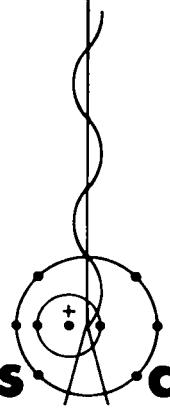
Spherical Explosions in Water



los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
6285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.95

LA-4635
UC-34
ISSUED: October 1971

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

Spherical Explosions in Water

by

L. W. Hantel
W. C. Davis

SPHERICAL EXPLOSIONS IN WATER

by

L. W. Hantel and W. C. Davis

ABSTRACT

Calibration data are presented for the shock wave in water driven by a centrally initiated sphere of explosive. The measured quantity is the shock position as a function of time. A simple function is fit to the data by a least-squares technique; the derivative of the function gives the shock velocity, which is used with the known Hugoniot for water to get shock pressure. The useful range of pressure in the water is from 150 to 5 kbar; over this range the uncertainty in pressure is less than 5%. For spheres of 3, 4-1/2, and 6 in. diam, no departure from simple scaling is found. The calibrated system is intended as a generator of a reproducible pressure pulse for use in explosive sensitivity tests and gauge calibration.

I. INTRODUCTION

The performance of centrally initiated spherical charges of explosive has been of interest for many years. In particular, considerable work on this problem has been done at the Naval Ordnance Laboratory. In 1949, Eyster, Smith, and Walton[1] described an underwater gap test designed to measure the critical initiation pressure of an explosive. In this test, centrally initiated spherical charges were used to generate spherically diverging water shocks, which were then allowed to impinge upon cylindrical acceptor charges located at various distances from the surface of the sphere. Liddiard[2] used this same technique to study the initiation of burning resulting from low-amplitude mechanical shocks. Interest in the interaction of spherical shocks in water prompted Coleburn and Roslund[3] to study shock-wave interactions resulting from the simultaneous detonation of spherical charges of explosive under water.

The water shock resulting from the central initiation of a sphere of explosive radiates outward more or less spherically depending upon the simultaneity of the breakout times around the sphere. The amplitude of the shock decreases with increasing distance from the sphere surface, providing a convenient method for subjecting objects to shocks of different intensities by placing them at different distances from the sphere. However, for quantitative use of the method, one must determine the relationship between the shock pressure and the distance from the sphere. If the relationship between the radial distance the shock wave has traveled and time, $R = R(t)$, can be established, it can be differentiated to give the shock velocity U. By using the equation-of-state data of Rice and Walsh,[4] the pressure as a function of distance can then be determined.

In many past experiments, the R-t data were obtained with framing cameras, with a polynomial of the form

$$R = A_o + A_1 t + A_2 t^2 + A_3 t^3 + \ldots + A_n t^n \qquad (1)$$

then being fit to the data. In a limited number of experiments at the Los Alamos Scientific Laboratory (LASL), Smith and Hantel[5] found the framing-camera, polynomial-fit method unsatisfactory because it gave inconsistent velocities in the low-pressure range. This was traced to the polynomial fits, which

oscillated in this range, giving oscillating values for the derivative. Also, the limited number of frames available per shot did not yield enough data points of sufficient resolution to give a reasonable fit for any one shot, thus making shot-to-shot comparisons difficult.

In this report we describe an approach designed to eliminate these problems. A rotating-mirror streak camera was used to record the progress of the shock, which results in a much larger number of data points and improved resolution. A more realistic equation with a basis in spherical detonation theory was also used to fit the R-t data. The objectives of the experiment were threefold: first, to collect data for calibration of an underwater gap test; second, to see if the data from spheres of different radii would scale; and third, to obtain R-t data of sufficient quality to serve as a basis for improving the theory of spherical detonation.

II. EXPERIMENTAL METHODS

Although the main difficulties in the earlier experiments were thought to be camera resolution and the small number of data points, we decided that an improved spherical initiator would be most desirable. With the help of LASL Groups GMX-3 and GMX-8, an initiator was developed that consisted of 2 gr/ft MDF, XTX,* and 9404.** Figure 1 is a schematic of the initiator. If one excludes a region from the point where the MDF enters the 9404 sphere down to a latitude of 45°, the breakout times measured on four different spheres were simultaneous to within 0.08 μsec. Generally, the lower hemisphere was simultaneous to within less than 0.03 μsec. Six centrally initiated 9205*** spheres were fired using this initiator, and arrival times measured in the area covered by the smear camera were simultaneous to within 0.09 μsec.

Once the initiator had been developed, a six-shot series with various diameter 9205 spheres was started. The series consisted of two shots each with 3-, 4-1/2-, and 6-in.-diam spheres. Figure 2 shows a completed 9205 sphere assembly with the

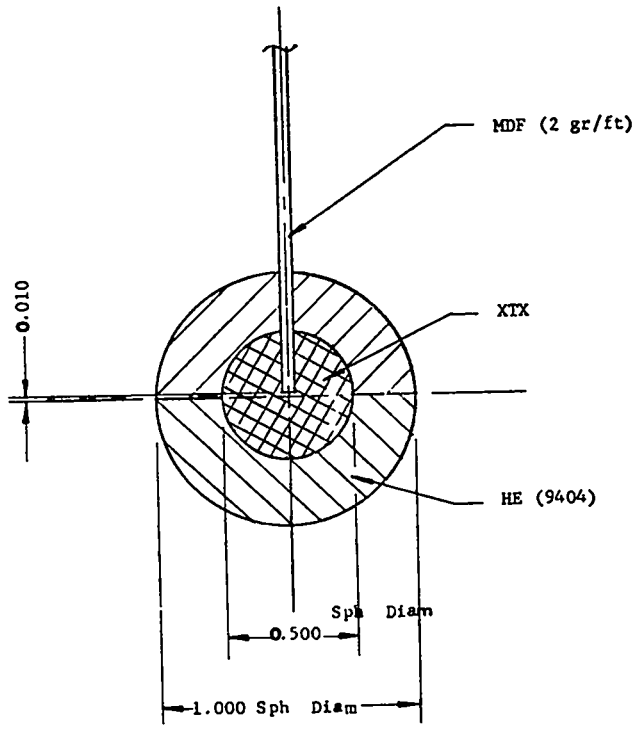


Fig. 1. Spherical initiator.

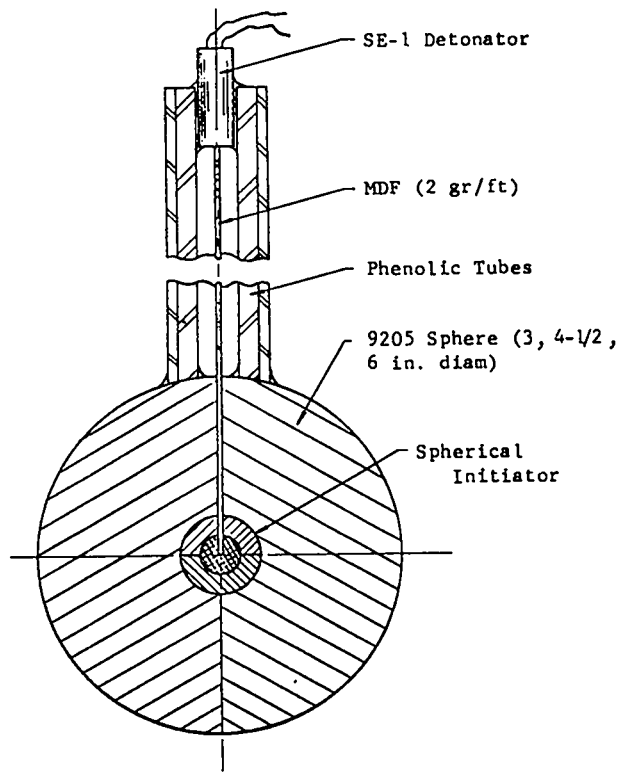


Fig. 2. Assembled spherical charge.

*80/20 - PETN/Sylgard 182, ρ = 1.533 g/cm^3.

**94/3/3 - HMX/nitrocellulose/tris(β-chloroethyl)-phosphate, ρ = 1.845 g/cm^3.

***92/6/2 - RDX/polystyrene/dioctyl phthalate, ρ = 1.686 g/cm^3.

initiator in place. The spheres were fired at 25°C inside 2 by 2 by 2 ft Plexiglas boxes containing tap water. The slit on the smear camera was oriented such that the expansion of the water shock on the right and left sides of the sphere could be recorded simultaneously. The system was backlighted with an argon flash collimated by a Fresnel lens to give shadowgraph lighting. The resolution was better than 1 mm at the object with a magnification of 1/30.

The films were read on a Bensen-Lehner comparator, and the data were converted to millimeters and microseconds by the PFIEFE[6] code, the standard code used to reduce cylinder-test data.[7] Approximately 240 data points were obtained for each sphere.

III. DATA ANALYSIS

Selected points from the raw data sets are plotted for each sphere in Figs. 3a through f. In each case the data taken from the left side of a sphere lie above those from the right side. This discrepancy was traced to a slight misalignment of the axis of the rotating mirror in the smear camera with respect to the axis of the film-track cylinder. Because the diameter of the shock wave is the quantity of interest, the only problem created by this is a slight complication in reducing the data.

It was assumed that the expanding shock wave was indeed spherical and symmetric, and that the difference between the right and left data sets resulted from losing track of the center of the system because of a systematic error introduced by the camera. The diameter of the expanding shock wave is well defined in any event, and it was used as the basic measured quantity. When the films were measured, readings of the right and left sides were not made at identical time points, and the diameter at an instant of time was not directly available; hence, the data were adjusted as follows.

The individual data sets (two for each sphere, one left and one right) were fit by equations of the form*

$$\beta = 1 + (A_0\tau^2 + A_1\tau + A_2)(\tau-1) + B(\tau-1)^{3/2} . \qquad (2)$$

The least-squares fits were obtained with the EILEEN[8] code. The data points for both sides were then combined, and the same equation was fit to the combined data to obtain a line that bisects the two previously calculated lines. These three calculated curves for each sphere are used to adjust the data. Consider the left-side data points for any one of the six spheres. Each of these points lies above the line calculated from the combined data. To adjust these points the R coordinate is corrected by subtracting from it a quantity δ, which is the distance between the curve calculated from the combined data and the curve calculated from the left-side data alone, at the time t. This is done for each left-side data point. The same process is applied to the right-side data points. Figures 4a through f show plots of the adjusted data for each sphere; the complete list of these measured data points is given in Tables Ia through f.

The ultimate success of this experiment largely depends upon the choice of an equation to describe the motion of the shock front as a function of time. The equation chosen is

$$\beta = 1 + (A_0\tau^2 + A_1\tau + A_2)(\tau-1) + B(\tau-1)^{3/2} . \qquad (3)$$

This equation is in reduced form, with

$$\tau = \frac{t + a/D}{a/D}$$

and

$$\beta = \frac{R + a}{a} ,$$

where t is the observed time from breakout, a is the original radius of the HE sphere, D (= 8.17 mm/μsec) is the detonation velocity of 9205, and R is the distance of the shock front from the surface of the sphere. The purpose of the reduced form is to make direct comparisons between spheres of different diameters possible. This particular form was chosen because all treatments of spherical detonation show that there is a very large pressure gradient behind the detonation front. The second derivative of Eq. (3), which represents the deceleration of the shock wave, contains a term in $(\tau-1)^{-1/2}$, which becomes infinite at the interface where $\tau = 1$. Taylor's[9] treatment of spherical detonation has infinite gradients, whereas others[10] have somewhat smaller ones. However, the value can be adjusted by using a term in $(\tau - 1 + \epsilon)^{3/2}$ to replace the last term in Eq. (3), choosing a small positive value for ϵ to make the gradients finite

*The reason for choosing this form is discussed below.

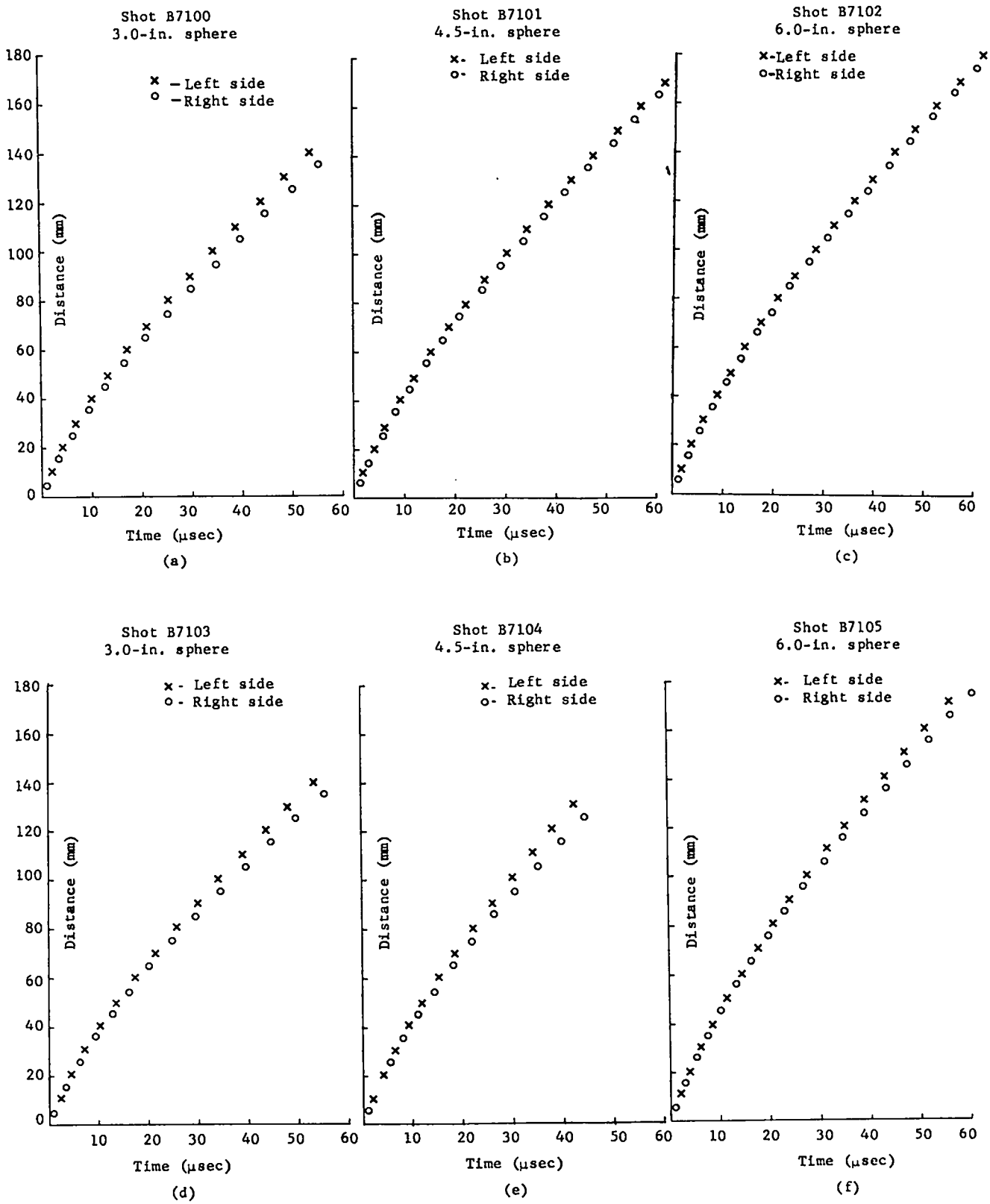


Fig. 3. Distance of water shock from explosive surface vs time.

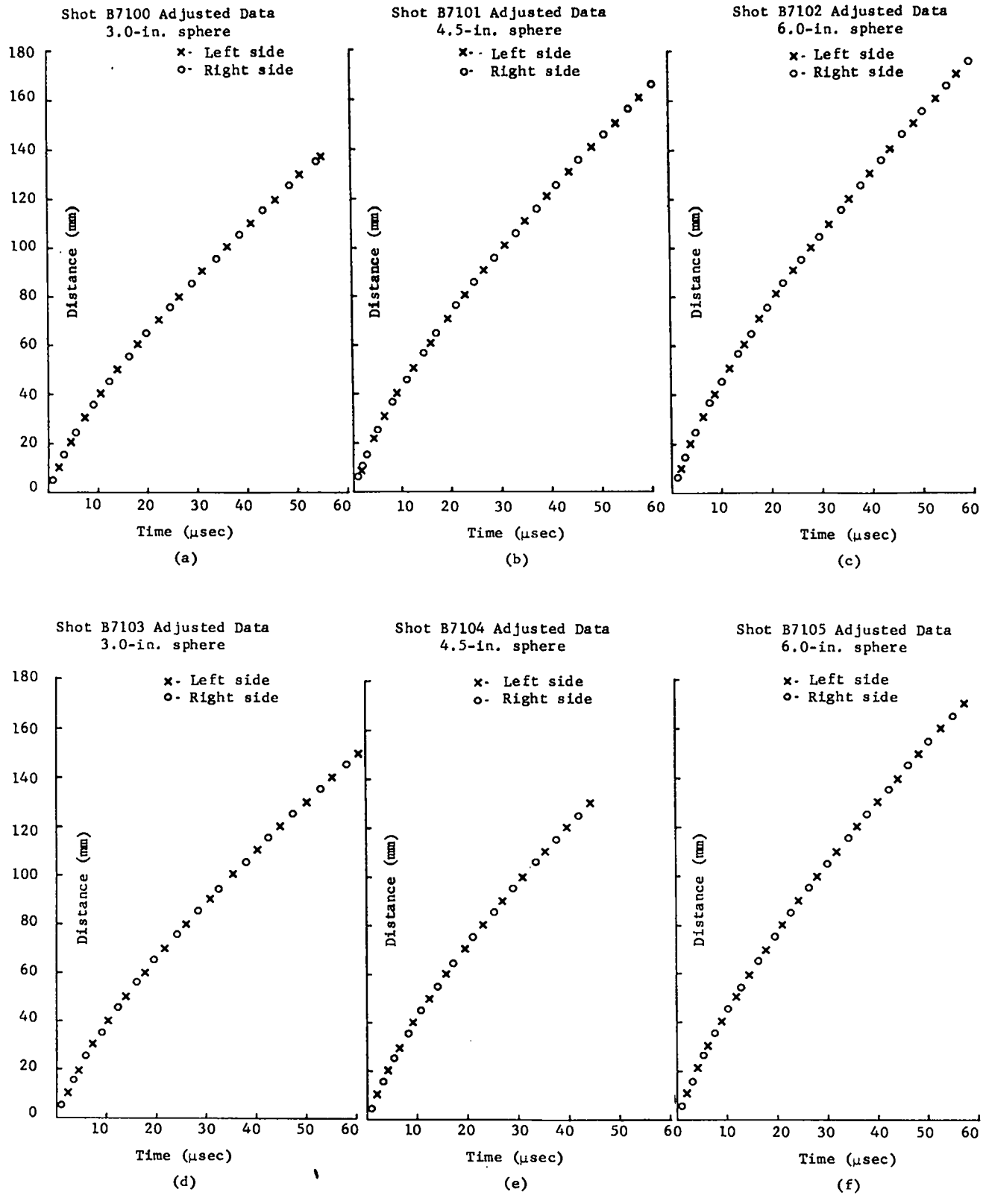


Fig. 4. Distance of water shock from explosive surface vs time.

TABLE Ia

SHOT B-7100 3-IN.-DIAM 9205 SPHERE

Left Side

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
0.182	1.045	1.082	-0.037	5.722
0.357	1.901	2.059	-0.158	5.482
0.515	2.821	2.910	-0.089	5.320
0.854	4.782	4.666	0.116	5.051
1.025	5.698	5.521	0.177	4.941
1.283	6.667	6.777	-0.110	4.794
1.433	7.336	7.489	-0.153	4.718
1.593	8.128	8.237	-0.109	4.642
1.701	8.802	8.737	0.065	4.594
1.855	9.594	9.441	0.154	4.528
2.003	10.326	10.104	0.222	4.469
2.334	11.782	11.563	0.219	4.346
2.498	12.449	12.274	0.176	4.290
2.609	13.309	12.745	0.564	4.254
2.760	13.478	13.384	0.094	4.206
2.885	14.085	13.907	0.178	4.168
3.032	14.566	14.519	0.047	4.125
3.365	16.023	15.874	0.149	4.033
3.539	16.813	16.574	0.239	3.988
3.719	17.601	17.289	0.312	3.942
3.866	17.957	17.864	0.094	3.907
4.018	18.625	18.455	0.170	3.872
4.173	19.480	19.054	0.426	3.836
4.546	20.743	20.469	0.274	3.756
4.724	21.408	21.135	0.273	3.720
4.910	22.134	21.823	0.311	3.684
5.091	22.736	22.487	0.248	3.649
5.268	23.338	23.130	0.208	3.616
5.466	24.062	23.843	0.218	3.581
5.858	25.234	25.224	0.340	3.514
6.063	26.173	25.951	0.223	3.481
6.267	26.773	26.657	0.116	3.449
6.546	27.550	27.611	-0.061	3.407
6.732	28.464	28.245	0.219	3.380
6.958	29.186	29.003	0.183	3.348
7.430	30.441	30.568	-0.127	3.284
7.631	31.291	31.227	0.064	3.258
7.864	31.887	31.983	-0.096	3.229
8.106	32.672	32.758	-0.087	3.200
8.313	33.521	33.419	0.102	3.175
8.526	34.121	34.092	0.029	3.151
9.114	35.990	35.926	0.064	3.087
9.387	36.895	36.767	0.128	3.059
9.649	37.428	37.563	-0.135	3.033
9.908	38.398	38.345	0.053	3.008
10.144	38.997	39.053	-0.056	2.986
10.460	40.149	39.992	0.157	2.957
11.004	41.402	41.588	-0.185	2.910
11.315	42.244	42.489	-0.245	2.884
11.601	43.275	43.311	-0.035	2.862
11.904	44.056	44.174	-0.118	2.838
12.171	44.590	44.929	-0.339	2.818
12.430	45.563	45.657	-0.093	2.800
13.076	47.185	47.451	-0.265	2.755
13.365	47.969	48.244	-0.275	2.736
13.741	49.057	49.268	-0.211	2.712
14.041	49.965	50.079	-0.114	2.693
14.353	50.872	50.916	-0.044	2.675
14.732	51.837	51.926	-0.089	2.653
15.342	53.405	53.534	-0.129	2.619
15.691	54.248	54.445	-0.197	2.601
16.069	55.152	55.424	-0.273	2.582
16.484	56.364	56.492	-0.127	2.562

TABLE Ia (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
16.924	57.576	57.614	-0.038	2.541
17.335	58.479	58.655	-0.176	2.523
17.982	60.300	60.278	0.022	2.495
18.248	60.841	60.941	-0.100	2.484
18.500	61.382	61.566	-0.183	2.474
18.784	61.922	62.267	-0.345	2.463
19.027	62.341	62.864	-0.523	2.454
19.275	62.697	63.472	-0.775	2.445
19.937	64.395	65.082	-0.687	2.421
20.241	65.309	65.817	-0.507	2.411
20.561	65.911	66.586	-0.676	2.400
20.890	66.824	67.374	-0.551	2.390
21.164	67.429	68.028	-0.599	2.381
21.450	68.096	68.708	-0.612	2.372
22.074	69.552	70.182	-0.630	2.354
22.438	70.526	71.037	-0.511	2.343
22.727	71.256	71.713	-0.457	2.335
22.992	71.925	72.331	-0.406	2.328
23.331	72.716	73.119	-0.403	2.319
23.612	73.384	73.769	-0.385	2.312
24.255	75.154	75.251	-0.096	2.296
24.563	75.385	75.957	-0.572	2.289
24.877	76.364	76.675	-0.311	2.282
25.211	77.280	77.436	-0.156	2.274
25.505	77.762	78.103	-0.342	2.268
25.827	78.554	78.832	-0.278	2.261
26.397	80.144	80.118	0.027	2.249
26.648	80.691	80.682	0.010	2.244
26.993	81.296	81.455	-0.159	2.237
27.297	81.965	82.134	-0.169	2.232
27.632	82.695	82.880	-0.185	2.225
27.956	83.363	83.600	-0.237	2.219
28.568	84.953	84.955	-0.003	2.209
28.990	85.741	85.886	-0.145	2.201
29.319	86.534	86.609	-0.075	2.196
29.669	87.264	87.377	-0.113	2.190
30.039	88.055	88.186	-0.131	2.185
30.400	88.972	88.974	-0.002	2.179
31.044	90.623	90.374	0.249	2.170
31.418	91.164	91.184	-0.020	2.164
31.797	91.768	92.004	-0.236	2.159
32.155	92.685	92.776	-0.091	2.154
32.523	93.602	93.567	0.034	2.149
32.878	94.207	94.329	-0.122	2.144
33.662	95.788	96.006	-0.218	2.134
34.017	96.581	96.763	-0.183	2.130
34.410	97.428	97.600	-0.171	2.125
34.740	98.160	98.300	-0.140	2.121
35.078	98.891	99.017	-0.126	2.117
35.364	99.505	99.622	-0.117	2.114
36.000	100.718	100.964	-0.246	2.107
36.320	101.390	101.638	-0.248	2.104
36.633	101.992	102.296	-0.303	2.100
36.938	102.724	102.936	-0.211	2.097
37.191	103.270	103.466	-0.196	2.094
37.460	103.564	104.029	-0.465	2.091
37.982	104.973	105.119	-0.146	2.086
38.285	105.334	105.750	-0.416	2.083
38.558	105.938	106.319	-0.381	2.080
38.871	106.419	106.969	-0.550	2.077
39.074	107.096	107.391	-0.294	2.075
39.328	107.391	107.917	-0.527	2.072
39.817	108.170	108.930	-0.760	2.068
40.065	108.594	109.442	-0.848	2.065
40.398	109.133	110.129	-0.996	2.062

TABLE Ia (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
40.733	110.051	110.819	-0.768	2.059
41.048	110.591	111.467	-0.877	2.056
41.348	111.381	112.084	-0.703	2.053
41.946	112.530	113.310	-0.779	2.047
42.160	112.766	113.748	-0.982	2.045
42.451	113.245	114.342	-1.097	2.042
42.746	114.165	114.944	-0.780	2.040
43.057	114.583	115.578	-0.996	2.037
43.339	115.242	116.152	-0.910	2.034
43.977	116.695	117.448	-0.753	2.028
44.272	117.613	118.046	-0.433	2.026
44.599	118.149	118.708	-0.560	2.023
44.884	118.627	119.284	-0.658	2.020
45.312	119.223	120.148	-0.925	2.016
45.597	119.820	120.722	-0.902	2.013
46.261	121.266	122.057	-0.791	2.007
46.598	122.048	122.733	-0.685	2.004
46.895	122.653	123.328	-0.675	2.001
47.221	123.315	123.979	-0.665	1.998
47.570	123.844	124.676	-0.832	1.995
47.867	124.378	125.268	-0.891	1.992
48.538	125.816	126.603	-0.786	1.986
48.871	126.345	127.263	-0.918	1.982
49.145	126.879	127.806	-0.927	1.980
49.433	127.601	128.376	-0.774	1.977
49.751	128.140	129.004	-0.864	1.974
50.066	128.539	129.625	-1.086	1.971
50.626	129.612	130.727	-1.115	1.965
50.927	130.200	131.318	-1.118	1.962
51.214	130.800	131.881	-1.081	1.959
51.460	131.334	132.362	-1.029	1.956
51.770	131.920	132.968	-1.048	1.953
52.122	132.511	133.655	-1.144	1.950
52.899	133.672	135.167	-1.494	1.941
53.265	134.379	135.877	-1.497	1.937
53.661	135.202	136.643	-1.441	1.933
54.059	135.783	137.411	-1.628	1.929
54.440	136.856	138.145	-1.290	1.924
54.866	137.361	138.964	-1.603	1.920
55.703	138.881	140.567	-1.686	1.910
Right Side				
0.075	0.594	0.459	0.135	5.944
0.190	1.074	1.127	-0.053	5.708
0.315	1.680	1.829	-0.150	5.532
0.465	2.539	2.645	-0.106	5.368
0.613	3.458	3.427	0.031	5.234
0.775	4.377	4.266	0.112	5.107
0.926	5.166	5.028	0.138	5.003
1.097	5.833	5.876	-0.043	4.898
1.220	6.549	6.473	0.076	4.828
1.332	7.262	7.013	0.249	4.768
1.468	7.791	7.653	0.138	4.701
1.666	8.769	8.576	0.193	4.609
1.891	9.812	9.603	0.209	4.513
2.083	10.535	10.460	0.074	4.438
2.347	11.768	11.622	0.146	4.342
2.596	12.996	12.693	0.303	4.258
2.827	13.780	13.667	0.113	4.186
3.100	15.257	14.797	0.459	4.106
3.367	16.231	15.883	0.348	4.032
3.598	17.260	16.807	0.453	3.973
3.838	17.603	17.753	-0.150	3.914
4.087	18.756	18.721	0.036	3.856

TABLE Ia (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
4.394	20.166	19.896	0.270	3.788
4.634	21.129	20.799	0.330	3.738
4.912	22.032	21.831	0.201	3.683
5.273	23.316	23.146	0.170	3.616
5.651	24.788	24.502	0.286	3.549
6.021	26.007	25.802	0.206	3.488
6.327	27.158	26.863	0.295	3.440
6.718	28.251	28.196	0.055	3.382
7.079	29.465	29.409	0.056	3.331
7.388	30.550	30.431	0.119	3.289
7.751	31.638	31.616	0.022	3.243
8.120	32.663	32.805	-0.142	3.198
8.465	33.623	33.900	-0.277	3.158
8.746	34.579	34.785	-0.207	3.126
9.091	35.726	35.856	-0.131	3.089
9.494	36.875	37.094	-0.219	3.048
9.898	38.025	38.315	-0.290	3.009
10.256	39.233	39.387	-0.154	2.975
10.566	40.064	40.305	-0.241	2.948
10.909	41.084	41.311	-0.227	2.918
11.263	42.105	42.339	-0.234	2.889
11.595	43.061	43.293	-0.232	2.862
11.980	44.146	44.390	-0.244	2.832
12.323	45.041	45.357	-0.316	2.807
12.727	46.501	46.485	0.016	2.779
13.070	46.894	47.434	-0.539	2.755
13.427	48.166	48.413	-0.248	2.732
13.809	49.125	49.452	-0.327	2.708
14.210	50.274	50.533	-0.259	2.683
14.622	51.360	51.634	-0.273	2.659
15.000	52.383	52.635	-0.252	2.638
15.455	53.598	53.829	-0.232	2.614
15.894	54.748	54.972	-0.223	2.591
16.271	55.772	55.945	-0.173	2.572
16.604	56.605	56.799	-0.194	2.556
17.012	57.443	57.838	-0.395	2.537
17.392	58.467	58.799	-0.332	2.520
17.822	59.994	59.879	0.116	2.502
18.172	60.580	60.752	-0.172	2.488
18.538	61.542	61.660	-0.118	2.473
18.886	62.502	62.518	-0.016	2.459
19.219	62.962	63.335	-0.373	2.447
19.590	64.301	64.240	0.061	2.433
19.923	65.011	65.048	-0.037	2.422
20.209	65.843	65.740	0.104	2.412
20.499	66.426	66.438	-0.012	2.402
20.655	67.124	66.812	0.312	2.397
20.887	67.704	67.367	0.336	2.390
21.153	68.285	68.002	0.283	2.381
21.503	68.936	68.833	0.102	2.371
21.795	69.519	69.524	-0.005	2.362
22.109	70.355	70.264	0.090	2.353
22.448	71.380	71.060	0.320	2.343
22.734	71.839	71.729	0.110	2.335
23.044	72.613	72.452	0.161	2.327
23.359	72.762	73.184	-0.421	2.319
23.621	73.470	73.790	-0.321	2.312
23.928	74.244	74.499	-0.255	2.304
24.260	74.957	75.262	-0.306	2.296
24.608	75.484	76.060	-0.576	2.288
24.924	76.510	76.782	-0.272	2.281
25.241	77.097	77.504	-0.407	2.274
25.522	77.682	78.142	-0.460	2.267
25.885	78.711	78.963	-0.252	2.260
26.283	79.494	79.861	-0.367	2.251

TABLE Ia (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
26.645	80.586	80.675	-0.089	2.244
27.038	81.430	81.555	-0.125	2.236
27.428	82.088	82.426	-0.338	2.229
27.825	83.058	83.310	-0.252	2.222
28.170	83.837	84.075	-0.238	2.216
28.577	84.371	84.975	-0.604	2.208
28.911	85.211	85.712	-0.501	2.203
29.268	85.928	86.497	-0.569	2.197
29.643	86.960	87.320	-0.360	2.191
30.047	87.743	88.204	-0.461	2.184
30.475	88.342	89.137	-0.795	2.178
30.834	89.496	89.918	-0.422	2.173
31.158	89.962	90.621	-0.660	2.168
31.535	90.930	91.438	-0.507	2.162
31.895	91.648	92.215	-0.568	2.157
32.236	92.426	92.950	-0.524	2.153
32.592	93.018	93.716	-0.698	2.148
33.001	94.114	94.593	-0.479	2.143
33.411	94.835	95.470	-0.635	2.138
33.807	95.742	96.316	-0.574	2.133
34.161	96.334	97.070	-0.736	2.128
34.588	97.305	97.978	-0.672	2.123
35.003	98.025	98.858	-0.832	2.118
35.353	99.053	99.598	-0.545	2.114
35.706	100.018	100.344	-0.326	2.110
36.085	100.547	101.143	-0.596	2.106
36.537	101.581	102.094	-0.513	2.101
36.901	102.358	102.858	-0.500	2.097
37.340	103.078	103.778	-0.700	2.092
37.750	103.791	104.635	-0.844	2.088
38.115	104.697	105.396	-0.700	2.084
38.508	105.594	106.215	-0.620	2.081
38.891	106.441	107.011	-0.570	2.077
39.221	107.023	107.696	-0.673	2.073
39.559	107.855	108.396	-0.540	2.070
39.876	108.566	109.051	-0.486	2.067
40.255	109.210	109.834	-0.624	2.063
40.627	110.173	110.601	-0.428	2.060
40.977	110.814	111.321	-0.508	2.056
41.188	111.766	111.755	0.011	2.054
41.337	112.154	112.061	0.093	2.053
41.661	112.853	112.726	0.127	2.050
42.051	113.504	113.525	-0.021	2.046
42.416	114.393	114.271	0.122	2.043
42.691	114.977	114.832	0.145	2.040
43.061	115.365	115.587	-0.222	2.037
43.461	116.263	116.401	-0.137	2.033
43.855	116.901	117.201	-0.300	2.030
44.207	117.605	117.915	-0.309	2.026
44.589	118.120	118.688	-0.568	2.023
44.939	119.003	119.395	-0.392	2.019
45.259	119.264	120.041	-0.777	2.016
45.565	119.774	120.658	-0.884	2.014
45.860	120.473	121.251	-0.779	2.011
46.191	121.102	121.916	-0.815	2.008
46.542	122.240	122.621	-0.380	2.004
46.951	122.939	123.440	-0.501	2.001
47.352	123.627	124.241	-0.615	1.997
47.738	124.202	125.011	-0.809	1.993
48.154	124.887	125.840	-0.952	1.989
48.471	125.330	126.470	-1.140	1.986
48.896	126.272	127.313	-1.041	1.982
49.324	127.083	128.160	-1.078	1.978
49.763	127.771	129.028	-1.256	1.974

TABLE Ia (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
50.055	128.639	129.604	-0.964	1.971
50.468	129.135	130.417	-1.281	1.966
50.857	129.820	131.181	-1.361	1.963
51.185	130.374	131.824	-1.450	1.959
51.508	131.307	132.456	-1.149	1.956
51.884	131.728	133.191	-1.463	1.952
52.257	132.347	133.918	-1.572	1.948
52.577	133.146	134.541	-1.395	1.945
52.870	133.695	135.111	-1.415	1.942
53.215	134.312	135.780	-1.468	1.938
53.537	134.987	136.403	-1.416	1.934
53.848	135.532	137.004	-1.472	1.931
54.162	136.136	137.610	-1.474	1.927
54.535	136.615	138.328	-1.713	1.923
54.918	137.532	139.064	-1.532	1.919
55.272	138.199	139.742	-1.544	1.915
55.677	138.850	140.517	-1.667	1.910

TABLE Ib

SHOT B-7101 4.5-IN.-DIAM 9205 SPHERE

Left Side

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
0.280	1.442	1.662	-0.219	5.714
0.652	3.621	3.724	-0.103	5.398
1.031	5.382	5.723	-0.341	5.173
1.358	7.353	7.387	-0.034	5.017
1.677	8.900	8.966	-0.066	4.886
2.079	10.501	10.902	-0.402	4.741
2.488	13.100	12.816	0.284	4.612
2.919	14.713	14.776	-0.063	4.491
3.408	16.946	16.939	0.007	4.368
3.990	19.488	19.444	0.044	4.238
4.527	21.794	21.690	0.104	4.129
5.083	23.920	23.958	-0.037	4.027
5.582	26.367	25.944	0.422	3.942
6.066	28.074	27.833	0.241	3.866
6.596	30.278	29.862	0.416	3.788
7.211	32.670	32.165	0.504	3.704
7.938	34.938	34.824	0.115	3.612
8.706	37.831	37.562	0.268	3.523
9.297	39.740	39.626	0.113	3.460
9.992	42.208	42.008	0.200	3.390
10.718	44.677	44.443	0.234	3.322
11.290	46.718	46.328	0.389	3.271
11.885	48.263	48.260	0.003	3.222
12.471	50.306	50.134	0.172	3.175
13.124	52.287	52.191	0.096	3.126
13.701	54.021	53.983	0.038	3.085
14.196	55.322	55.502	-0.179	3.051
14.762	57.181	57.218	-0.037	3.014
15.364	59.041	59.021	0.020	2.977
15.922	60.652	60.673	-0.020	2.943
16.452	61.954	62.225	-0.270	2.913
17.125	63.814	64.172	-0.359	2.876
17.666	65.674	65.721	-0.047	2.848
18.212	67.038	67.268	-0.230	2.821
18.586	68.463	68.320	0.143	2.802
18.999	69.268	69.473	-0.205	2.783

TABLE Ib (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
19.412	70.260	70.618	-0.359	2.764
19.882	72.180	71.912	0.268	2.743
20.324	73.109	73.121	-0.012	2.724
20.831	74.595	74.496	0.098	2.703
21.323	75.894	75.821	0.073	2.683
21.897	77.318	77.355	-0.036	2.661
22.397	78.679	78.680	-0.001	2.642
22.933	80.659	80.091	0.568	2.622
23.416	81.523	81.353	0.170	2.605
23.971	83.192	82.794	0.398	2.586
24.488	84.614	84.127	0.487	2.570
25.022	86.097	85.494	0.602	2.553
25.562	87.640	86.868	0.772	2.536
26.125	88.811	88.291	0.520	2.519
26.706	90.291	89.750	0.541	2.503
27.224	91.896	91.043	0.853	2.488
27.843	93.500	92.578	0.921	2.472
28.390	94.668	93.927	0.742	2.458
28.966	95.651	95.338	0.312	2.444
29.437	97.254	96.486	0.767	2.432
29.931	98.238	97.685	0.552	2.421
30.473	99.526	98.994	0.532	2.408
31.007	100.756	100.277	0.479	2.397
31.553	102.426	101.582	0.844	2.385
32.071	103.585	102.815	0.771	2.374
32.700	105.003	104.304	0.699	2.362
33.389	106.538	105.927	0.612	2.348
33.962	107.886	107.269	0.617	2.338
34.483	109.304	108.485	0.820	2.328
35.064	110.341	109.834	0.507	2.318
35.610	111.439	111.098	0.341	2.309
36.149	112.797	112.340	0.457	2.300
36.654	113.715	113.499	0.216	2.292
37.145	114.384	114.623	-0.239	2.284
37.652	115.732	115.779	-0.047	2.277
38.080	117.272	116.752	0.520	2.270
38.403	117.945	117.485	0.460	2.266
38.943	119.302	118.706	0.596	2.258
39.518	120.529	120.002	0.527	2.250
40.067	121.687	121.235	0.451	2.243
40.668	123.104	122.581	0.523	2.235
41.221	124.262	123.815	0.447	2.228
41.845	125.739	125.203	0.536	2.220
42.381	126.848	126.391	0.456	2.214
42.890	127.768	127.517	0.251	2.208
43.406	128.928	128.655	0.273	2.202
43.946	130.228	129.842	0.386	2.196
44.505	131.639	131.068	0.571	2.190
45.052	132.620	132.265	0.355	2.185
45.615	133.912	133.493	0.419	2.179
46.171	135.205	134.703	0.501	2.173
46.613	136.379	135.663	0.716	2.169
47.149	137.613	136.824	0.789	2.164
47.832	138.907	138.300	0.607	2.158
48.536	140.202	139.817	0.386	2.151
49.166	141.689	141.170	0.519	2.146
49.775	142.868	142.475	0.393	2.140
50.341	144.227	143.685	0.542	2.136
51.028	145.529	145.150	0.378	2.130
51.633	147.332	146.438	0.894	2.125
52.230	148.326	147.705	0.621	2.120
52.817	149.262	148.948	0.314	2.116
53.352	150.139	150.079	0.059	2.112
53.956	151.388	151.353	0.035	2.107
54.446	152.697	152.385	0.312	2.104
54.957	153.698	153.459	0.239	2.100

TABLE Ib (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
55.416	154.579	154.422	0.156	2.097
55.749	155.387	155.120	0.267	2.094
56.141	156.268	155.940	0.328	2.092
56.536	157.400	156.766	0.634	2.089
57.040	158.527	157.818	0.709	2.085
57.518	159.354	158.814	0.540	2.082
58.068	160.176	159.958	0.218	2.078
58.550	161.127	160.959	0.168	2.075
59.094	162.332	162.087	0.245	2.072
59.560	163.096	163.052	0.044	2.069
60.071	164.053	164.108	-0.055	2.065
60.532	165.140	165.060	0.080	2.062
60.985	166.157	165.993	0.164	2.060
61.331	166.610	166.705	-0.096	2.057
61.736	167.757	167.538	0.219	2.055
61.995	168.145	168.070	0.075	2.053
62.354	168.971	168.807	0.164	2.051
62.667	169.304	169.448	-0.144	2.049
Right Side				
0.401	1.770	2.345	-0.575	5.594
0.782	4.387	4.420	-0.032	5.314
1.189	6.319	6.536	-0.217	5.094
1.594	8.305	8.561	-0.256	4.918
2.946	14.991	14.898	0.093	4.484
3.378	16.835	16.810	0.025	4.375
3.838	18.742	18.799	-0.058	4.270
4.351	21.020	20.958	0.061	4.164
4.824	22.672	22.909	-0.237	4.073
5.298	25.250	24.819	0.432	3.989
5.832	26.529	26.924	-0.395	3.902
6.310	29.102	28.772	0.330	3.829
6.792	30.744	30.600	0.144	3.760
7.236	32.319	32.257	0.062	3.700
7.778	34.518	34.246	0.271	3.632
8.342	36.467	36.272	0.195	3.564
8.874	38.351	38.154	0.197	3.505
9.381	39.922	39.916	0.006	3.451
10.018	42.055	42.095	-0.040	3.387
10.602	43.997	44.057	-0.060	3.332
11.147	45.875	45.860	0.016	3.284
11.764	47.630	47.869	-0.240	3.232
12.295	49.875	49.574	0.302	3.189
12.863	51.317	51.373	-0.056	3.145
13.444	53.191	53.188	0.003	3.103
13.987	54.629	54.862	-0.233	3.065
14.554	56.501	56.590	-0.089	3.028
15.084	58.371	58.185	0.186	2.994
15.615	59.682	59.766	-0.084	2.961
16.164	61.366	61.383	-0.018	2.929
16.689	63.296	62.913	0.382	2.900
17.190	64.543	64.359	0.184	2.873
17.707	66.162	65.838	0.325	2.846
18.189	67.224	67.203	0.020	2.822
18.579	68.344	68.300	0.044	2.803
18.953	69.775	69.345	0.430	2.785
19.325	71.081	70.378	0.703	2.768
19.747	72.574	71.542	1.032	2.749
20.387	74.193	73.292	0.901	2.721
21.107	75.999	75.241	0.758	2.692
21.799	77.680	77.094	0.586	2.664
22.382	79.297	78.641	0.657	2.642
23.068	81.287	80.445	0.843	2.618
23.727	82.533	82.162	0.371	2.595
24.328	84.088	83.715	0.372	2.575

TABLE Ib (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
24.938	85.766	85.280	0.487	2.555
25.583	87.012	86.922	0.091	2.535
26.199	88.567	88.478	0.089	2.517
26.783	89.749	89.943	-0.194	2.501
27.450	91.862	91.605	0.257	2.482
28.137	93.354	93.304	0.050	2.464
28.784	95.094	94.893	0.201	2.448
29.420	96.338	96.445	-0.107	2.433
30.119	98.079	98.140	-0.061	2.416
30.760	99.695	99.684	0.011	2.402
31.318	101.063	101.021	0.042	2.390
31.895	102.243	102.396	-0.154	2.378
32.538	103.737	103.921	-0.184	2.365
33.160	105.542	105.388	0.153	2.353
33.816	107.026	106.928	0.098	2.340
34.320	108.149	108.105	0.044	2.331
34.981	109.513	109.642	-0.129	2.320
35.553	111.257	110.966	0.291	2.310
36.036	112.619	112.080	0.540	2.302
36.472	113.362	113.082	0.280	2.295
36.988	114.235	114.264	-0.029	2.287
37.480	115.287	115.387	-0.100	2.279
38.023	116.530	116.623	-0.093	2.271
38.661	119.633	118.069	1.564	2.262
39.300	120.755	119.511	1.244	2.253
39.995	122.368	121.074	1.294	2.244
40.739	123.730	122.740	0.991	2.234
41.422	124.912	124.263	0.650	2.226
42.050	126.714	125.658	1.056	2.218
42.768	128.445	127.247	1.198	2.210
43.450	129.686	128.752	0.934	2.202
44.121	131.296	130.227	1.070	2.194
44.789	132.476	131.690	0.786	2.187
45.377	133.836	132.975	0.861	2.181
45.864	135.075	134.036	1.039	2.176
46.411	135.944	135.225	0.719	2.171
46.897	136.873	136.279	0.594	2.166
47.356	137.861	137.272	0.589	2.162
47.833	138.909	138.302	0.607	2.158
48.287	139.837	139.281	0.557	2.153
48.710	141.135	140.191	0.945	2.150
49.122	141.693	141.076	0.617	2.146
49.515	142.061	141.918	0.142	2.143
49.928	143.298	142.803	0.495	2.139
50.380	144.284	143.769	0.516	2.135
50.877	145.520	144.829	0.692	2.131
51.247	146.077	145.617	0.460	2.128
51.766	146.812	146.720	0.092	2.124
52.252	147.677	147.752	-0.075	2.120
52.702	148.482	148.705	-0.223	2.117
53.178	149.276	149.712	-0.436	2.113
53.656	150.510	150.721	-0.211	2.110
54.134	151.803	151.728	0.075	2.106
54.574	152.786	152.654	0.132	2.103
54.919	153.591	153.379	0.212	2.100
55.327	154.574	154.236	0.338	2.097
55.794	155.376	155.214	0.162	2.094
56.215	156.298	156.095	0.203	2.091
56.674	156.969	157.054	-0.085	2.088
57.104	158.070	157.951	0.119	2.085
57.476	158.742	158.727	0.015	2.082
57.684	159.177	159.160	0.018	2.081
57.999	160.100	159.815	0.285	2.079
58.391	161.201	160.629	0.572	2.076
58.842	161.750	161.565	0.184	2.073

TABLE Ib (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
59.304	162.918	162.522	0.395	2.070
59.777	163.955	163.501	0.454	2.067
60.194	164.873	164.362	0.510	2.064
60.645	165.789	165.293	0.496	2.062
61.138	166.204	166.308	-0.104	2.058
61.506	167.122	167.065	0.057	2.056
61.932	167.798	167.941	-0.143	2.053
62.318	169.084	168.733	0.351	2.051
62.713	169.750	169.543	0.207	2.049

TABLE Ic

SHOT B-7102 6.0-IN.-DIAM 9205 SPHERE

Left Side

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
1.557	8.400	8.568	-0.168	5.104
1.807	9.851	9.834	0.017	5.018
2.064	11.156	11.113	0.043	4.936
2.377	12.604	12.643	-0.039	4.845
2.656	14.059	13.983	0.076	4.771
2.955	15.662	15.399	0.263	4.696
3.245	17.120	16.749	0.371	4.629
3.532	18.282	18.069	0.214	4.566
3.824	19.743	19.394	0.349	4.505
4.123	21.057	20.733	0.324	4.446
4.382	22.078	21.876	0.202	4.398
4.660	23.543	23.095	0.448	4.348
4.924	24.417	24.236	0.182	4.302
5.192	25.958	25.382	0.576	4.258
5.468	26.834	26.552	0.283	4.214
5.769	28.080	27.811	0.268	4.168
6.101	29.769	29.186	0.583	4.120
6.400	30.498	30.412	0.086	4.078
6.744	32.337	31.807	0.530	4.031
7.111	33.659	33.278	0.380	3.983
7.509	35.202	34.856	0.346	3.934
7.923	36.671	36.472	0.199	3.885
8.304	37.995	37.943	0.052	3.841
8.699	39.615	39.454	0.161	3.798
9.095	41.162	40.949	0.213	3.756
9.538	43.079	42.604	0.475	3.711
9.941	44.775	44.090	0.685	3.672
10.470	46.248	46.020	0.228	3.622
10.939	47.723	47.709	0.014	3.580
11.365	49.050	49.226	-0.176	3.544
11.725	50.601	50.496	0.104	3.514
12.102	51.855	51.815	0.040	3.483
12.492	53.406	53.168	0.239	3.452
12.995	55.105	54.894	0.211	3.414
13.410	56.879	56.305	0.574	3.383
13.842	58.134	57.760	0.375	3.353
14.278	59.389	59.215	0.174	3.323
14.679	60.498	60.542	-0.044	3.296
15.080	61.753	61.858	-0.105	3.270
15.497	63.454	63.216	0.238	3.243
15.884	64.563	64.467	0.096	3.219
16.260	65.596	65.673	-0.076	3.197
16.636	67.001	66.871	0.130	3.175
17.016	68.183	68.073	0.111	3.153

TABLE Ic (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
17.413	69.513	69.320	0.193	3.131
17.786	70.844	70.484	0.360	3.111
18.187	72.175	71.727	0.448	3.089
18.625	73.430	73.075	0.355	3.066
19.081	74.686	74.468	0.218	3.044
19.509	76.163	75.766	0.397	3.022
19.937	77.493	77.056	0.438	3.002
20.321	78.527	78.205	0.322	2.984
20.781	79.782	79.573	0.209	2.963
21.161	80.889	80.696	0.194	2.946
21.482	82.146	81.639	0.507	2.932
21.871	82.882	82.777	0.105	2.916
22.238	84.212	83.844	0.368	2.900
22.699	85.541	85.177	0.364	2.882
23.151	86.720	86.475	0.245	2.864
23.655	87.825	87.913	-0.088	2.844
24.121	89.079	89.235	-0.156	2.826
24.620	90.331	90.640	-0.309	2.808
25.101	91.880	91.987	-0.106	2.791
25.567	92.985	93.284	-0.299	2.775
26.039	94.238	94.590	-0.352	2.759
26.487	95.490	95.822	-0.332	2.744
26.974	96.964	97.154	-0.191	2.728
27.515	98.363	98.626	-0.263	2.711
28.070	99.985	100.125	-0.140	2.694
28.551	101.156	101.417	-0.261	2.679
29.038	102.337	102.719	-0.381	2.665
29.511	103.508	103.976	-0.468	2.652
30.104	105.057	105.544	-0.487	2.635
30.636	106.676	106.942	-0.266	2.621
31.165	108.365	108.324	0.041	2.607
31.773	109.472	109.904	-0.432	2.591
32.363	111.749	111.429	0.320	2.577
32.990	112.625	113.040	-0.415	2.561
33.539	114.692	114.442	0.250	2.548
34.106	115.709	115.884	-0.175	2.536
34.603	116.887	117.141	-0.254	2.524
35.211	118.572	118.672	-0.100	2.511
35.764	119.818	120.057	-0.239	2.500
36.356	121.363	121.533	-0.170	2.487
37.008	122.756	123.151	-0.394	2.474
37.581	124.072	124.565	-0.494	2.463
38.197	126.055	126.079	-0.024	2.451
38.826	127.589	127.617	-0.029	2.440
39.410	128.613	129.039	-0.426	2.429
39.973	130.008	130.404	-0.396	2.420
40.492	131.924	131.658	0.266	2.411
40.998	132.720	132.875	-0.155	2.402
41.610	134.113	134.342	-0.229	2.392
42.173	135.878	135.687	0.191	2.383
42.754	137.042	137.069	-0.027	2.374
43.370	138.435	138.528	-0.093	2.365
43.893	139.681	139.763	-0.082	2.357
44.331	141.079	140.794	0.284	2.351
44.632	141.961	141.502	0.460	2.347
45.052	142.840	142.486	0.354	2.341
45.528	143.707	143.599	0.108	2.334
45.996	144.885	144.690	0.195	2.328
46.413	145.914	145.659	0.255	2.323
46.839	146.793	146.648	0.146	2.317
47.290	147.442	147.691	-0.250	2.311
47.737	148.690	148.723	-0.033	2.306
48.244	149.568	149.891	-0.323	2.300
48.784	150.665	151.131	-0.466	2.293
49.300	152.063	152.312	-0.250	2.287

TABLE Ic (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
49.858	153.380	153.587	-0.207	2.281
50.432	154.627	154.894	-0.267	2.274
51.055	156.614	156.308	0.305	2.267
51.624	157.792	157.597	0.195	2.261
52.091	158.522	158.652	-0.129	2.256
52.621	159.322	159.846	-0.524	2.251
53.086	160.574	160.892	-0.318	2.246
53.603	161.685	162.052	-0.367	2.241
54.142	162.936	163.258	-0.322	2.236
54.687	164.177	164.475	-0.298	2.231
55.162	165.510	165.534	-0.023	2.226
55.691	166.683	166.710	-0.027	2.221
56.237	167.277	167.922	-0.645	2.216
56.785	168.301	169.135	-0.834	2.212
57.303	170.156	170.279	-0.124	2.207
57.777	170.812	171.325	-0.513	2.203
58.243	172.148	172.350	-0.202	2.199
58.797	173.475	173.567	-0.092	2.195
59.298	174.663	174.666	-0.003	2.191
60.065	175.691	176.344	-0.653	2.185
60.490	177.030	177.272	-0.241	2.181
60.938	177.771	178.248	-0.478	2.178
61.360	178.731	179.167	-0.435	2.175
61.720	179.473	179.949	-0.476	2.172
Right Side				
0.194	0.754	1.175	-0.422	5.889
0.436	2.251	2.572	-0.320	5.665
0.668	3.290	3.863	-0.573	5.510
0.893	4.467	5.092	-0.625	5.386
1.156	6.314	6.489	-0.175	5.263
1.515	7.805	8.352	-0.547	5.120
1.919	9.887	10.392	-0.504	4.982
2.283	12.174	12.187	-0.013	4.872
2.756	14.395	14.462	-0.067	4.745
3.117	16.369	16.156	0.213	4.658
3.556	18.346	18.180	0.166	4.560
3.987	20.389	20.127	0.262	4.472
4.447	22.132	22.162	-0.031	4.386
4.932	24.538	24.271	0.267	4.301
5.442	26.643	26.443	0.200	4.218
5.971	29.261	28.653	0.609	4.138
6.547	31.728	31.010	0.718	4.058
7.165	33.819	33.495	0.324	3.977
7.780	36.350	35.916	0.434	3.902
8.346	38.431	38.105	0.327	3.837
8.986	40.954	40.540	0.415	3.768
9.491	42.808	42.427	0.381	3.716
10.078	45.028	44.593	0.435	3.659
10.614	46.581	46.541	0.040	3.609
11.123	48.651	48.366	0.285	3.564
11.755	50.939	50.602	0.337	3.511
12.321	52.858	52.576	0.282	3.466
12.837	54.554	54.354	0.200	3.426
13.460	56.543	56.474	0.069	3.380
14.148	58.902	58.782	0.119	3.332
14.801	61.186	60.944	0.243	3.288
15.462	63.026	63.103	-0.077	3.245
16.105	64.718	65.177	-0.459	3.206
16.626	67.079	66.839	0.240	3.175
17.227	68.846	68.737	0.109	3.141
17.611	70.246	69.939	0.307	3.120
18.039	71.572	71.269	0.303	3.097
18.466	72.750	72.587	0.163	3.075

TABLE Ic (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
18.911	74.299	73.950	0.349	3.052
19.374	75.478	75.358	0.120	3.029
19.872	77.026	76.860	0.166	3.005
20.311	78.132	78.175	-0.043	2.985
20.649	79.313	79.181	0.132	2.969
21.006	80.569	80.238	0.331	2.953
21.293	81.307	81.084	0.223	2.941
21.488	82.268	81.657	0.611	2.932
21.792	82.857	82.546	0.311	2.919
22.113	83.966	83.481	0.485	2.906
22.554	85.148	84.758	0.389	2.887
22.995	86.553	86.028	0.525	2.870
23.470	88.031	87.387	0.645	2.851
24.009	89.067	88.918	0.149	2.831
24.477	90.251	90.238	0.012	2.813
24.863	91.361	91.322	0.040	2.799
25.359	92.547	92.706	-0.158	2.782
25.746	93.881	93.780	0.101	2.768
26.217	94.920	95.080	-0.160	2.753
26.782	96.552	96.630	-0.078	2.734
27.197	97.443	97.762	-0.318	2.721
27.726	99.003	99.197	-0.194	2.704
28.242	101.080	100.588	0.492	2.688
28.823	101.756	102.145	-0.389	2.671
29.432	103.682	103.767	-0.084	2.654
29.904	104.658	105.016	-0.358	2.641
30.421	106.446	106.378	0.068	2.626
30.886	107.263	107.596	-0.333	2.614
31.376	108.681	108.874	-0.193	2.601
31.830	110.019	110.052	-0.034	2.590
32.292	111.067	111.246	-0.179	2.578
32.710	112.185	112.322	-0.136	2.568
33.211	113.455	113.605	-0.150	2.556
33.653	114.725	114.733	-0.008	2.546
34.170	115.696	116.046	-0.349	2.534
34.630	116.967	117.209	-0.242	2.524
35.148	117.940	118.514	-0.574	2.513
35.595	118.921	119.635	-0.714	2.503
36.078	120.263	120.841	-0.578	2.493
36.585	121.536	122.102	-0.566	2.483
37.094	122.810	123.364	-0.554	2.473
37.585	123.864	124.575	-0.712	2.463
38.058	125.207	125.738	-0.531	2.454
38.486	125.959	126.787	-0.828	2.446
39.025	127.604	128.103	-0.498	2.436
39.576	129.100	129.442	-0.342	2.426
40.148	130.827	130.827	-0.000	2.416
40.703	131.283	132.166	-0.882	2.407
41.269	132.640	133.526	-0.885	2.398
41.665	134.792	134.474	0.318	2.391
42.214	135.628	135.784	-0.156	2.383
42.743	136.234	137.043	-0.809	2.374
43.231	137.658	138.200	-0.542	2.367
43.700	139.301	139.308	-0.007	2.360
44.102	140.502	140.256	0.247	2.354
44.447	140.732	141.067	-0.335	2.349
44.647	141.548	141.537	0.012	2.347
44.934	142.595	142.210	0.386	2.343
45.372	143.567	143.234	0.333	2.336
45.910	144.921	144.489	0.432	2.329
46.354	145.962	145.522	0.440	2.323
46.770	147.163	146.488	0.675	2.318
47.218	147.913	147.525	0.388	2.312
47.735	148.815	148.719	0.096	2.306
48.302	150.307	150.024	0.283	2.299

TABLE Ic (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
48.765	151.357	151.087	0.270	2.293
49.281	152.256	152.269	-0.012	2.287
49.824	153.526	153.509	0.017	2.281
50.320	155.013	154.639	0.374	2.275
50.830	155.761	155.798	-0.037	2.270
51.275	156.656	156.807	-0.150	2.265
51.858	158.072	158.126	-0.053	2.259
52.360	159.107	159.258	-0.152	2.254
52.892	160.890	160.456	0.434	2.248
53.386	161.562	161.565	-0.003	2.243
53.878	162.223	162.667	-0.445	2.238
54.302	163.563	163.616	-0.053	2.234
54.812	164.671	164.754	-0.082	2.230
55.299	165.479	165.839	-0.360	2.225
55.738	166.886	166.814	0.071	2.221
56.247	167.991	167.944	0.047	2.216
56.717	168.954	168.984	-0.030	2.212
57.208	169.607	170.070	-0.463	2.208
57.581	170.570	170.893	-0.323	2.205
58.005	171.451	171.827	-0.376	2.201
58.467	172.700	172.843	-0.143	2.197
58.899	173.198	173.791	-0.593	2.194
59.312	174.376	174.697	-0.320	2.191
59.660	175.035	175.458	-0.424	2.188
60.089	176.280	176.396	-0.116	2.184
60.456	176.406	177.198	-0.792	2.182
60.843	176.840	178.041	-1.201	2.179
61.213	178.004	178.847	-0.843	2.176
61.580	179.177	179.645	-0.468	2.173
61.825	179.605	180.177	-0.572	2.171

TABLE Id

SHOT B-7103 3-IN.-DIAM 9205 SPHERE

Left Side

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
0.075	0.799	0.454	0.345	5.946
0.167	1.670	0.993	0.677	5.748
0.338	2.601	1.954	0.648	5.505
0.563	3.451	3.166	0.284	5.276
0.741	4.312	4.091	0.221	5.132
0.905	5.103	4.924	0.179	5.017
1.053	5.972	5.659	0.313	4.924
1.262	6.685	6.675	0.009	4.805
1.442	7.626	7.534	0.092	4.713
1.704	8.632	8.752	-0.120	4.592
1.972	9.640	9.965	-0.324	4.481
2.276	10.497	11.309	-0.812	4.367
2.520	11.958	12.366	-0.407	4.283
2.741	13.273	13.304	-0.032	4.212
2.986	14.215	14.330	-0.114	4.138
3.301	15.524	15.618	-0.094	4.050
3.608	16.611	16.848	-0.237	3.970
3.962	18.292	18.239	0.053	3.885
4.392	19.595	19.889	-0.294	3.789
4.863	21.270	21.650	-0.380	3.693
5.243	22.878	23.039	-0.161	3.621
5.666	24.485	24.556	-0.071	3.546

TABLE Id (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
6.075	26.093	25.991	0.103	3.479
6.475	27.481	27.371	0.110	3.417
6.798	28.650	28.467	0.184	3.370
7.205	30.262	29.827	0.435	3.314
7.639	31.128	31.253	-0.126	3.257
8.015	32.445	32.469	-0.024	3.210
8.391	33.984	33.667	0.317	3.166
8.800	35.226	34.951	0.275	3.121
9.307	36.759	36.521	0.238	3.067
9.774	38.295	37.941	0.354	3.021
10.329	39.975	39.604	0.371	2.969
10.744	40.993	40.828	0.165	2.932
11.200	42.084	42.157	-0.072	2.894
11.667	43.397	43.499	-0.102	2.856
12.146	44.859	44.859	-0.000	2.820
12.532	45.952	45.942	0.010	2.792
13.013	47.338	47.277	0.062	2.759
13.471	48.949	48.534	0.415	2.729
13.938	49.963	49.801	0.162	2.700
14.398	51.276	51.036	0.239	2.672
14.796	52.443	52.095	0.347	2.649
15.208	53.087	53.182	-0.095	2.627
15.642	54.326	54.317	0.008	2.604
16.071	55.564	55.430	0.135	2.582
16.459	56.359	56.428	-0.069	2.563
16.896	57.744	57.543	0.201	2.543
17.309	59.205	58.590	0.616	2.524
17.709	60.072	59.596	0.476	2.507
18.100	61.162	60.573	0.590	2.491
18.538	62.100	61.660	0.441	2.473
19.012	63.332	62.827	0.505	2.455
19.470	64.268	63.948	0.320	2.438
19.931	65.277	65.068	0.209	2.421
20.424	66.729	66.257	0.472	2.405
20.918	67.958	67.441	0.517	2.389
21.359	68.967	68.492	0.475	2.375
21.789	70.051	69.510	0.541	2.362
22.225	71.059	70.537	0.522	2.349
22.575	71.850	71.358	0.493	2.340
23.036	72.856	72.433	0.422	2.327
23.290	73.877	73.024	0.853	2.320
23.712	74.811	74.000	0.801	2.310
24.187	76.112	75.095	1.017	2.298
24.690	77.335	76.248	1.087	2.286
25.123	77.968	77.235	0.733	2.276
25.622	79.117	78.368	0.748	2.265
26.082	80.342	79.408	0.934	2.256
26.565	81.192	80.495	0.697	2.246
26.986	82.272	81.439	0.833	2.237
27.450	83.050	82.475	0.574	2.229
27.917	84.198	83.514	0.684	2.220
28.378	85.570	84.535	1.035	2.212
28.892	86.714	85.670	1.044	2.203
29.342	87.416	86.660	0.756	2.196
29.791	88.564	87.644	0.921	2.188
30.297	89.485	88.749	0.735	2.181
30.773	90.407	89.786	0.622	2.173
31.237	91.924	90.792	1.132	2.167
31.727	92.696	91.852	0.843	2.160
32.129	93.327	92.720	0.608	2.154
32.538	94.626	93.600	1.026	2.149
32.977	95.328	94.542	0.786	2.143
33.475	96.543	95.607	0.935	2.137
33.973	97.680	96.670	1.011	2.131
34.490	98.970	97.770	1.200	2.124

TABLE Id (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
34.952	99.524	98.750	0.774	2.119
35.396	100.670	99.689	0.981	2.114
35.912	101.509	100.779	0.730	2.108
36.387	102.351	101.779	0.573	2.103
36.874	103.573	102.801	0.771	2.097
37.418	104.628	103.941	0.687	2.092
37.871	105.703	104.887	0.815	2.087
38.355	106.764	105.896	0.868	2.082
38.815	107.388	106.853	0.535	2.077
39.330	108.896	107.921	0.975	2.072
39.836	109.886	108.969	0.917	2.067
40.270	110.742	109.865	0.877	2.063
40.778	111.581	110.912	0.669	2.058
41.198	112.359	111.776	0.584	2.054
41.612	113.578	112.625	0.953	2.050
42.095	114.720	113.615	1.106	2.046
42.593	115.561	114.632	0.929	2.041
43.061	116.265	115.587	0.679	2.037
43.533	117.259	116.547	0.712	2.032
43.999	118.104	117.493	0.611	2.028
44.472	119.468	118.451	1.017	2.024
44.939	120.024	119.395	0.628	2.019
45.413	121.019	120.352	0.667	2.015
45.790	121.873	121.111	0.762	2.012
46.197	122.805	121.928	0.876	2.008
46.500	123.297	122.536	0.760	2.005
46.907	124.449	123.352	1.098	2.001
47.341	125.230	124.219	1.011	1.997
47.775	125.860	125.085	0.776	1.993
48.204	126.782	125.939	0.843	1.989
48.672	127.641	126.869	0.772	1.984
49.179	128.637	127.873	0.763	1.979
49.698	129.702	128.899	0.803	1.974
50.209	130.629	129.907	0.722	1.969
50.722	131.707	130.916	0.791	1.964
51.175	132.710	131.804	0.906	1.959
51.677	133.261	132.787	0.474	1.954
52.113	134.347	133.638	0.709	1.950
52.569	135.352	134.526	0.826	1.945
53.028	135.908	135.417	0.491	1.940
53.515	136.992	136.361	0.632	1.935
53.941	137.632	137.184	0.448	1.930
54.319	138.196	137.912	0.283	1.926
54.773	139.285	138.786	0.500	1.921
55.243	140.074	139.687	0.388	1.915
55.665	140.938	140.494	0.444	1.910
56.146	141.728	141.412	0.316	1.905
56.575	142.513	142.228	0.285	1.899
56.959	143.831	142.956	0.875	1.895
57.385	144.187	143.762	0.425	1.890
57.834	145.123	144.609	0.514	1.884
58.254	146.142	145.399	0.743	1.878
58.693	146.871	146.223	0.648	1.873
59.067	147.524	146.922	0.601	1.868
59.419	148.318	147.579	0.739	1.863
59.812	149.052	148.310	0.741	1.858
60.164	149.927	148.963	0.964	1.853
60.526	150.284	149.633	0.651	1.848
60.907	150.940	150.336	0.604	1.843
Right Side				
0.183	1.130	1.086	0.224	5.720
0.403	2.324	2.310	0.014	5.432
0.647	3.485	3.607	-0.122	5.205

TABLE Id (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
0.919	5.018	4.992	0.026	5.008
1.111	6.088	5.945	0.143	4.889
1.394	6.946	7.303	-0.357	4.737
1.653	8.393	8.515	-0.122	4.615
1.920	9.690	9.733	-0.044	4.502
2.151	10.980	10.761	0.218	4.412
2.423	11.901	11.951	-0.050	4.315
2.658	13.115	12.955	0.160	4.238
2.943	14.406	14.150	0.256	4.151
3.377	15.856	15.926	-0.069	4.030
3.737	17.446	17.358	0.088	3.938
4.064	18.438	18.633	-0.195	3.861
4.433	19.654	20.043	-0.388	3.780
4.851	21.245	21.605	-0.360	3.695
5.200	22.977	22.882	0.095	3.629
5.569	24.486	24.209	0.278	3.563
5.911	25.474	25.417	0.056	3.506
6.247	26.460	26.588	-0.128	3.452
6.573	27.593	27.704	-0.111	3.403
7.033	29.402	29.254	0.148	3.337
7.429	30.464	30.565	-0.102	3.284
7.816	31.972	31.826	0.146	3.235
8.269	33.184	33.279	-0.095	3.180
8.630	34.391	34.420	-0.029	3.139
8.994	35.153	35.554	-0.401	3.100
9.413	36.885	36.845	0.040	3.056
9.790	37.646	37.990	-0.344	3.019
10.239	38.858	39.336	-0.478	2.977
10.736	40.296	40.805	-0.509	2.933
11.146	41.878	42.000	-0.122	2.898
11.517	43.012	43.070	-0.058	2.868
11.908	44.148	44.185	-0.037	2.838
12.355	45.509	45.446	0.063	2.805
12.764	46.647	46.588	0.059	2.776
13.182	47.784	47.742	0.042	2.748
13.625	49.371	48.953	0.418	2.719
14.057	50.287	50.122	0.165	2.692
14.516	51.652	51.351	0.301	2.665
14.896	52.566	52.360	0.206	2.644
15.322	53.632	53.481	0.151	2.621
15.745	54.923	54.585	0.338	2.598
16.146	55.989	55.623	0.366	2.578
16.531	57.128	56.612	0.516	2.560
16.954	58.122	57.691	0.432	2.540
17.401	59.193	58.822	0.372	2.520
17.823	60.560	59.881	0.679	2.502
18.295	61.857	61.058	0.799	2.483
18.609	62.548	61.835	0.713	2.470
18.991	63.542	62.773	0.769	2.456
19.256	64.305	63.425	0.880	2.446
19.634	65.151	64.347	0.804	2.432
20.116	66.748	65.515	1.233	2.415
20.595	67.603	66.668	0.935	2.400
21.096	68.460	67.866	0.594	2.383
21.605	69.617	69.075	0.542	2.367
22.058	70.620	70.144	0.476	2.354
22.455	71.694	71.077	0.617	2.343
22.837	72.693	71.970	0.724	2.332
23.203	73.244	72.822	0.423	2.323
23.584	74.839	73.705	1.134	2.313
24.056	75.847	74.794	1.054	2.301
24.340	76.466	75.446	1.020	2.294
24.734	77.320	76.348	0.972	2.285
25.241	78.408	77.504	0.904	2.274
25.683	79.712	78.506	1.206	2.264

TABLE Id (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
26.149	80.276	79.559	0.716	2.254
26.628	81.437	80.637	0.800	2.244
27.025	82.144	81.526	0.618	2.237
27.518	83.381	82.626	0.755	2.227
27.964	84.243	83.618	0.624	2.219
28.428	85.180	84.646	0.534	2.211
28.882	86.192	85.648	0.544	2.203
29.382	87.358	86.748	0.611	2.195
29.804	88.367	87.672	0.694	2.188
30.333	89.314	88.828	0.486	2.180
30.774	90.549	89.788	0.761	2.173
31.226	91.487	90.769	0.719	2.167
31.673	92.501	91.736	0.765	2.161
32.083	93.510	92.620	0.890	2.155
32.511	94.670	93.541	1.129	2.150
33.027	95.691	94.649	1.042	2.142
33.513	96.114	95.688	0.426	2.136
33.994	97.577	96.714	0.863	2.130
34.509	98.152	97.810	0.342	2.124
35.041	99.325	98.938	0.386	2.118
35.521	100.713	99.954	0.760	2.112
35.948	101.353	100.854	0.499	2.108
36.434	102.446	101.877	0.568	2.102
36.985	103.467	103.034	0.433	2.096
37.490	104.790	104.091	0.699	2.091
38.016	105.585	105.190	0.395	2.086
38.541	106.980	106.283	0.696	2.080
39.065	108.154	107.372	0.782	2.075
39.498	108.869	108.269	0.599	2.071
39.991	110.329	109.289	1.040	2.066
40.464	111.047	110.265	0.782	2.061
40.890	112.200	111.142	1.057	2.057
41.379	112.999	112.147	0.851	2.053
41.932	113.943	113.281	0.662	2.047
42.385	114.807	114.207	0.600	2.043
42.900	116.047	115.258	0.788	2.038
43.463	116.990	116.405	0.585	2.033
44.023	118.012	117.542	0.470	2.028
44.483	119.164	118.474	0.691	2.024
45.064	120.556	119.648	0.908	2.018
45.581	121.572	120.690	0.882	2.013
46.091	122.725	121.716	1.010	2.009
46.611	123.739	122.759	0.980	2.004
47.061	124.665	123.660	1.006	2.000
47.365	125.060	124.267	0.793	1.997
47.766	125.611	125.067	0.544	1.993
48.121	126.688	125.774	0.914	1.990
48.487	127.526	126.501	1.024	1.986
48.785	128.068	127.093	0.975	1.983
48.968	128.601	127.456	1.145	1.981
49.418	129.382	128.346	1.036	1.977
49.813	130.299	129.126	1.173	1.973
50.264	131.299	130.015	1.284	1.969
50.789	132.152	131.047	1.105	1.963
51.346	133.075	132.139	0.936	1.958
51.835	133.843	133.095	0.748	1.952
52.299	134.758	134.000	0.758	1.948
52.786	135.753	134.947	0.805	1.942
53.275	136.296	135.896	0.400	1.937
53.754	137.357	136.823	0.534	1.932
54.268	138.267	137.814	0.453	1.926
54.748	139.405	138.738	0.667	1.921
55.209	140.160	139.622	0.538	1.916
55.640	140.923	140.446	0.476	1.911
55.965	141.821	141.067	0.755	1.907

TABLE Id (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
56.465	142.503	142.019	0.484	1.901
56.930	143.402	142.901	0.501	1.895
57.272	144.147	143.548	0.599	1.891
57.682	144.902	144.323	0.580	1.886
58.111	145.496	145.130	0.366	1.880
58.493	146.018	145.848	0.170	1.875
58.862	147.069	146.539	0.530	1.871
59.201	147.508	147.172	0.336	1.866
59.529	148.396	147.784	0.613	1.862
59.838	148.994	148.358	0.636	1.858
60.185	149.510	149.002	0.508	1.853
60.543	150.475	149.665	0.810	1.848
60.934	150.987	150.386	0.601	1.842

TABLE Ie

SHOT B-7104 4.5-IN.-DIAM 9205 SPHERE

Left Side

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
0.186	0.861	1.119	-0.258	5.829
0.385	1.943	2.254	-0.311	5.609
0.554	2.735	3.188	-0.453	5.469
0.811	4.329	4.571	-0.242	5.296
1.208	6.130	6.631	-0.501	5.085
1.581	7.936	8.496	-0.560	4.923
1.974	10.405	10.402	0.003	4.777
2.370	11.842	12.267	-0.426	4.648
2.744	13.502	13.986	-0.483	4.539
3.110	15.534	15.628	-0.094	4.442
3.439	17.127	17.077	0.050	4.361
3.861	18.785	18.896	-0.111	4.265
4.246	20.226	20.523	-0.297	4.184
4.632	22.036	22.125	-0.089	4.109
5.037	23.771	23.770	0.001	4.035
5.416	25.139	25.289	-0.150	3.969
5.758	26.807	26.635	0.172	3.914
6.122	28.324	28.051	0.273	3.857
6.495	29.694	29.479	0.215	3.802
6.898	31.060	30.998	0.062	3.746
7.247	32.580	32.300	0.280	3.699
7.607	33.877	33.620	0.257	3.653
8.072	35.829	35.306	0.523	3.596
8.468	37.271	36.721	0.550	3.550
8.866	38.490	38.127	0.363	3.506
9.319	40.074	39.704	0.370	3.457
9.656	41.152	40.861	0.291	3.423
10.064	42.296	42.249	0.047	3.383
10.431	43.444	43.486	-0.041	3.348
10.800	44.814	44.714	0.100	3.314
11.204	46.254	46.046	0.209	3.279
11.551	47.257	47.178	0.079	3.249
11.993	48.767	48.607	0.160	3.213
12.386	49.617	49.864	-0.247	3.182
12.808	50.907	51.199	-0.292	3.150
13.183	52.128	52.376	-0.248	3.122
13.553	53.275	53.526	-0.252	3.095
13.922	54.422	54.663	-0.241	3.070
14.289	55.716	55.786	-0.070	3.045

TABLE Ie (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
14.685	56.565	56.986	-0.421	3.019
15.088	58.078	58.197	-0.119	2.994
15.427	58.931	59.208	-0.276	2.973
15.810	60.002	60.344	-0.342	2.950
16.201	61.293	61.491	-0.198	2.927
16.609	62.509	62.681	-0.172	2.904
17.029	63.797	63.897	-0.100	2.881
17.371	64.797	64.878	-0.081	2.863
17.791	65.863	66.077	-0.214	2.842
18.208	67.151	67.256	-0.105	2.821
18.633	68.290	68.452	-0.163	2.800
19.036	69.356	69.576	-0.220	2.781
19.484	70.566	70.816	-0.250	2.761
19.897	71.557	71.954	-0.397	2.742
20.375	73.059	73.259	-0.200	2.722
20.803	73.974	74.422	-0.448	2.704
21.202	75.040	75.496	-0.456	2.688
21.579	76.256	76.506	-0.251	2.673
21.885	76.961	77.323	-0.361	2.661
22.241	77.957	78.269	-0.311	2.648
22.431	78.602	78.769	-0.167	2.641
22.780	79.598	79.690	-0.092	2.628
23.198	80.586	80.784	-0.198	2.613
23.583	81.578	81.788	-0.210	2.600
24.134	82.846	83.215	-0.368	2.581
24.571	84.201	84.339	-0.138	2.567
25.131	85.320	85.773	-0.453	2.549
25.637	86.444	87.059	-0.615	2.534
26.107	87.868	88.245	-0.378	2.520
26.637	89.505	89.578	-0.073	2.505
27.145	90.702	90.846	-0.144	2.491
27.615	91.681	92.015	-0.334	2.478
28.177	92.722	93.403	-0.681	2.463
28.730	94.503	94.760	-0.257	2.449
29.172	95.632	95.841	-0.209	2.439
29.668	96.606	97.049	-0.443	2.427
30.149	98.025	98.212	-0.187	2.416
30.608	98.928	99.320	-0.392	2.405
31.034	99.910	100.342	-0.433	2.396
31.467	101.333	101.377	-0.043	2.387
31.862	102.391	102.317	0.074	2.378
32.418	103.282	103.637	-0.356	2.367
32.868	104.333	104.701	-0.368	2.358
33.335	105.381	105.800	-0.419	2.349
33.750	106.214	106.773	-0.559	2.342
34.104	107.350	107.600	-0.250	2.335
34.531	108.107	108.596	-0.489	2.328
34.961	109.233	109.595	-0.362	2.320
35.429	110.501	110.679	-0.178	2.312
35.867	111.625	111.690	-0.065	2.305
36.286	112.013	112.654	-0.642	2.298
36.656	112.997	113.504	-0.507	2.292
36.995	113.690	114.279	-0.589	2.287
37.314	114.756	115.010	-0.254	2.282
37.657	115.670	115.791	-0.121	2.277
38.036	116.726	116.651	0.075	2.271
38.459	117.703	117.611	0.092	2.265
38.955	118.668	118.734	-0.066	2.258
39.416	119.417	119.773	-0.357	2.252
39.868	120.463	120.789	-0.326	2.245
40.287	121.438	121.729	-0.291	2.240
40.718	122.634	122.694	-0.060	2.234
41.129	123.536	123.611	-0.075	2.229
41.543	123.921	124.532	-0.611	2.224
41.971	124.893	125.484	-0.590	2.219

TABLE Ie (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
42.331	126.025	126.280	-0.255	2.215
42.762	126.775	127.234	-0.458	2.210
43.188	127.600	128.174	-0.574	2.205
43.638	128.939	129.165	-0.226	2.200
44.035	129.841	130.038	-0.197	2.195
44.532	130.803	131.127	-0.324	2.190
45.080	131.830	132.327	-0.496	2.184
Right Side				
0.166	1.085	1.000	0.085	5.858
0.363	2.095	2.131	-0.036	5.629
0.615	3.257	3.521	-0.264	5.424
0.868	4.931	4.873	0.058	5.263
1.091	6.003	6.033	-0.030	5.142
1.306	6.701	7.127	-0.427	5.040
1.517	8.060	8.180	-0.120	4.949
1.751	9.273	9.327	-0.054	4.857
1.982	10.335	10.441	-0.106	4.774
2.238	11.398	11.651	-0.253	4.689
2.546	13.277	13.078	0.199	4.595
2.884	14.492	14.619	-0.127	4.501
3.227	15.851	16.146	-0.295	4.412
3.518	17.353	17.421	-0.068	4.342
3.842	18.634	18.815	-0.181	4.269
4.169	20.136	20.198	-0.061	4.200
4.488	21.858	21.530	0.328	4.136
4.813	22.841	22.865	-0.025	4.075
5.154	23.971	24.241	-0.270	4.014
5.420	25.097	25.305	-0.208	3.969
5.658	26.590	26.245	0.344	3.930
5.875	27.712	27.092	0.620	3.895
6.198	28.397	28.345	0.052	3.846
6.554	29.822	29.701	0.121	3.794
6.891	31.100	30.973	0.126	3.747
7.182	32.595	32.058	0.537	3.708
7.491	33.354	33.197	0.157	3.668
7.835	34.484	34.452	0.032	3.625
8.292	36.361	36.096	0.265	3.570
9.167	39.301	39.176	0.125	3.473
9.632	40.738	40.781	-0.043	3.425
10.065	42.173	42.254	-0.081	3.383
10.481	43.756	43.654	0.102	3.343
10.869	45.042	44.943	0.099	3.308
11.306	46.186	46.380	-0.194	3.270
11.704	47.844	47.677	0.168	3.236
12.119	48.988	49.012	-0.024	3.203
12.522	49.984	50.296	-0.312	3.171
12.951	51.575	51.648	-0.073	3.139
13.381	52.797	52.991	-0.193	3.108
13.787	54.314	54.249	0.066	3.079
14.205	54.947	55.529	-0.582	3.051
14.563	56.166	56.616	-0.450	3.027
15.029	57.767	58.022	-0.255	2.997
15.425	59.287	59.204	0.084	2.973
15.885	60.151	60.564	-0.413	2.946
16.229	61.372	61.575	-0.202	2.926
16.618	62.526	62.709	-0.183	2.904
17.006	63.902	63.831	0.071	2.883
17.405	64.837	64.976	-0.139	2.861
17.833	66.146	66.197	-0.051	2.839
18.267	67.457	67.424	0.032	2.818
18.696	68.546	68.628	-0.081	2.797
19.178	69.644	69.969	-0.325	2.775
19.537	70.726	70.963	-0.236	2.758

TABLE Ie (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
19.958	72.114	72.122	-0.008	2.740
20.378	73.132	73.267	-0.134	2.722
20.685	74.210	74.101	0.108	2.709
20.911	74.611	74.712	-0.101	2.699
21.213	75.466	75.526	-0.059	2.687
21.573	75.961	76.492	-0.530	2.673
22.002	77.280	77.634	-0.354	2.656
22.470	78.457	78.873	-0.416	2.639
22.893	79.923	79.986	-0.063	2.624
23.358	80.436	81.203	-0.767	2.607
23.859	81.990	82.504	-0.514	2.590
24.362	83.397	83.804	-0.407	2.574
24.898	84.366	85.179	-0.813	2.556
25.399	85.921	86.455	-0.534	2.541
25.931	87.629	87.802	-0.173	2.525
26.455	88.894	89.121	-0.228	2.510
26.916	90.000	90.276	-0.755	2.497
27.387	91.626	91.448	0.177	2.484
27.845	92.510	92.584	-0.074	2.472
28.296	93.245	93.695	-0.450	2.460
28.683	94.340	94.647	-0.306	2.451
29.128	95.666	95.734	-0.069	2.440
29.621	96.481	96.933	-0.452	2.428
30.096	97.736	98.083	-0.347	2.417
30.475	98.607	98.999	-0.392	2.408
30.936	100.302	100.107	0.195	2.398
31.317	100.655	101.020	-0.364	2.390
31.749	101.754	102.048	-0.294	2.381
32.188	102.631	103.092	-0.461	2.372
32.648	103.880	104.181	-0.301	2.363
33.626	106.162	106.483	-0.321	2.344
34.127	107.488	107.654	-0.166	2.335
34.627	108.515	108.821	-0.306	2.326
35.109	109.539	109.939	-0.400	2.317
35.611	110.860	111.100	-0.240	2.309
36.053	111.802	112.119	-0.318	2.302
36.466	112.517	113.067	-0.550	2.295
36.833	113.447	113.909	-0.462	2.289
37.253	114.677	114.870	-0.193	2.283
37.694	115.539	115.875	-0.336	2.276
38.169	116.550	116.954	-0.403	2.269
38.683	118.302	118.119	0.183	2.262
39.241	118.873	119.378	-0.505	2.254
39.729	120.100	120.477	-0.377	2.247
40.166	121.393	121.457	-0.064	2.242
40.546	122.014	122.307	-0.293	2.237
41.046	122.865	123.426	-0.561	2.230
41.627	124.160	124.719	-0.559	2.223
42.150	125.300	125.879	-0.578	2.217
42.564	126.505	126.798	-0.293	2.212
42.973	127.263	127.700	-0.437	2.207
43.415	128.611	128.674	-0.063	2.202
43.389	129.441	129.713	-0.272	2.197
44.390	130.341	130.817	-0.476	2.192
44.823	131.679	131.764	-0.085	2.187
45.189	132.349	132.564	-0.215	2.183

TABLE If

SHOT B-7105 6.0-IN.-DIAM 9205 SPHERE

Left Side

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
0.697	3.958	4.023	-0.065	5.492
0.956	5.355	5.429	-0.074	5.355
1.220	6.978	6.824	0.154	5.236
1.489	8.304	8.217	0.087	5.130
1.734	9.558	9.467	0.091	5.042
2.028	10.960	10.933	0.027	4.948
2.321	12.513	12.371	0.141	4.861
2.583	13.694	13.636	0.058	4.790
2.832	14.802	14.818	-0.016	4.726
3.048	16.286	15.834	0.452	4.674
3.330	17.244	17.145	0.010	4.609
3.580	18.503	18.290	0.214	4.555
4.153	21.319	20.867	0.451	4.440
4.528	22.574	22.518	0.056	4.371
4.918	24.428	24.209	0.219	4.303
5.304	26.431	25.857	0.575	4.240
5.622	27.690	27.196	0.494	4.191
5.957	28.650	28.594	0.056	4.140
6.236	30.209	29.741	0.468	4.101
6.627	31.690	31.334	0.356	4.047
7.340	34.432	34.187	0.245	3.955
7.732	36.062	35.729	0.332	3.907
8.142	37.990	37.322	0.668	3.860
8.523	39.247	38.782	0.465	3.817
8.937	40.728	40.354	0.375	3.773
9.291	41.911	41.685	0.227	3.736
9.642	43.095	42.988	0.107	3.701
10.026	44.575	44.402	0.173	3.664
10.818	47.236	47.275	-0.039	3.591
11.149	48.568	48.459	0.109	3.562
11.535	49.749	49.827	-0.078	3.529
11.868	50.782	50.998	-0.216	3.502
12.232	52.113	52.267	-0.155	3.473
12.611	53.516	53.578	-0.062	3.443
12.937	54.698	54.696	0.002	3.418
13.344	55.876	56.081	-0.205	3.388
14.093	58.757	58.599	0.158	3.335
14.489	59.711	59.914	-0.204	3.308
14.976	61.406	61.518	-0.112	3.276
15.430	62.803	62.999	-0.196	3.247
15.846	63.978	64.344	-0.366	3.222
16.230	65.304	65.577	-0.273	3.198
16.632	66.777	66.858	-0.081	3.175
17.025	67.877	68.101	-0.224	3.152
17.806	70.002	70.546	-0.545	3.109
18.177	71.251	71.696	-0.446	3.090
18.571	72.722	72.910	-0.188	3.069
18.998	73.818	74.216	-0.398	3.048
19.436	75.137	75.546	-0.409	3.026
19.851	76.232	76.797	-0.565	3.006
20.248	77.402	77.987	-0.584	2.988
20.516	78.282	78.786	-0.504	2.975
21.162	80.333	80.699	-0.365	2.946
21.530	81.355	81.780	-0.425	2.930
21.843	82.903	82.695	0.208	2.917
22.054	82.739	83.310	-0.570	2.908
22.246	83.698	83.867	-0.170	2.900
22.527	84.425	84.680	-0.256	2.886
22.930	85.593	85.841	-0.248	2.872
23.341	86.834	87.018	-0.184	2.856

TABLE If (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
24.108	88.797	89.198	-0.401	2.827
24.449	89.893	90.160	-0.267	2.814
24.769	91.214	91.058	0.155	2.803
25.144	91.560	92.107	-0.547	2.789
25.499	92.803	93.095	-0.292	2.777
25.887	93.819	94.170	-0.351	2.764
26.219	94.914	95.086	-0.171	2.753
26.583	95.932	96.085	-0.153	2.741
27.304	97.744	98.053	-0.309	2.717
27.653	98.691	98.999	-0.308	2.706
28.085	100.067	100.166	-0.098	2.693
28.555	101.300	101.428	-0.128	2.679
28.979	102.167	102.561	-0.395	2.667
29.454	103.179	103.825	-0.646	2.653
29.853	104.487	104.881	-0.395	2.642
30.263	105.723	105.962	-0.239	2.631
31.184	108.258	108.374	-0.116	2.606
31.607	108.973	109.474	-0.501	2.595
32.115	110.790	110.789	0.001	2.583
32.551	111.504	111.913	-0.409	2.572
32.972	112.589	112.994	-0.405	2.562
33.440	113.749	114.190	-0.441	2.551
33.888	114.681	115.330	-0.649	2.540
34.361	115.681	116.529	-0.848	2.530
35.238	117.777	118.740	-0.963	2.511
35.615	119.385	119.685	-0.300	2.503
36.055	120.467	120.784	-0.317	2.493
36.507	121.619	121.909	-0.290	2.484
36.961	123.000	123.035	-0.034	2.475
37.414	123.782	124.154	-0.372	2.466
37.861	124.944	125.254	-0.310	2.458
38.313	126.176	126.363	-0.188	2.449
39.263	128.186	128.682	-0.496	2.432
39.687	129.340	129.711	-0.371	2.424
40.180	130.720	130.905	-0.185	2.416
40.707	131.796	132.175	-0.379	2.407
41.091	132.805	133.099	-0.294	2.401
41.505	133.671	134.091	-0.420	2.394
41.943	134.605	135.138	-0.533	2.387
42.423	135.537	136.282	-0.745	2.379
43.265	137.790	138.280	-0.490	2.367
43.727	138.944	139.372	-0.428	2.360
44.154	139.881	140.378	-0.497	2.354
44.602	140.967	141.431	-0.464	2.347
44.992	142.138	142.345	-0.207	2.342
45.216	142.411	142.870	-0.458	2.339
45.490	143.071	143.510	-0.439	2.335
45.921	143.860	144.515	-0.655	2.329
46.708	145.813	146.344	-0.530	2.319
47.075	146.608	147.194	-0.586	2.314
47.408	147.565	147.964	-0.399	2.310
47.753	148.362	148.760	-0.398	2.306
48.094	149.079	149.546	-0.467	2.301
48.515	149.951	150.513	-0.562	2.296
48.907	150.816	151.413	-0.596	2.292
49.323	151.910	152.365	-0.455	2.287
50.196	153.807	154.357	-0.550	2.277
50.628	154.822	155.339	-0.517	2.272
51.127	156.134	156.472	-0.338	2.266
51.546	156.861	157.420	-0.559	2.262
52.016	157.806	158.482	-0.676	2.257
52.418	158.836	159.389	-0.553	2.253
52.780	159.788	160.204	-0.416	2.249
53.119	160.742	160.966	-0.224	2.246

TABLE If (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
53.930	162.276	162.784	-0.508	2.238
54.363	163.378	163.752	-0.374	2.234
54.784	163.881	164.691	-0.810	2.230
55.147	164.687	165.500	-0.813	2.226
55.556	165.343	166.410	-1.067	2.222
56.027	166.377	167.456	-1.079	2.218
56.402	167.485	168.287	-0.802	2.215
56.832	168.213	169.239	-1.026	2.211
57.848	170.958	171.481	-0.523	2.203
58.293	171.919	172.460	-0.542	2.199
58.643	172.952	173.229	-0.277	2.196
59.079	173.696	174.186	-0.490	2.192
59.492	175.030	175.091	-0.061	2.189
59.894	175.926	175.970	-0.044	2.186
60.338	176.743	176.940	-0.197	2.183
60.702	177.191	177.734	-0.543	2.180
Right Side				
0.103	0.921	0.633	0.288	6.015
0.310	1.783	1.847	-0.064	5.770
0.502	2.636	2.944	-0.308	5.616
0.746	3.866	4.290	-0.424	5.465
1.006	5.243	5.697	-0.454	5.331
1.312	6.994	7.306	-0.311	5.198
1.612	8.516	8.849	-0.333	5.085
1.930	10.259	10.447	-0.188	4.978
2.294	12.227	12.239	-0.012	4.869
2.597	13.739	13.701	0.037	4.786
2.964	15.551	15.439	0.112	4.694
3.336	17.136	17.170	-0.033	4.608
3.673	18.718	18.710	0.008	4.536
4.022	20.448	20.280	0.167	4.466
4.416	21.804	22.025	-0.220	4.391
4.843	23.757	23.887	-0.130	4.316
5.271	26.380	25.718	0.662	4.245
5.657	27.582	27.344	0.238	4.185
6.056	29.158	29.004	0.154	4.126
6.431	30.881	30.540	0.341	4.073
6.821	32.455	32.118	0.337	4.021
7.133	33.505	33.368	0.137	3.981
7.556	35.602	35.038	0.564	3.928
7.925	36.727	36.481	0.246	3.884
8.404	38.450	38.330	0.120	3.830
8.766	40.172	39.707	0.465	3.791
9.160	41.596	41.192	0.405	3.750
9.514	42.646	42.514	0.132	3.714
9.969	44.146	44.194	-0.048	3.669
10.341	45.794	45.552	0.242	3.634
10.821	47.370	47.286	0.084	3.591
11.232	48.572	48.754	-0.182	3.555
11.653	50.073	50.243	-0.171	3.520
12.051	51.499	51.638	-0.139	3.487
12.467	53.002	53.081	-0.080	3.454
12.930	54.803	54.672	0.131	3.419
13.426	56.533	56.359	0.174	3.382
13.822	57.589	57.693	-0.103	3.354
14.246	59.318	59.109	0.210	3.325
14.693	60.526	60.588	-0.062	3.295
15.148	62.035	62.080	-0.046	3.265
15.576	63.542	63.472	0.070	3.238
15.983	64.602	64.785	-0.183	3.213
16.383	65.738	66.066	-0.328	3.189
16.821	67.024	67.457	-0.433	3.164
17.199	68.757	68.649	0.108	3.143

TABLE If (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
17.594	69.970	69.886	0.084	3.121
18.038	70.960	71.266	-0.306	3.097
18.466	72.325	72.587	-0.262	3.075
18.903	73.989	73.926	0.063	3.052
19.365	75.581	75.331	0.250	3.030
19.835	76.278	76.749	-0.471	3.007
20.302	77.873	78.148	-0.275	2.985
20.817	79.472	79.680	-0.208	2.962
21.267	80.693	81.008	-0.315	2.942
21.678	82.063	82.213	-0.150	2.924
22.121	83.511	83.504	0.007	2.905
22.554	84.884	84.758	0.126	2.888
22.854	85.129	85.623	-0.494	2.875
23.083	86.787	86.280	0.507	2.866
23.410	86.959	87.215	-0.256	2.854
23.786	88.405	88.286	0.120	2.839
24.228	89.334	89.537	-0.202	2.822
24.704	90.714	90.876	-0.162	2.805
25.162	92.019	92.157	-0.138	2.789
25.582	93.397	93.325	0.071	2.774
26.052	94.480	94.625	-0.146	2.758
26.481	95.784	95.806	-0.021	2.744
26.906	96.940	96.969	-0.028	2.730
27.323	97.872	98.104	-0.232	2.717
27.838	98.663	99.500	-0.836	2.701
28.317	100.125	100.790	-0.665	2.686
28.816	101.662	102.126	-0.465	2.672
29.239	102.300	103.254	-0.954	2.659
29.632	103.457	104.297	-0.840	2.648
30.094	105.220	105.517	-0.298	2.635
30.636	106.241	106.942	-0.701	2.621
31.126	107.178	108.223	-1.045	2.608
31.605	109.164	109.469	-0.305	2.595
32.020	110.105	110.544	-0.439	2.585
32.542	111.346	111.890	-0.544	2.572
33.014	112.513	113.101	-0.588	2.561
33.488	113.530	114.312	-0.783	2.550
33.901	114.621	115.363	-0.742	2.540
34.407	115.862	116.646	-0.784	2.529
34.876	117.259	117.829	-0.570	2.518
35.351	117.977	119.023	-1.046	2.508
35.831	120.115	120.225	-0.109	2.498
36.258	120.528	121.290	-0.761	2.489
36.639	121.167	122.237	-1.070	2.482
37.048	122.398	123.250	-0.852	2.473
37.592	124.103	124.593	-0.490	2.463
38.099	125.494	125.839	-0.345	2.453
38.623	126.746	127.122	-0.376	2.444
39.085	127.682	128.249	-0.567	2.435
39.574	128.780	129.437	-0.657	2.426
40.040	129.566	130.566	-1.001	2.418
40.609	131.711	131.939	-0.229	2.409
41.119	132.580	133.166	-0.586	2.400
41.577	133.603	134.263	-0.660	2.393
41.990	134.982	135.250	-0.268	2.386
42.497	135.849	136.458	-0.609	2.378
43.035	137.238	137.735	-0.498	2.370
43.555	138.554	138.966	-0.412	2.362
43.995	139.643	140.004	-0.361	2.356
44.394	140.717	140.943	-0.226	2.350
44.970	141.736	142.294	-0.558	2.342
45.436	142.754	143.384	-0.630	2.336
45.927	144.053	144.529	-0.476	2.329
46.358	145.057	145.532	-0.475	2.323
46.756	145.467	146.455	-0.988	2.318

TABLE If (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
47.153	147.216	147.374	-0.158	2.313
47.519	147.983	148.220	-0.237	2.308
47.824	148.824	148.924	-0.100	2.305
48.118	149.894	149.601	0.294	2.301
48.557	150.814	150.610	0.204	2.296
49.115	151.969	151.889	0.080	2.289
49.597	152.748	152.991	-0.243	2.284
50.036	153.673	153.992	-0.319	2.279
50.539	155.041	155.137	-0.096	2.273
51.165	156.412	156.558	-0.145	2.266
51.777	157.790	157.943	-0.152	2.260
52.354	158.704	159.245	-0.540	2.254
52.958	159.997	160.604	-0.607	2.247
53.646	161.589	162.148	-0.559	2.241
54.267	163.245	163.537	-0.293	2.235

TABLE If (cont)

Time (μsec)	Meas Shock Distance (mm)	Calc Shock Distance (mm)	Residual $R_{meas}-R_{calc}$ (mm)	Calc Shock Velocity (mm/μsec)
54.902	164.458	164.955	-0.497	2.229
55.439	165.436	166.150	-0.714	2.224
56.091	166.862	167.598	-0.736	2.218
56.740	169.174	169.035	0.139	2.212
57.165	169.543	169.975	-0.431	2.208
57.654	170.290	171.053	-0.763	2.204
58.078	171.335	171.987	-0.652	2.201
58.462	171.919	172.832	-0.913	2.197
58.809	172.592	173.594	-1.002	2.195
59.228	173.842	174.513	-0.671	2.191
59.750	174.726	175.655	-0.929	2.187
60.155	175.682	176.541	-0.859	2.184
60.501	176.938	177.296	-0.358	2.181
60.879	177.591	178.120	-0.528	2.178

at $\tau = 1$. Within the accuracy of our data there is no indication that any improvement in the fit is obtained with nonzero ϵ.

Figures 5a through f show plots of the residuals ($\beta_{measured}-\beta_{calculated}$) for the fits to the measured data for each sphere. These residuals represent position errors of about 0.5 mm; the total distance under observation is 500 mm.

One of the goals of this experiment was to see if the data from spheres of different diameters would scale. Figure 6 is a plot of the data points from all six spheres in reduced variables. It is obvious that the data do scale quite well. The next step was to use the EILEEN code to fit the above equation to the data from all six spheres lumped together as one data set. The equation resulting from this fit is

$$\beta = 1 + (7.303 \times 10^{-1} + 4.928 \times 10^{-2}\tau - 5.948 \times 10^{-4}\tau^2)(\tau-1) - 2.77 \times 10^{-1}(\tau-1)^{3/2} \quad . \qquad (4)$$

Figures 7a through f are plots of the residuals for the individual spheres, and the calculated β is from the equation fitted to the data from all six spheres. Tables Ia through f give a complete list of the measured and calculated distances and the residuals for each sphere in millimeters. Although these residuals do not appear to be completely random, they do give a good measure of the experimental error from shot to shot, which is in the neighborhood of 1 mm. Probably the largest uncertainty, which may be responsible for most of the difference, is in the determination of effective camera magnification.

The next point of interest is the calculated shock velocity and resulting pressure-distance plots. The expression for the reduced shock velocity obtained by differentiating Eq. (4) with respect to τ, is

$$\frac{d\beta}{d\tau} = U_{red} = 6.810 \times 10^{-1} + 9.975 \times 10^{-2}\tau - 1.784 \times 10^{-3}\tau^2 - 4.166 \times 10^{-1}(\tau-1)^{1/2}. \qquad (5)$$

The shock velocity in mm/μsec is then obtained by multiplying U_{red} by D (8.17 mm/μsec). A plot of shock velocity vs reduced distance is shown in Fig. 8. The pressure is determined from the conservation of momentum equation

$$P = \rho_o U u \quad . \qquad (6)$$

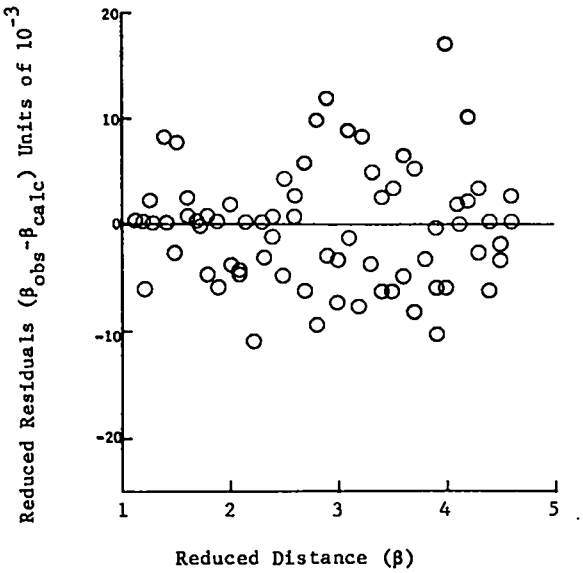
The relationship between U and u used in this calculation is [4,11]

$$U = 1.647 + 1.921\, u - 0.096\, u^2. \qquad (7)$$

The density ρ_o is that of the water before being shocked. A plot of pressure vs reduced distance is shown in Fig. 9. The relationship between U and u is not really known to be satisfactory. It was obtained from data taken at higher pressures than our experiment, and there are no data for our lower pressure range. Additional Hugoniot data for water in the low-pressure region would be of considerable interest for this and other problems.

Residual Plot, Shot B7100, 3.0-in. Sphere

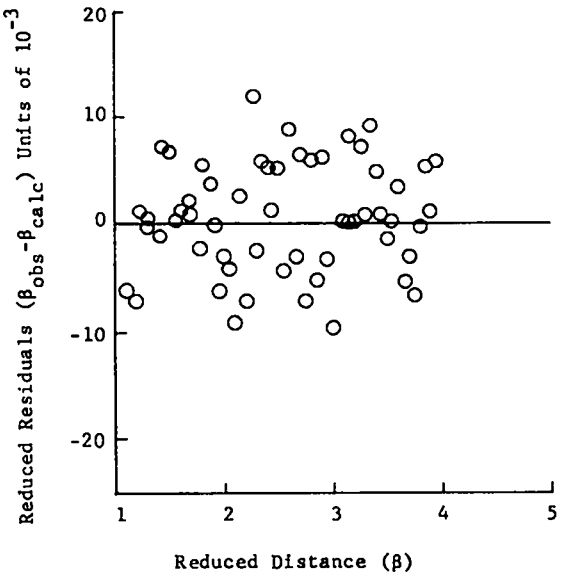
$$\beta = 1 + (7.436 \times 10^{-1} + 5.872 \times 10^{-2}\tau - 8.528 \times 10^{-4}\tau^2)(\tau-1) - 3.055 \times 10^{-1}(\tau-1)^{3/2}$$



(a)

Residual Plot, Shot B7101, 4.5-in. Sphere

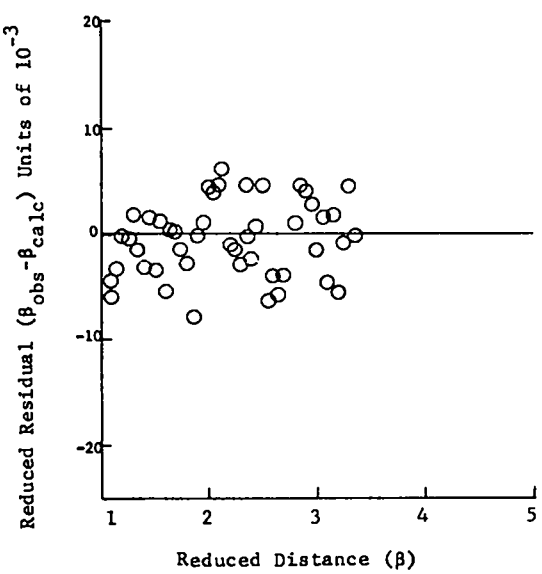
$$\beta = 1 + (7.300 \times 10^{-1} + 5.118 \times 10^{-2}\tau - 7.130 \times 10^{-4}\tau^2)(\tau-1) - 2.800 \times 10^{-1}(\tau-1)^{3/2}$$



(b)

Residual Plot, Shot B7102, 6.0-in. Sphere

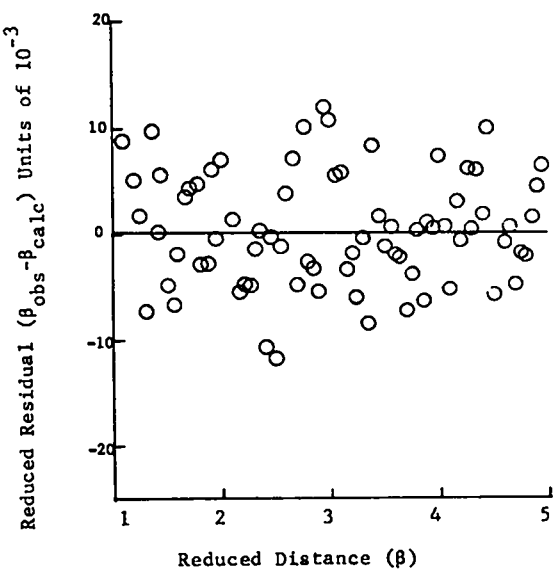
$$\beta = 1 + (7.437 \times 10^{-1} + 6.406 \times 10^{-2}\tau - 1.142 \times 10^{-3}\tau^2)(\tau-1) - 3.146 \times 10^{-1}(\tau-1)^{3/2}$$



(c)

Residual Plot, Shot B7103, 3.0-in. Sphere

$$\beta = 1 + (7.171 \times 10^{-1} + 4.331 \times 10^{-2}\tau - 4.970 \times 10^{-4}\tau^2)(\tau-1) - 2.558 \times 10^{-1}(\tau-1)^{3/2}$$

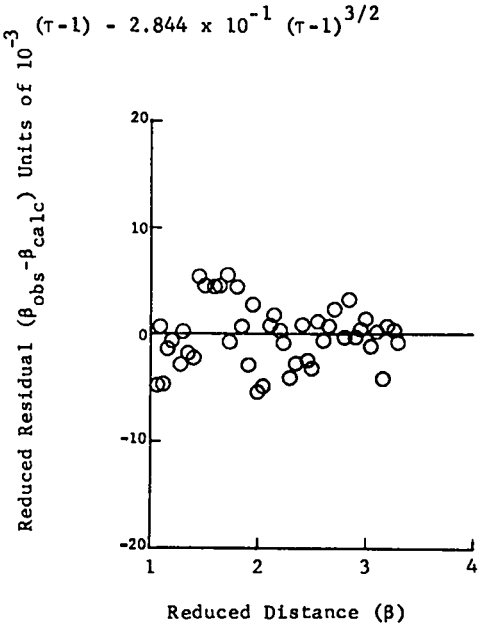


(d)

Fig. 5. Residual plots from fit to each individual sphere.

Residual Plot, Shot B7104, 4.5-in. Sphere

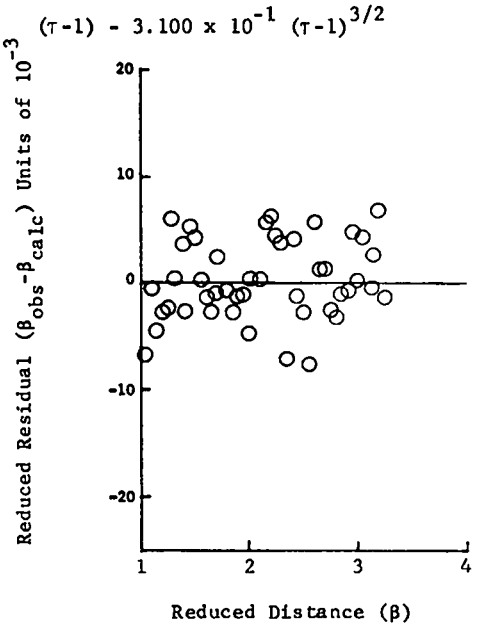
$\beta = 1 + (7.338 \times 10^{-1} + 5.099 \times 10^{-2}\tau - 5.932 \times 10^{-4}\tau^2)(\tau-1) - 2.844 \times 10^{-1}(\tau-1)^{3/2}$



(e)

Residual Plot, Shot B7105, 6.0-in. Sphere

$\beta = 1 + (7.401 \times 10^{-1} + 6.222 \times 10^{-2}\tau - 1.051 \times 10^{-3}\tau^2)(\tau-1) - 3.100 \times 10^{-1}(\tau-1)^{3/2}$



(f)

Fig. 5. (cont)

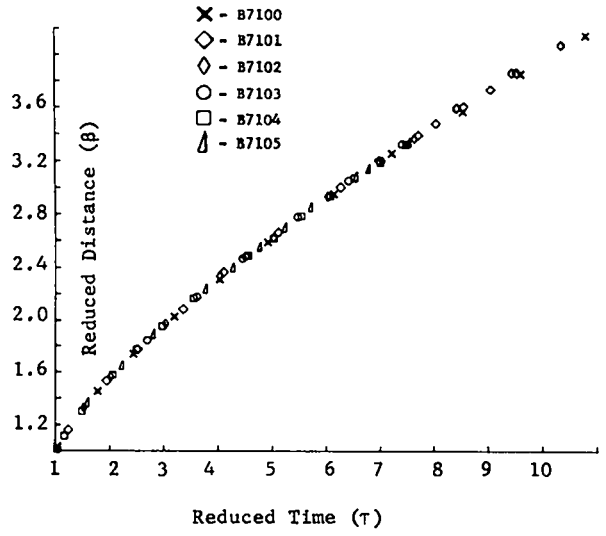


Fig. 6. Reduced distance vs reduced time. Adjusted data for all six spheres.

A test of the appropriateness of the equation chosen is provided by considering the initial velocity of the water shock. The equation is chosen to make the deceleration of the shock infinite at the initial point. If this assumption were greatly in error, the detonation pressure of the explosive implied by the initial shock velocity in water would be far from any reasonable value. The fit gives an initial velocity of 6.36 mm/μsec, which corresponds to a pressure of 183 kbar in the water. Making the match in the P-u plane, one finds that the explosive pressure necessary to drive this shock is about 281 kbar. Extensive experimental data for 9205 are not available, but a few shots by Craig[12] give a pressure of 275 ± 15 kbar, whereas a BKW calculation[13] by Mader[14] gives 288 kbar. The agreement among these values does not mean that fitting the shock trajectory with Eq. (3) and extrapolating back is a good way to obtain detonation pressure, but it does mean that the fitting form is appropriate and that no large error is introduced by setting c [discussed in the paragraph following Eq. (3)] equal to zero.

Effective use of the data presented in this report requires not only knowledge of the peak pressure at any time t, but also an indication of how the pressure changes with distance behind the shock front. The pressure gradient behind the shock front can be calculated from the rate of

change of pressure at the shock front. Using the flow equations, the total derivatives of pressure and particle velocity along the shock path, the Hugoniot relationship, and the conservation of mass equation, it can be shown that

$$\left(\frac{\partial P}{\partial r}\right)_t = -\left(\frac{\rho_o U}{\eta}\right)\left\{\frac{2u}{r} + \frac{1}{\rho c^2}\left(\frac{dP}{dt}\right)_s\left[1 + \frac{\rho_o U}{M^2}\left(\frac{du}{dP}\right)_H\right]\right\} \quad (8)$$

where $\eta = 1 - M^2$ and $M = \frac{(U-u)}{c}$. In this expression, $\left(\frac{\partial P}{\partial r}\right)_t$ is the pressure gradient behind the shock at some instant of time, ρ is the density of the water at the corresponding shock pressure, r is the distance from the center of the spherical coordinate system, and c is the sound velocity in water at the shock pressure. $\left(\frac{dP}{dt}\right)_s$ is the rate of change of pressure at the shock front. This expression

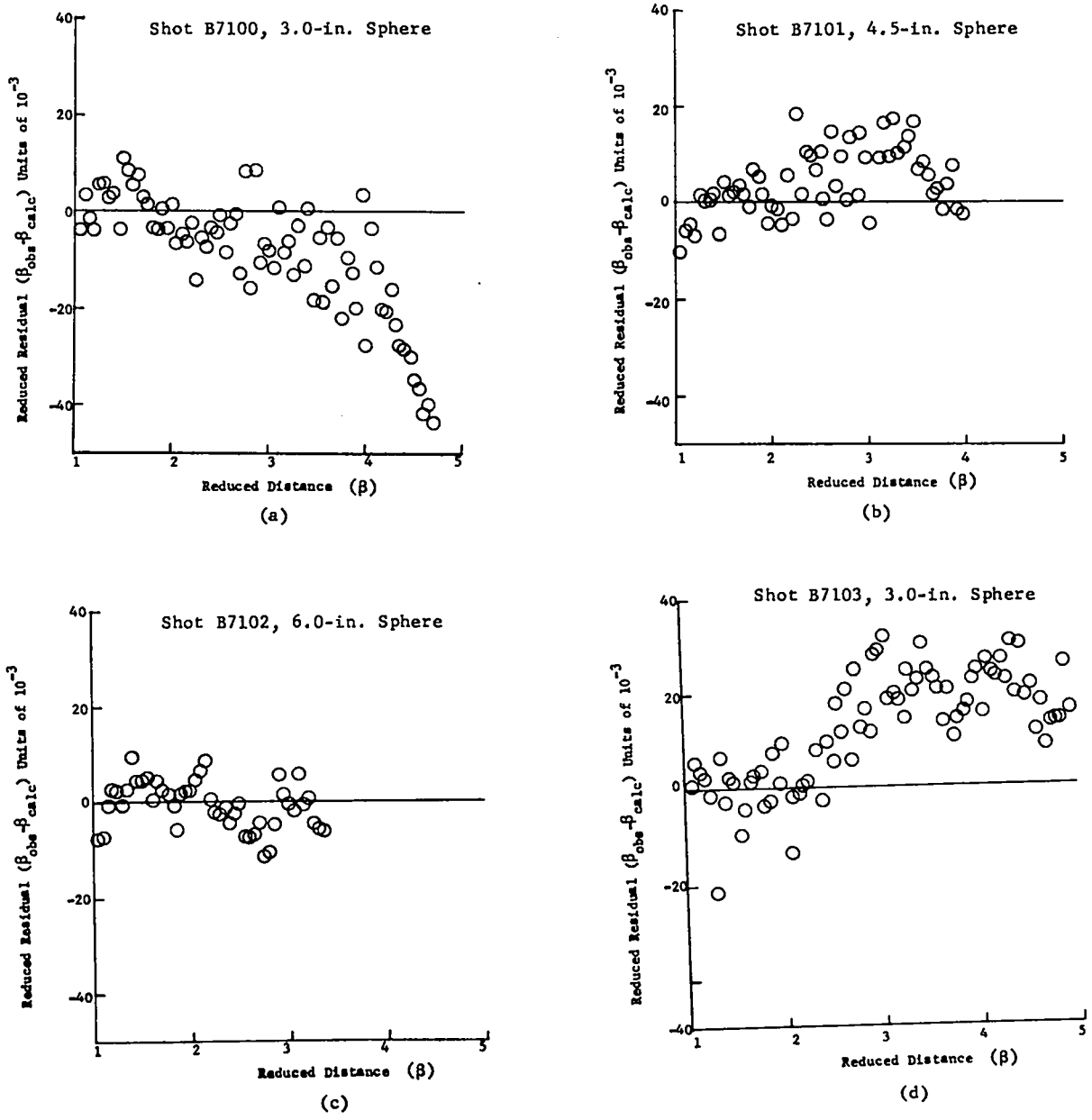
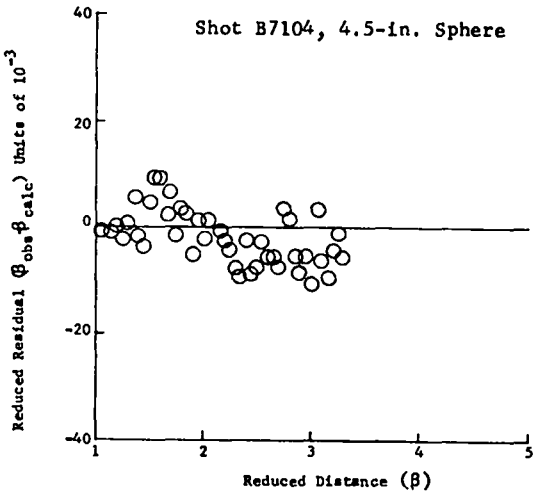
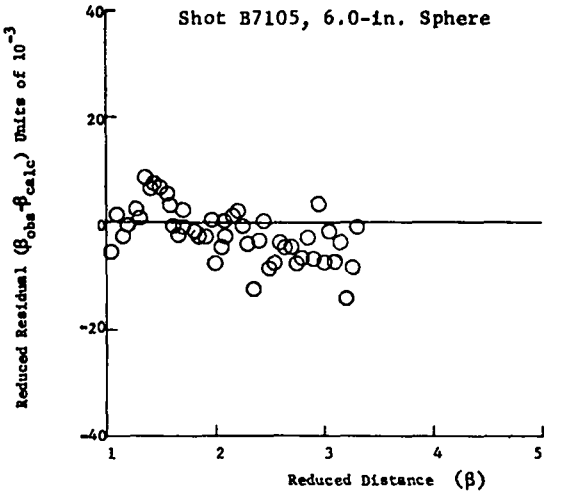


Fig. 7. Residual plots from fit to all six spheres.



(e)



(f)

Fig. 7. (cont)

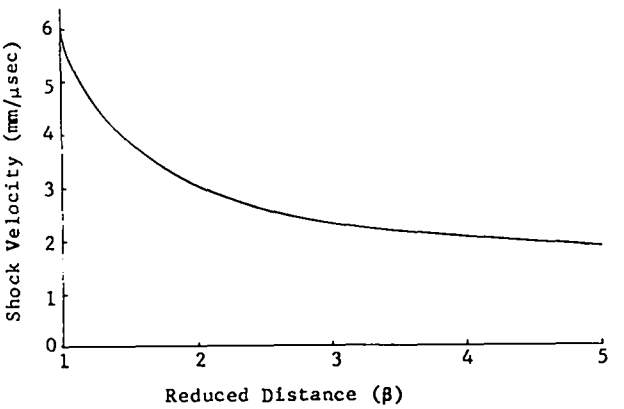


Fig. 8. Shock velocity vs reduced distance. Calculated from fit to all six spheres.

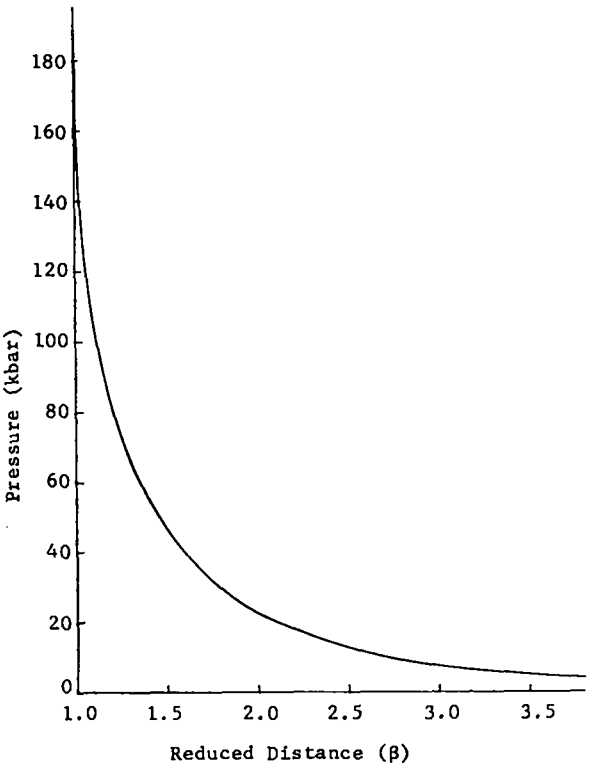


Fig. 9. Pressure vs reduced distance. Calculated from fit to all six spheres.

can be obtained from the pressure-time relationship [obtained by combining Eqs. (5), (6), and (7)]. $\left(\frac{du}{dP}\right)_H$ is the derivative of the particle velocity with respect to pressure along the shock Hugoniot [obtained by combining Eqs. (6) and (7)]. The sound velocity can be found from a table given by Rice and Walsh.[4] Table II lists some calculated values for the gradient.

IV. SUMMARY

With this set of experiments, a good calibration of the underwater gap test has been obtained. The water shock pressure is known to about 5% throughout the range from 150 to 5 kbar, and the system can be used without any further development. A good fit to all the data has been found, and the remaining uncertainties in calibration result from real shot-to-shot differences and experimental errors.

No departure from scaling can be seen in the results. The size range, only a factor of two, is

TABLE II

PRESSURE GRADIENT BEHIND SHOCK
9205 SPHERE (5.715 CM RAD.) IN WATER

Time (μsec)	Distance (cm)	Radius (cm)	U (cm/μs)	u (cm/μs)	p (Mbar)	c (cm/μs)	$(\partial p/\partial r)_t$ (Mbar/cm)
1.0	0.5563	6.2713	0.5190	0.2057	0.10653	0.5080	0.0948
1.5	0.8096	6.5246	0.4956	0.1904	0.09417	0.4960	0.0648
2.5	1.2852	7.0020	0.4611	0.1685	0.07756	0.4770	0.0391
3.5	1.7342	7.4492	0.4346	0.1521	0.06597	0.4600	0.0279
7.0	3.1382	8.8532	0.3731	0.1151	0.04295	0.4178	0.0137
10.5	4.3717	10.0867	0.3341	0.0925	0.03083	0.3837	0.0092

not large enough to make this a sensitive test of scaling, but the data are good enough that an effect of a few percent would be detected. We are confident that the reduced fit can be used for other sizes near the experimental range.

In a spherical explosion, there is a second shock that arises when the rarefaction from the explosive surface propagates back through the burned products and reflects at the center. This second shock propagates outward and eventually overtakes the first shock. Berger and Holt[15] did some calculations for a PETN sphere exploded in sea water and found that overtake occurs at about 7 radii. Our experimental range does not go this far, and we saw no evidence of the second shock. The effects of the initiator have not been calculated. It seems certain that it perturbs the flow to some extent, but no evidence of such effects has been seen.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance furnished by many members of the Los Alamos Scientific Laboratory, especially of Groups GMX-2, GMX-3, GMX-8, and GMX-10, without whose help these experiments could not have been done. Special acknowledgment is accorded G. G. Hill, GMX-3, for reading the films and to E. G. Hantel, Group CNC-11, for many helpful suggestions concerning the use of the EILEEN code.

REFERENCES

1. E. H. Eyster, L. C. Smith, and S. R. Walton, "The Sensitivity of High Explosives to Pure Shock," U. S. Naval Ordnance Laboratory Memorandum 10,336 (1949).

2. T. P. Liddiard, Jr., "The Initiation of Burning in High Explosives by Shock Waves," Proceedings Fourth Symposium (International) on Detonation, U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland (1965), pp. 487-495.

3. N. L. Coleburn and L. A. Roslund, "Collision of Spherical Shock Waves in Water," U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland. NOLTR-68-110 (1968).

4. M. H. Rice and J. M. Walsh, "Equation of State of Water to 250 Kilobars," J. Chem. Phys. 26, 824 (1957).

5. L. C. Smith and L. W. Hantel, unpublished work.

6. The PFIEFE code was written by L. Gritzo LASL Group GMX-3 for use on the CDC 6600 computers to convert x-y input data from smear-camera film to time-distance data (1970).

7. J. W. Kury, H. C. Hornig, E. L. Lee, J. L. McDonnel, D. L. Ornellas, M. Finger, F. M. Strange, and M. L. Wilkins, "Metal Acceleration by Chemical Explosives," Proceedings Fourth Symposium (International) on Detonation, U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland (1965), pp. 3-13.

8. The EILEEN code is a least-squares fitting routine written by E. G. Hantel, LASL Group CNC-11, for use on the IBM 7030 computer. In this program all data points are considered to be of equal weight (1969).

9. R. Courant and K. O. Friedrichs, Supersonic Flow and Shock Waves (Interscience Publishers, Inc., New York, 1948), pp. 424-433.

10. C. L. Mader, in Twelfth International Symposium on Combustion (The Williams and Wilkins Co., Baltimore, Maryland, 1968), p. 499.

11. LASL Group GMX-6, "Selected Hugoniots," LA-4167-MS, Los Alamos Scientific Laboratory (1969).

12. B. G. Craig, private communication (1970).

13. C. L. Mader, "Detonation Properties of Condensed Explosives Computed Using Becker-Kistiakowsky-Wilson Equations of State," LA-2900, Los Alamos Scientific Laboratory (1963).

14. C. L. Mader, private communication (1970).

15. S. A. Berger and M. Holt, "Implosive Phase of a Spherical Explosion in Sea Water," Phys. Fluids 5, 426 (1962).

ALT/mj:331(50)