314
		140	1550	2050	5/32	0.0040	0.0047	0.0043	0.0043	0.0043	5.7	107
4	590	370	0	218	3/8	0.0200	0.0184	0.0178	0.0203	0.0191	5.4	1353
		287	0	301	3/8	0.0143	0.0148	0.0138	0.0139	0.0142	2.7	1004
		250	0	335	3/8	0.0127	0.0116	0.0109	0.0114	0.0117	5.6	807
		90	0	498	3/8	0.0089	0.0088	0.0080	0.0078	0.0084	5.7	604
		210	0	387	5/32	0.0249	0.0251	0.0242	0.0240	0.0246	1.8	572
		65	0	523	5/32	0.0173	0.0175	0.0179	0.0178	0.0176	1.4	551
5	100	12	212	229	3/8	0.0157	0.0172	0.0200	0.0178	0.0177	8.5	1364
		3	252	270	3/8	0.0142	0.0149	0.0149	0.0142	0.0146	2.4	1199
		12	290	300	3/8	0.0137	0.0123	0.0127	0.0124	0.0128	4.3	1029
		15	302	314	3/8	0.0135	0.0131	0.0123	0.0124	0.0128	3.9	990
		12	349	360	3/8	0.0118	0.0107	0.0112	0.0105	0.0111	5.2	873
		12	472	480	5/32	0.0170	0.0162	0.0155	0.0162	0.0164	3.5	590
		140	1400	1400	5/32	0.0068	0.0065	0.0061	0.0061	0.0064	4.6	177

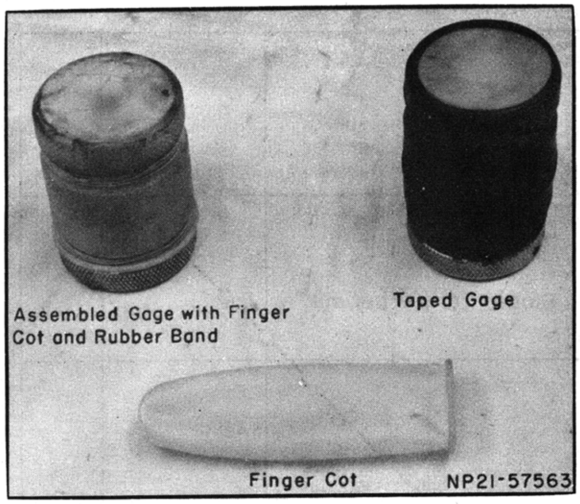

Figure 1 - Assembled Ball Crusher Gages and Finger Cot Used for Waterproofing

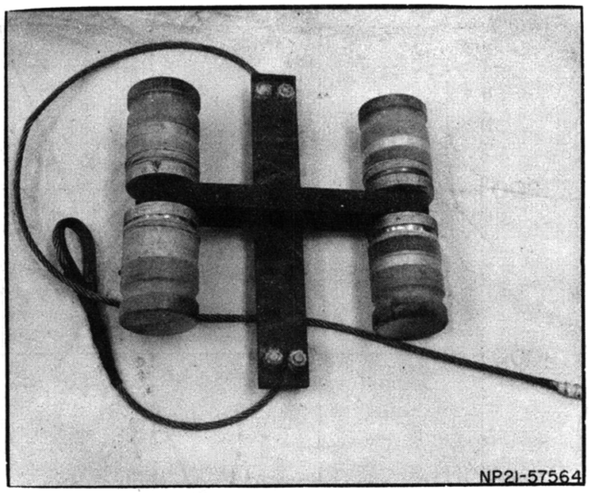

Figure 2 - Ball Crusher Gages Assembled on "T" Bracket

All gages were waterproofed by means of a large finger cot, which was held in place by a rubber band; see Figure 1. After the first two tests, it was found that a very large percentage of gages had leaked. In subsequent tests Scotch insulating tape was wound around the gage body, as shown in Figure 1, and no leakage was observed. Gages were mounted in clusters of four on "T" brackets, as shown in Figure 2, and hung freely from small structures attached to the line supporting the charge. The distance between the structures and all the ball crusher gages was nominally 2 ft. This distance was considered adequate to prevent reflected pressures from influencing the shock wave during the response time of the gage.

Gages were outfitted with either 5/32 or 3/8 in. copper balls. Deadweight calibrations of the balls were made using a beam balance scale with a capacity of 250 lb. A fine threaded drive screw was used to apply a force normal to the piston; see Figure 3. The assembled gage was centered on the scale, and the scale was adjusted to balance out the fixed load. By turning the set screw to apply a load to the piston, the force was applied to the ball. The applied force was then read directly on the balance.

Calibration curves are plotted in Figure 4. They are linear over the test range.

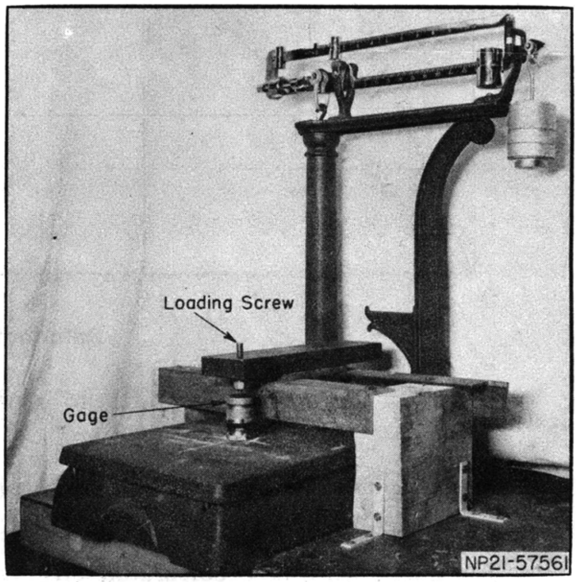

Figure 3 - Deadweight Calibrator Showing Method of Screw Loading of Balls in Assembled Gage

The screw was rotated until the load so applied just balanced the load preset on the scales. A new copper ball was used for each point on the calibration curve.

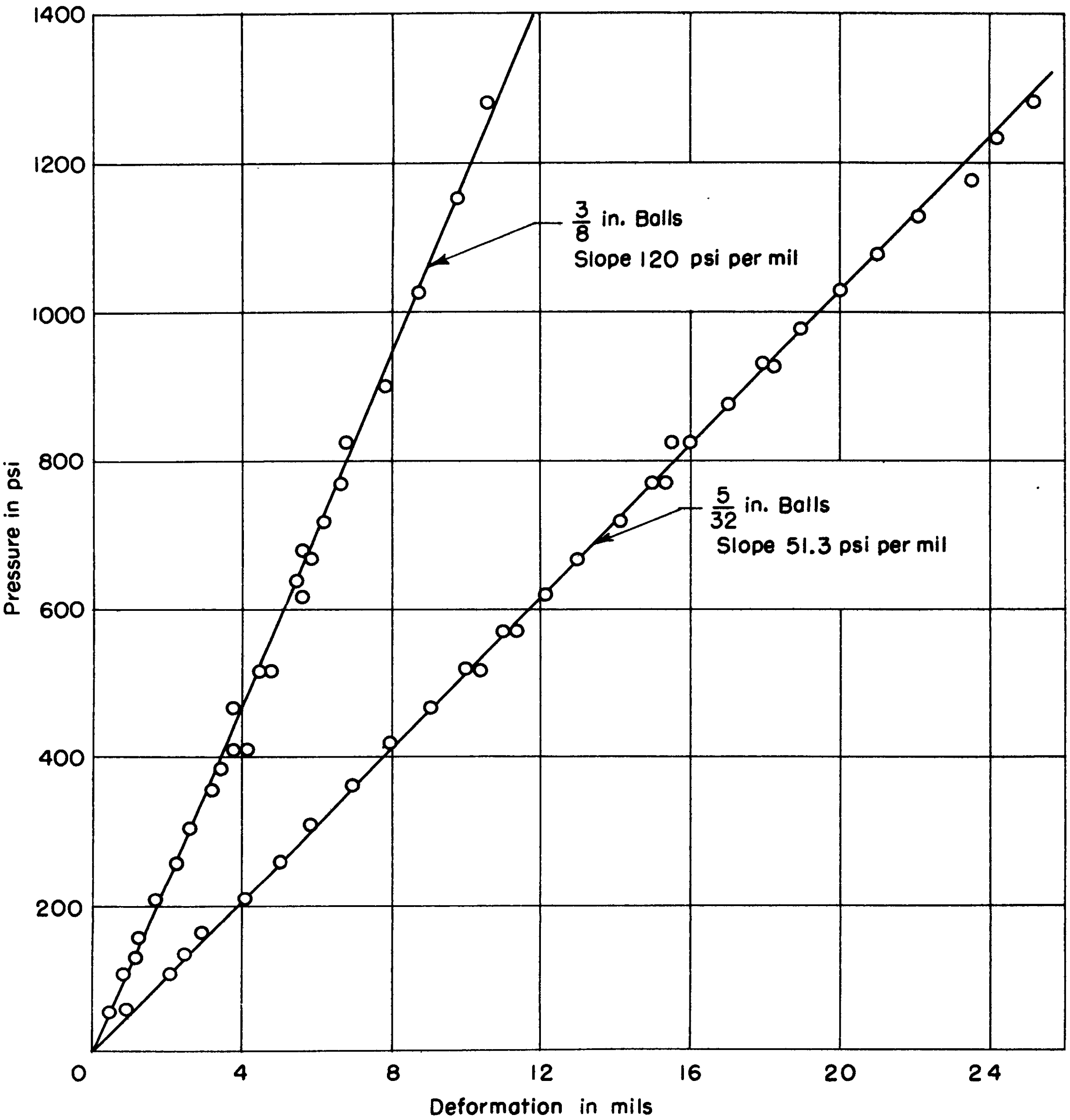

Figure 4 - Deadweight Calibration of 3/8-Inch and 5/32-Inch Copper Balls

Estimated best curves indicate static sensitivities of 51.3 psi/mil for 5/32-in. balls and 120 psi/mil for 3/8-in. balls.

The gages were also calibrated with hydrostatic pressures. The test device consisted of a water pump, a chamber sufficiently large to hold two assembled gages, and a laboratory Bourdon-tube test gage graduated in increments of 10 psi up to 2000 psi. Assembled and waterproofed gages were tested in this chamber. It was found (Figure 5) that there was a systematic deviation toward reduced sensitivity for gages with 5/32-in. balls when deformations exceeded 12 mils. This occurred when waterproofing consisted of a Scotch tape strip over

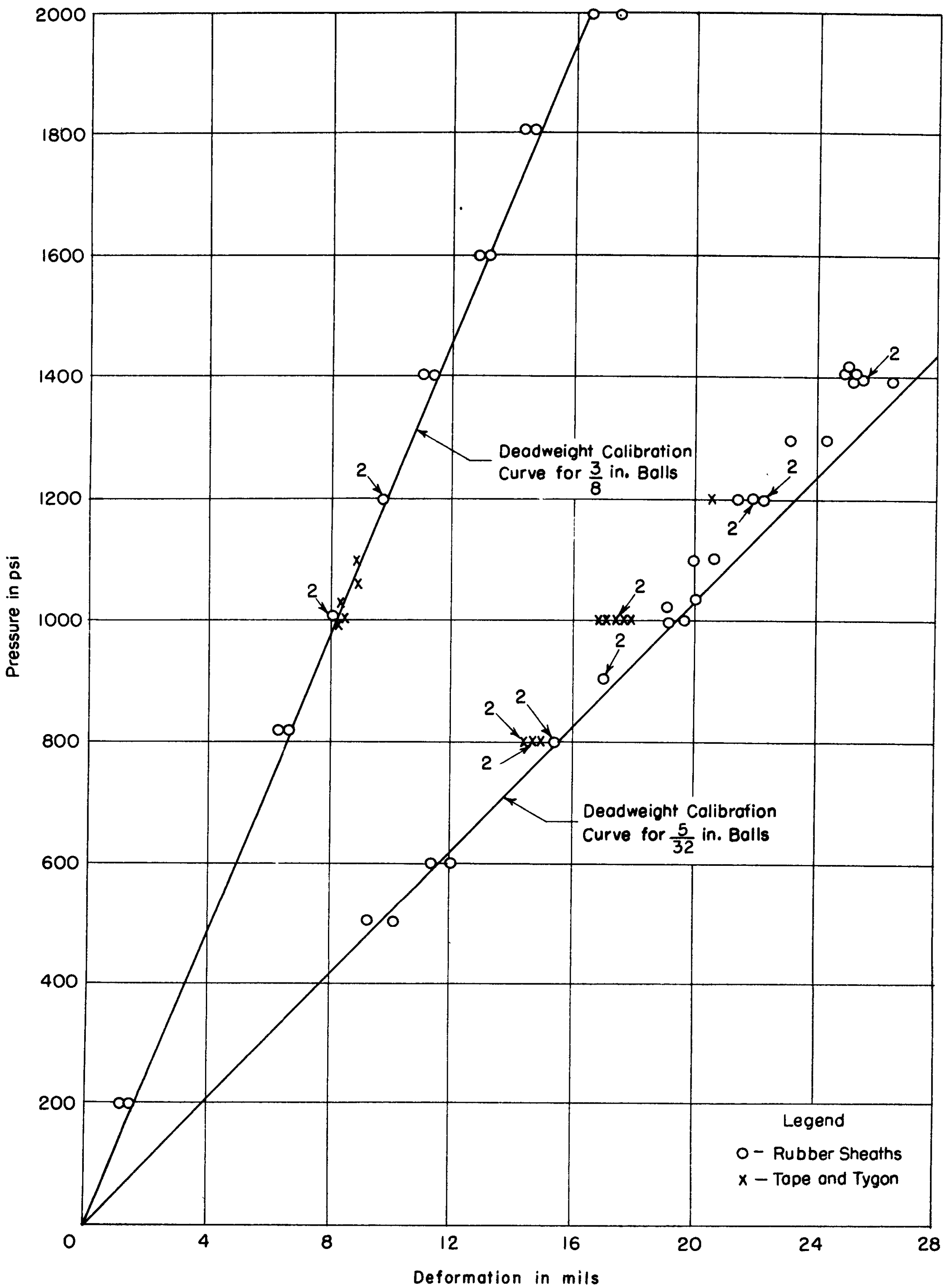

Figure 5 - Hydrostatic Calibrations of Assembled and Waterproofed Gages

the piston and several coats of Tygon paint. The probable cause of the decreased sensitivities was the action of the tape as a diaphragm in supporting the applied load. This effect did not appear in the static calibration of the 3/8-in. balls. It apparently does not become significant until displacements are larger than 12 mils. Gages with 3/8-in. balls and Tygon-and-tape waterproofing were not calibrated for displacements beyond 9 mils.

As a consequence of the observed nonlinearity, thin rubber finger cots[4] were used for waterproofing all gages. The hydrostatic sensitivities of gages so protected are also plotted in Figure 5. Large-size finger cots were found to provide satisfactory waterproofing at hydrostatic pressures up to 2000 psi, although there is evidence of nonlinearity at deformations beyond 20 mils for 5/32-in. balls. It was not necessary to go beyond this limit during the field tests.

The dynamic sensitivities of the gages were not experimentally determined. Instead, it was assumed that the static-dynamic relationships between the spring constant terms, $k_D/k_s = 1.18$ determined in Reference 5, was applicable to the balls used in this test. Thus the dynamic sensitivities of the 5/32- and 3/8-in. balls for a step of pressure were computed to be 30.3 and 71.0 psi/mil, respectively. These values include a factor of one-half relative to static figures for dynamic overshoot.

GAGE RESULTS

Table 1 shows the measured deformations of all gages used in the explosion tests. Readings were obtained from clusters at a total of 39 stations for the five tests. Where there was water in the gage, the deformations were very small. These measurements (enclosed in parentheses in Table 1) were considered unreliable and were not used in computing the averages and deviations. The remaining deformations were internally consistent with an average standard deviation of ± 3.7 percent.

ANALYSIS OF DATA

Peak dynamic pressures have been calculated from the measured deformations by means of the equation

$$P_D = [S_D x_m - 0.41 P_0]\left[1 + \frac{\pi}{2}\frac{\mu}{\omega}\right] \qquad [1]$$

where x_m is the final set deformation of the ball,

S_D is the dynamic sensitivity of the ball,

P_0 is the hydrostatic pressure at the level of the gage,

μ is the time constant of the incident pressure wave, and

$\frac{\pi}{2\omega}$ is one-half the response time of the gage to a step pressure wave.

Equation [1] is derived in the Appendix and is based on plausible assumptions on the dynamic action of the gage in the presence of a hydrostatic pressure. Unfortunately, except for these tests, there are no independent checks on the applicability of the equation where the hydrostatic pressure is appreciable. The second factor in Equation [1] is a correction term to allow for the decay in the applied pressure during the response of the gage. The value of μ was obtained from similitude curves derived from experimental work on spherical HBX charges.[1] The response time of the gage was taken as 131×10^{-6} sec for the 5/32-in. ball and 85.4×10^{-6} sec for the 3/8-in. ball. The decay corrections ranged from 2.9 to 6.6 percent. Errors in μ as great as 50 percent would not have much effect.

The calculated values for P_D are tabulated in Table 1 and are plotted in Figure 6 versus the factor $W^{1/3}/R$. From a least-squares computation, the best curve for the data can be represented by the equation

$$P_D = 2.22 \times 10^4 \left(\frac{W^{1/3}}{R}\right)^{1.10}$$

with an average standard deviation of ± 8.5 percent. Also plotted in Figure 6 is the curve

$$P_D = 2.48 \times 10^4 \left(\frac{W^{1/3}}{R}\right)^{1.15}$$

which was obtained from ball-crusher measurements described in Reference 1 for the region $W^{1/3}/R > 0.035$.

The rather large standard deviation (8.5 percent) from a best curve should be discussed. The consistency of the gages within a cluster was good, the average standard deviation being ± 3.7 percent.

An examination of Figure 6 discloses that there is a systematic difference between the pressures measured in Test 5, where the gages were at shallow submergence off the side of the charge, and the pressures measured in the other tests, where the gages were off the end of the charge. In order to examine the situation more closely, the off-side data are plotted separately in Figure 7, and the off-end data are plotted in Figure 8. Also plotted are the peak pressures measured by means of tourmaline and diaphragm gages as reported in Reference 3.

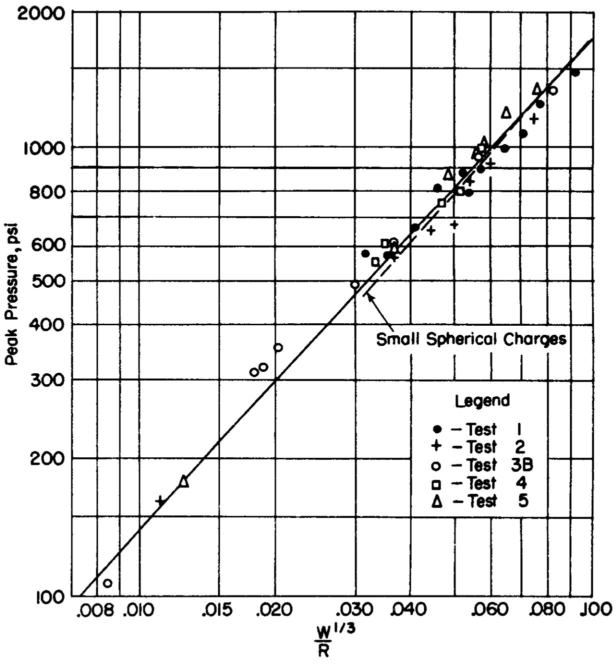

Figure 6 - Composite Curve of Peak Pressures from All Ball Crusher Gages

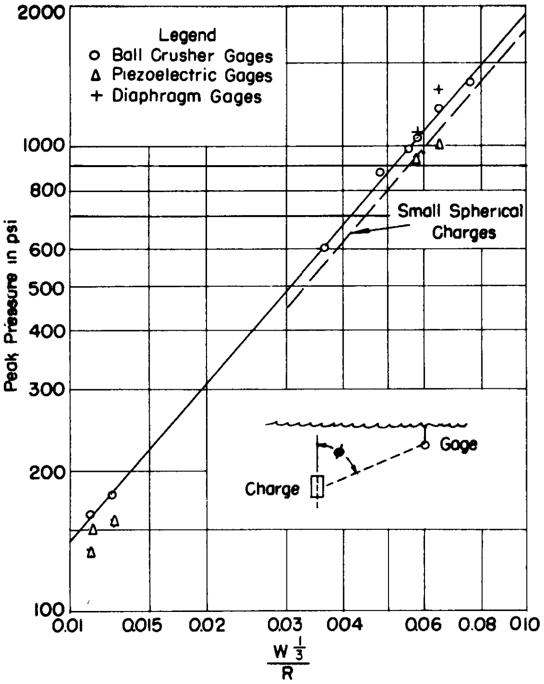

Figure 7 - Peak Pressures for Tests where ϕ = 70 to 90 Degrees

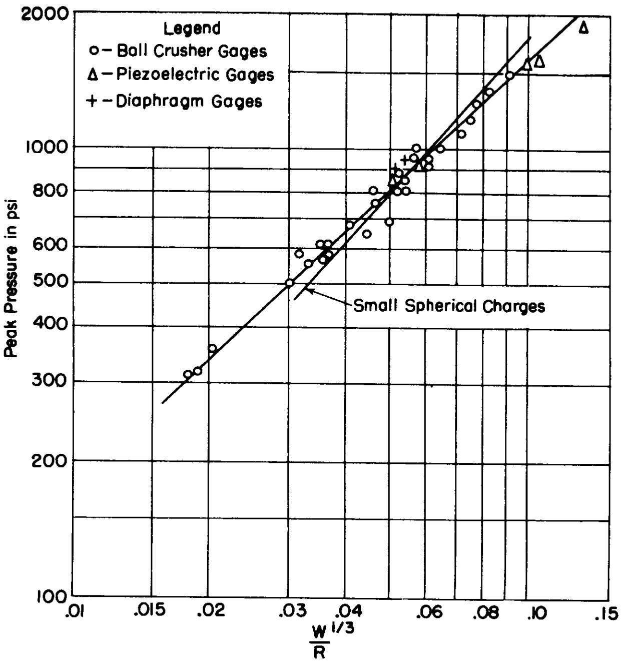

Figure 8 - Peak Pressures for Tests where $\phi \cong 0$ Degrees

The pressures off the side, Figure 7, run about 10 percent higher than the average. It is not clear whether this is a real effect due perhaps to the cylindrical shape of the charge,[6-8] or to some experimental error, or to an error in the calibration equation. There is some evidence in the pressure measurements from piezoelectric gages, made in these tests and described in Reference 3, that the pressure-time history in off-end measurements was not as simple as expected for spherical charges.

Figures 7 and 8 show fair agreement between pressures from the ball-crusher gages and the peak pressures as measured on this test by both piezoelectric gages and diaphragm gages.

The experimental data were examined to check the validity of the correction for initial hydrostatic pressure. Data were grouped into discrete depths and compared with the average curve of peak pressure versus $W^{1/3}/R$. Any error in the correction formula would show up as a systematic departure from the average curve with depth. No such departure could be observed.

CONCLUSIONS

There seems to be good evidence that the peak pressure curves derived from data from small charges can be applied to large charges. The systematic deviations from the spherical charge curve reported here may result from a combination of experimental errors and/or asymmetry in the pressure field due to the cylindrical shape of the charge.

Where there is a high hydrostatic pressure, the equation for the interpretation of the response of ball-crusher gages yields results which are internally consistent and which agree reasonably well with the results obtained with electrical gages.

The finger cots are a successful method of waterproofing that seems to have a minimum effect on gage response. The necessity for gage taping could be eliminated if a suitable rubber sheath is molded with thick abrasion-resistant sides.

APPENDIX

DYNAMIC ACTION OF A BALL CRUSHER GAGE IN THE PRESENCE OF A HYDROSTATIC PRESSURE

We assume that the piston is simultaneously exposed to a hydrostatic pressure P_s and to a dynamic pressure $P_D e^{-\mu t}$ and that the copper ball resists the motion of the piston with a force proportional to the displacement of the piston from its position when the ball was not deformed. Then the equation of motion of the piston is

$$m\ddot{x} + k_D x = A(P_s + P_D e^{-\mu t}) \qquad [2]$$

where $t > 0$

A is the area of the piston, 0.195 sq. in.,

k_D is the dynamic spring constant of the gage,

m is the effective mass of the piston (including entrained water), and

x is the displacement of the piston.

The initial conditions at $t = 0$ are assumed to be $\dot{x} = 0$ and $x_0 = P_s A/k_s$ where k_s is the static spring constant of the gage. Hence the solution is

$$\begin{aligned} x = \frac{\mu}{\omega}\left[\frac{A P_D}{m(\mu^2 + \omega^2)}\right] \sin \omega t + \frac{A P_D}{k_D}\left[1 - \left(\frac{k_s - k_D}{k_s}\right) \cos \omega t\right] \\ - \frac{A P_D}{m(\mu^2 + \omega^2)} \cos \omega t + \frac{A P_D e^{-\mu t}}{m(\mu^2 + \omega^2)} \end{aligned} \qquad [3]$$

The maximum displacement x_m occurs at time T when $x = 0$:

$$\begin{aligned} x_m = \left(\frac{\mu}{\omega}\right) \frac{A P_D}{m(\mu^2 + \omega^2)} \sin \omega T + \frac{A P_s}{k_D}\left[1 - \frac{k_s - k_D}{k_s} \cos \omega T\right] \\ + \left(\frac{\mu}{\omega}\right) \frac{P_D A}{m(\mu^2 + \omega^2)} \sin \omega T + \frac{\omega}{\mu}\ \frac{P_s A}{k_D}\left[\frac{k_s - k_D}{k_s} \sin \omega T\right] \end{aligned}$$

The dynamic deflection of the ball can be written as $x_m - x_0$, so, rewriting Equation [3], we get for small values of x:

$$x_m - x_0 = \frac{AP_D}{k_D} \phi \frac{\sin \omega T}{\left(\frac{\mu}{\omega}\right)} + \frac{AP_s}{k_D} \left(\frac{k_s - k_D}{k_s}\right) (1 - \cos \omega T) \qquad [4]$$

$$\text{where} \quad \phi = \left[1 + \frac{P_s}{P_D} \left(\frac{k_s - k_D}{k_s}\right)\right]$$

An expression for the velocity may be obtained by differentiating Equation [3]. The velocity is zero at time T. From this relation, by successive approximations through terms of the order of $(\mu/\omega)^2$, we obtain for the case $\mu/\omega << 1$:

$$\omega T = \pi - \frac{2}{\phi}\left(\frac{\mu}{\omega}\right) + \frac{\pi}{\phi}\left(\frac{\mu}{\omega}\right)^2 + - - - -$$

Substitution in Equation [4] yields

$$x_m - x_0 = \frac{2AP_D}{k_D}\left[1 - \frac{\pi}{2}\left(\frac{\mu}{\omega}\right)\right] + \frac{2AP_s}{k_D} - 2x_0 \qquad [5]$$

or

$$P_D = \left[\frac{k_D}{2A}(x_m + x_0) - P_s\right]\left[1 + \frac{\pi}{2}\left(\frac{\mu}{\omega}\right)\right] \qquad [6]$$

At $P_0 = 0$ this equation becomes

$$P_D = \frac{k_D}{2A} x_m \left[1 + \frac{\pi}{2}\left(\frac{\mu}{\omega}\right)\right]$$

which is the equation for the dynamic response of a ball crusher gage to an exponentially decaying shock wave[9] where $(\mu/\omega) << 1$.

Equation [6] can be simplified to a more useful form if we express $k_D/2A$ as S_D, where S_D is the dynamic sensitivity of the ball, and if P_s/S_s is substituted for x_0, where S_s is the static sensitivity. The ratio S_D/S_s is equal to 0.41 for both size balls; hence Equation [6] can be rewritten

$$P_D = (S_D x_m - 0.41 P_0)\left(1 + \frac{\pi}{2}\frac{\mu}{\omega}\right) \qquad [7]$$

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32	CDR, New York Naval Shipyard
33	CDR, Charleston Naval Shipyard
34	CDR, Pearl Harbor Naval Shipyard
35	CDR, Philadelphia Naval Shipyard
36	CDR, Portsmouth Naval Shipyard
37	CDR, San Francisco Naval Shipyard
38	CDR, Mare Island Naval Shipyard
39	CHIEF, AFSWP, Washington, D.C.
40	CAPT N.W. Gokey, USN (Ret), Prof of Nav Arch, Webb Inst of Nav Arch, via INSMAT, New York

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MEASUREMENTS OF PEAK PRESSURE FROM 5350-POUND CYLINDRICAL CHARGES OF HBX-1 WITH BALL CRUSHER GAGES, by Arthur E. Hirsch and Carl D. Martin. May 1955. ii, 13 p. incl. table, figs., refs. CONFIDENTIAL

Peak pressures from a 5350-lb cylindrical charge of HBX-1 with a length-diameter ratio of 1.6 have been measured with ball crusher gages. They agree within ± 10 percent with published data obtained from small spherical charges of HBX-1. However, there is some evidence that the pressure field was not spherically symmetric.

A formula is derived for the interpretation of ball deformation when an exponential shock wave is superposed on a hydrostatic pressure. Gage waterproofing techniques are also discussed.

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2. Underwater explosions - Pressure - Measurement
3. Crusher gages - Test results
4. Crusher gages - Deformation - Mathematical analysis
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