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BRL

MEMORANDUM REPORT NO. 1241

January 1960

THE EFFECT OF ATMOSPHERIC PRESSURE ON THE REFLECTED IMPULSE FROM AIR BLAST WAVES

W. C. Olson

J. D. Patterson, II

J. S. Williams

Department of the Army Project No. 5B03-04-002

Ordnance Management Structure Code 5010.11.815

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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ABERDEEN PROVING GROUND, MARYLAND

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WCOlson/JDPatterson, II/JSWilliams/ebh
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THE EFFECT OF ATMOSPHERIC PRESSURE ON THE REFLECTED IMPULSE FROM AIR BLAST WAVES

ABSTRACT

The authors report measurements of reflected impulses in air blast waves generated by explosive spheres (up to one pound in weight) detonated under reduced ambient pressures simulating altitudes up to 100,000 ft (8 mm of mercury). Analysis reveals that the data scale according to Sachs' law.

INTRODUCTION

Attempts to correlate damage to aircraft structures with air blast indicate that an important parameter to consider for internal blast is the normally reflected impulse.[1]* Usually scaled distances** associated with damage caused to aircraft by internal detonations range from 15 down to 0.5 $ft/lb^{1/3}$. Measurements made by Hoffman and Mills[2] of reflected pressures and impulses using piezoelectric gages were carried out to scaled distances only as small as 1.5 $ft/lb^{1/3}$ for sea level atmospheric conditions. This work[2] reported that piezoelectric gages were erratic at small scaled distances where peak pressures were high (greater than 3000 psi) and durations were short. On the other hand, a technique recently developed which utilizes a mechanical or plug method[3] for measuring normally reflected impulse yields satisfactory measures under sea level conditions over scaled distances from 2.5 to 0.5 $ft/lb^{1/3}$.

It was decided for the present study to use this latest mechanical method for obtaining measurements of impulses at small scaled distances not only under sea level conditions but also under simulated high altitudes. Although the effect of altitude on blast has been considered theoretically[4] and experimentally[5] by a number of authors, little data on normally reflected impulse have been reported especially at small scaled distances. In the present tests, however, only ambient pressure, but not ambient temperature, could be controlled.

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* Superscripts refer to references listed at end of the report.

** Scaled distance, $Z = R/W^{1/3}$ is the actual distance, R, in feet from the charge center to the point in question divided by the cube root of the charge weight, W, in lbs.

Examination of the resulting data for conformity with laws of similitude, i.e., geometric scaling* and Sachs'** law, are discussed in later sections.

TEST PROCEDURE

The mechanical technique consists of measuring the velocity at which a cylindrical plug of known mass is projected from a hole in a large rigid surface by a blast wave normally incident on the plate and then inferring the impulse from Newton's second law. (A detailed discussion of this method is given by Johnson, Patterson, and Olson[3] in a previous BRL publication). The present experiments were carried out in an altitude simulating Blast Sphere (Figure 1) located on Spesutie Island, Aberdeen Proving Ground, Maryland.

A steel platform was welded inside the 30 ft. diameter sphere to support the test apparatus approximately at the center of the sphere so as to minimize the effects of shock reflection from the chamber walls. The apparatus was designed to simulate as closely as possible the desired conditions of subjecting a free plug in an infinite rigid plane to a normally

---

* Geometric scaling predicts that if the linear size of the charges differ by a factor K the pressure-time histories at the same scaled distance will have the same amplitude (peak overpressure) but will vary in duration and impulse in direct proportion to the linear scale factor K.

** Sachs' scaling predicts that the parameters $I(T_o/T_n)^{1/2}/P_o^{2/3}W^{1/3}$ and P/P_o are uniquely determined by the values of $ZP_o^{1/3}$

where I = positive impulse in psi-milliseconds

T_o = ambient temperature at altitude in degrees Kelvin

T_n = sea level temperature in degrees Kelvin

P = peak overpressure, psi

P_o = ambient atmospheric pressure in sea level atmospheres (1 atmosphere = 14.7 psi)

W = weight of explosive charge in lbs.

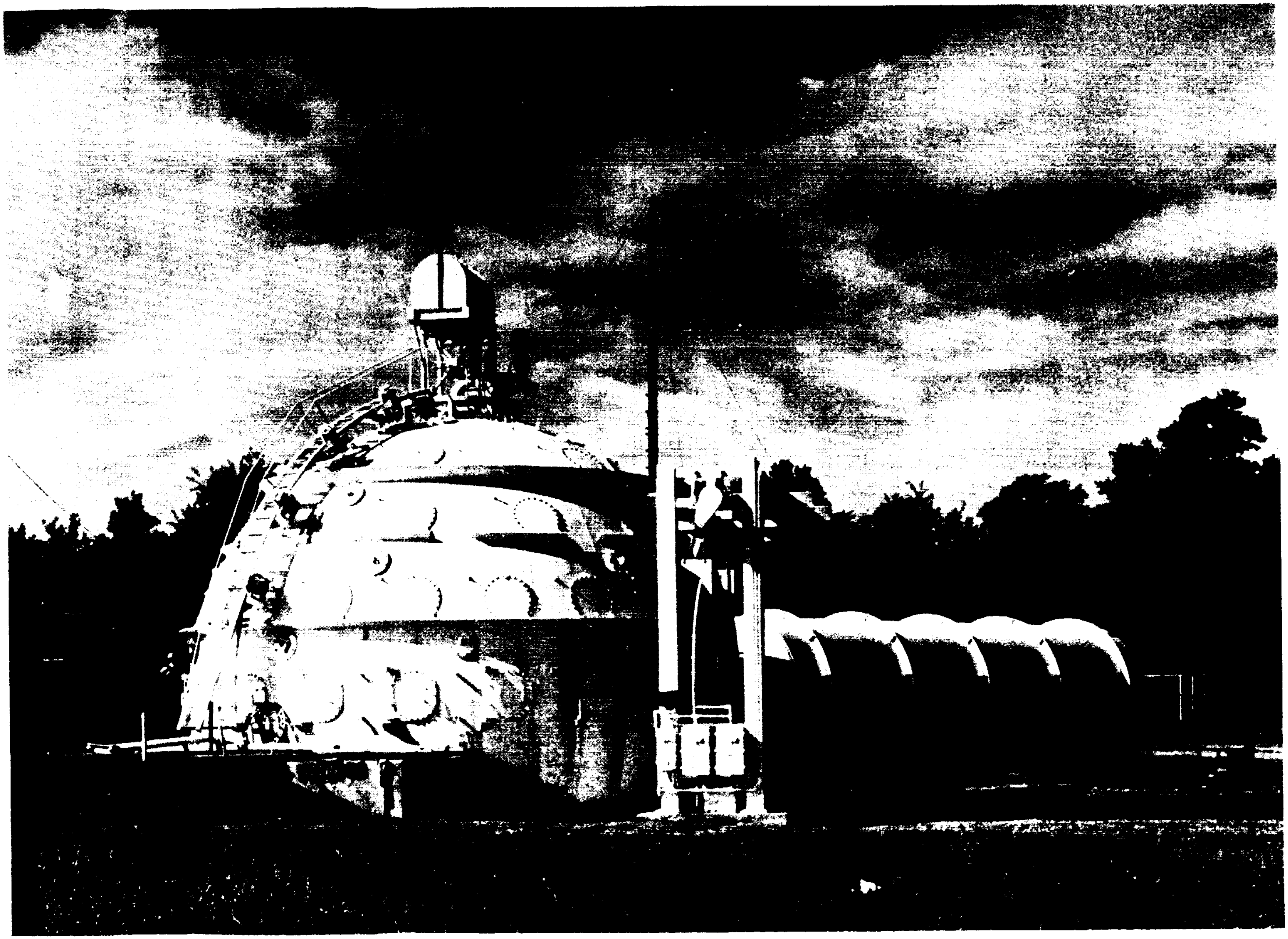

Fig. I. Altitude Simulating Blast Sphere incident blast wave. An inch thick 6 x 6 ft. rectangular steel plate forming the plane surface was supported on steel posts welded to the steel platform. To prevent diffractive shock disturbances from affecting the motion of the plug before its velocity could be recorded, three sides were enclosed with plywood. The front side was fitted with a door containing a transparent lucite window through which the interior of the enclosure could be photographed. Mechanisms to hold and position the explosive charge and plug were the same as those used for sea level firings.[3]

Measurements of plug velocities were taken simultaneously by both optical and electronic methods. For optical measurements a scale mounted behind the plug indicated the distance in inches from the top side of the plate. The scale was located in a vertical plane about 1-1/2 ft. behind the path of the plug. Flood lights were mounted on two of the supports to furnish illumination for motion picture photography. Maximum contrast was obtained by painting the plug black and the scale background white.

Plug motion was observed through the lucite window by an Eastman high-speed camera equipped with a neon timing light which impressed 1000-cps timing marks on the edge of the film. Thus, time axis calibration was obtained by photographing the pulsed light simultaneously with the record of the plug flight. The camera, in a protective steel case, was mounted approximately 11.5 ft from the scale giving adequate coverage of plug motion with a relatively long focal length lens.

For the electronic method of measuring plug velocity, the time required for the plug to travel between two fixed points was recorded by counter chronographs. As for the sea level firings, a piezoelectric time-of-arrival gage threaded into the underside of the top plate sensed the blast wave as it struck the plate and started the counters. A similar gage threaded into a bottom plate, located 40-1/4 inches below the top plate, sensed the impact of the plug and stopped the counters. The lower plate was mounted on shockmounts and a four-inch thick blanket of sponge rubber so as to minimize the possibility of shock prematurely reaching the lower plate through the metal components of the test structure. Even with these precautions, the bottom piezoelectric gage proved to be erratic, and was replaced by a foil screen "make circuit" which, when struck by the plug, generated the stop input pulse for the counters. Two counters connected in parallel were used to obtain two readings and thereby minimize loss of information.

Events in each firing were initiated automatically by an electronic sequence timer. This timer, the counter, and other associated equipment were housed in an instrument trailer outside the sphere.

The test procedure was the same as that used for sea level firings of reference 3, except the altitude simulating blast sphere was evacuated to the desired ambient pressure before firing.

ANALYSIS

Although reference 3 contains the theoretical development for the mechanical technique, formulae necessary for computation are repeated herein. If the time origin is known, as for computing the impulse from counter data, impulse is calculated directly by measuring the time taken for the plug to travel a known distance from

$$I = \frac{m}{A} \left(\frac{X}{t} - gt/2\right) \tag{1}$$

where I = impulse, psi-milliseconds

m = mass of plug, $lb\text{-}ms^2/in.$

A = area of plug, in^2

X = distance plug travels between top and bottom plate, inches

g = acceleration of gravity, in/ms^2

t = time of travel, milliseconds.

For the optical measurements, where the time origin is not known but the time interval over a predetermined distance is known, the velocity at distance X_1 is given in terms of a known time interval by

$$\dot{X}_1 = \frac{X_2 - X_1}{t_2 - t_1} - g/2\,(t_2 - t_1). \tag{2)*$$

where $X_2 - X_1$ = predetermined distance for optical methods

$t_2 - t_1$ = time interval in milliseconds to travel $(X_2 - X_1)$ interval

$\dot{X}_1$ = velocity of plug at X_1

$\dot{X}_o$ = " " " at X_o (top plate)

* dot above variable represents differentiation with respect to time.

The initial velocity, $\dot{X}_o$, or impulse, I, is then computed from

$$\dot{X}_o = \frac{A}{m} I = (\dot{X}_1^{\,2} - 2gX_1)^{1/2} \tag{3}$$

At least five experiments were conducted for each of the following test conditions. The charges were cast spheres of Pentolite and ranged in weight, W, from 1/4 to 1 lb. The scaled distances, $Z = R/W^{1/3}$, ranged from 0.50 to 2.00 $ft/lbs^{1/3}$. Ambient pressures, P_o, simulated three altitudes.

W (lbs)	Z ($ft/lbs^{1/3}$)	Altitude (ft)	P_o (mm of Hg)
1	2	32,500	200
1	1	"	"
1	1/2	"	"
1	2	66,000	40
1	1	"	"
1/2	1	"	"
1/4	1	"	"
1	1/2	"	"
1	2	100,500	8
1	1	"	"
1	1/2	"	"

RESULTS

Round-by-round data together with mean values and standard deviations of an individual measurement are presented in Table I. (Detailed data are contained in the Appendix). Table II is an extract of Table I and is included so that a direct comparison can be made at one simulated high altitude condition and at one scaled distance of data obtained with different weights of explosive. Figure 2 is a graphical display of the data together with the sea-level data contained in reference 3. Figure 3 is a plot of the data scaled according to the laws of similitude (geometric scaling and Sach's law). The curves drawn through the points are not least square fits but are merely fitted "by eye". Table III is a summary of the scaled impulse data.

TABLE I

Geometrically Scaled Positive Impulse($I/W^{1/3}$, psi-millisec/$lb^{1/3}$) vs Nominal Scaled Distance($Z=R/W^{1/3}$, ft/$lb^{1/3}$)

Alt. 32,500 ft.			
Rd. No.	Z*	$I/W^{1/3}$, Film	$I/W^{1/3}$, Counter
61	2.00	69.9	80.6
62	2.00	74.7	101.8 d
63	2.00	a	57.9
64	2.00	71.2	83.3
65	2.00	62.1	b
Ave	71.4		
s	9.2		
66	1.00	189.4	b
67	1.00	317.7 d	b
68	1.00	234.9 d	282.5 d
69	1.00	191.5	b
70	1.00	194.9	321.4 d
78	1.00	219.0	b
79	1.00	209.1	b
80	1.00	202.9	195.5
Ave	200.3		
s	10.7		
72	0.50	714.6	733.5
73	0.50	745.2	b
74	0.50	765.0	b
75	0.50	762.7	1529.0 d
76	0.50	737.6	b
77	0.50	672.6	1345.3 d
Ave	733.0		
s	31.8		

Ave= average of film and counter impulse
s = Standard deviation of the individual
a = no film reading
b = no counter reading
* = nominal chg, wt. is one lb. unless specially noted otherwise.
d = rejected as outlying observation

Alt. 66,000 ft.			
Rd. No.	Z*	$I/W^{1/3}$, Film	$I/W^{1/3}$, Counter
29	2.00	61.5	59.9
30	2.00	60.3	58.3
31	2.00	59.0	57.2
32	2.00	62.1	61.0
33	2.00	50.0	51.4
Ave	58.1		
s	4.2		
50	1.00	186.3	189.2
51	1.00	186.6	b
52	1.00	190.6	190.6
53	1.00	179.1	178.8
54	1.00	186.1	187.6
81	1.00 c	184.1	180.1
82	1.00 c	186.9	184.8
83	1.00 c	207.2	201.0
84	1.00 c	185.8	191.2
85	1.00 c	190.6	188.0
86	1.00 e	195.0	188.7
87	1.00 e	184.1	b
88	1.00 e	183.4	249.6 d
89	1.00 e	183.8	179.1
90	1.00 e	186.5	b
Ave	187.5		
s	6.4		
55	0.50	725.4	b
56	0.50	711.6	b
57	0.50	758.1	734.1
58	0.50	742.1	752.4
59	0.50	776.2	733.5
60	0.50	a	716.1
Ave	738.9		
s	20.8		

Alt. 100,500 ft.			
Rd. No.	Z*	$I/W^{1/3}$, Film	$I/W^{1/3}$ Counter
24	2.00	62.5	87.5
26	2.00	56.9	107.9 d
27	2.00	57.2	b
28	2.00	57.7	b
34	2.00	53.3	51.9
35	2.00	63.0	62.1
Ave	58.1		
s	4.2		
40	1.00	193.0	189.5
41	1.00	162.7 d	368.9 d
42	1.00	185.7	185.3
43	1.00	199.2	190.1
44	1.00	192.3	190.1
45	1.00	185.8	b
Ave	190.1		
s	4.4		
38	0.50	Plug obscured by exp. gases	727.3
46	0.50		b
47	0.50		739.9
48	0.50		710.3
49	0.50		759.0
Ave	734.1		
s	20.5		

c = these rds. had nominal chg. wt. of 0.5 lbs.
e = these rds. had nominal chg. wt. of 0.25 lbs.

TABLE II

Positive Scaled Impulse $I/W^{1/3}$, psi Milliseconds/$lb^{1/3}$ for Nominal Scaled Distance Z = 1, at Simulated Altitude 66,000 ft.

Rd. No.	Nominal Chg. Wt. lbs	$I/W^{1/3}$, Film	$I/W^{1/3}$, Counter	$I/W^{1/3}$, Average*	Standard Dev. of Ind. obs. s
50	1.00	186.3	189.2	$\bar{I}/W^{1/3}$ = 186.1	s = 4.41
51		186.6	b		
52		190.6	190.6		
53		179.1	178.8		
54		186.1	187.6		
81	0.50	184.1	180.1	$\bar{I}/W^{1/3}$ = 189.9	s = 8.30
82		186.9	184.8		
83		207.2	201.0		
84		185.8	191.2		
85		190.6	188.0		
86	0.25	195.0	188.7	$\bar{I}/W^{1/3}$ = 185.8	s = 5.00
87		184.1	b		
88		183.4	249.6[d]		
89		183.8	179.1		
90		186.5	b		

b = counter reading lost

d = rejected as outlying

* = $\bar{I}/W^{1/3}$ is the average of film and counter impulse for each nominal charge weight.

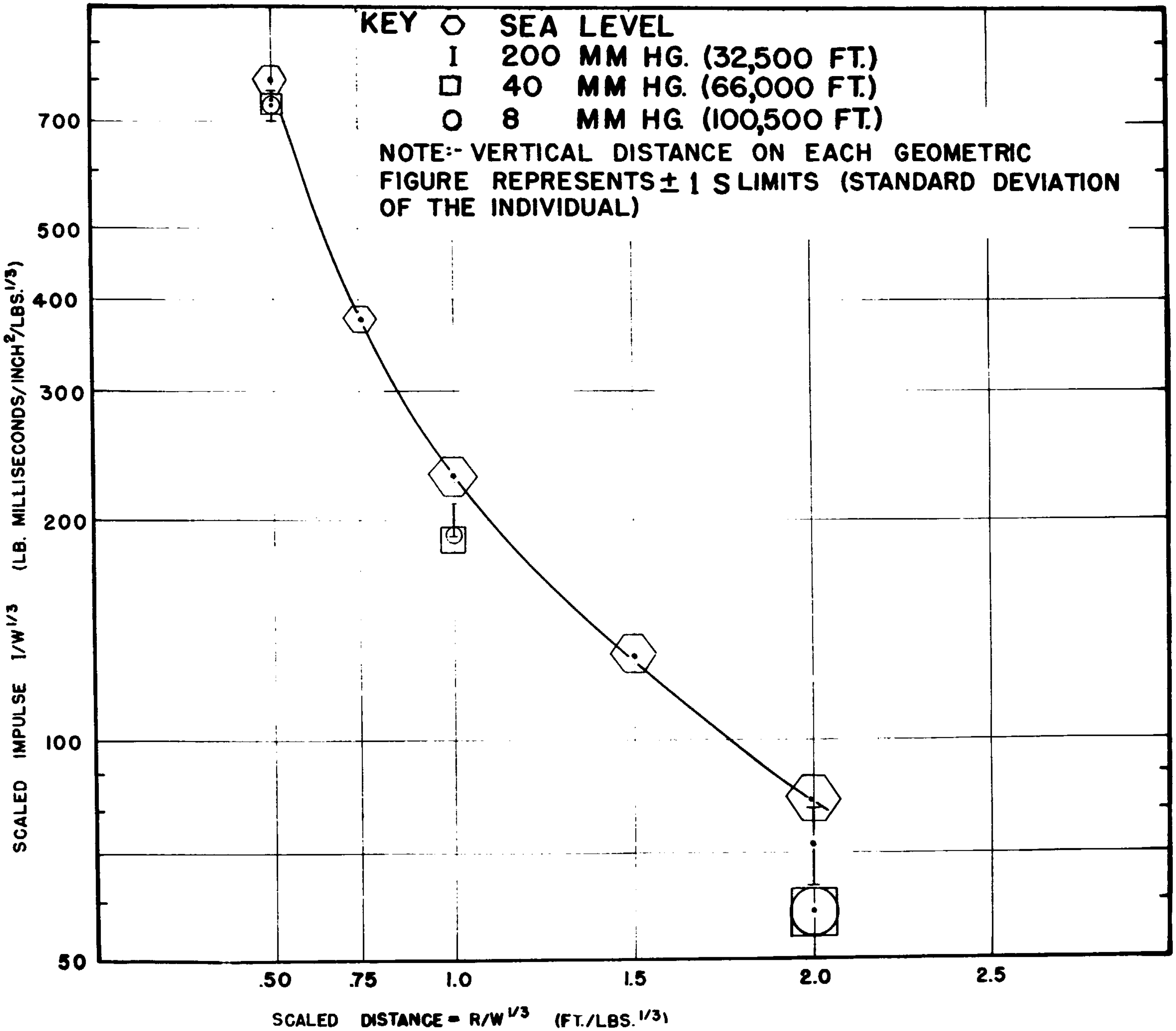

Fig. 2 Geometrically Scaled Impulse vs. Scaled Distance at Different Atmospheric Pressures.

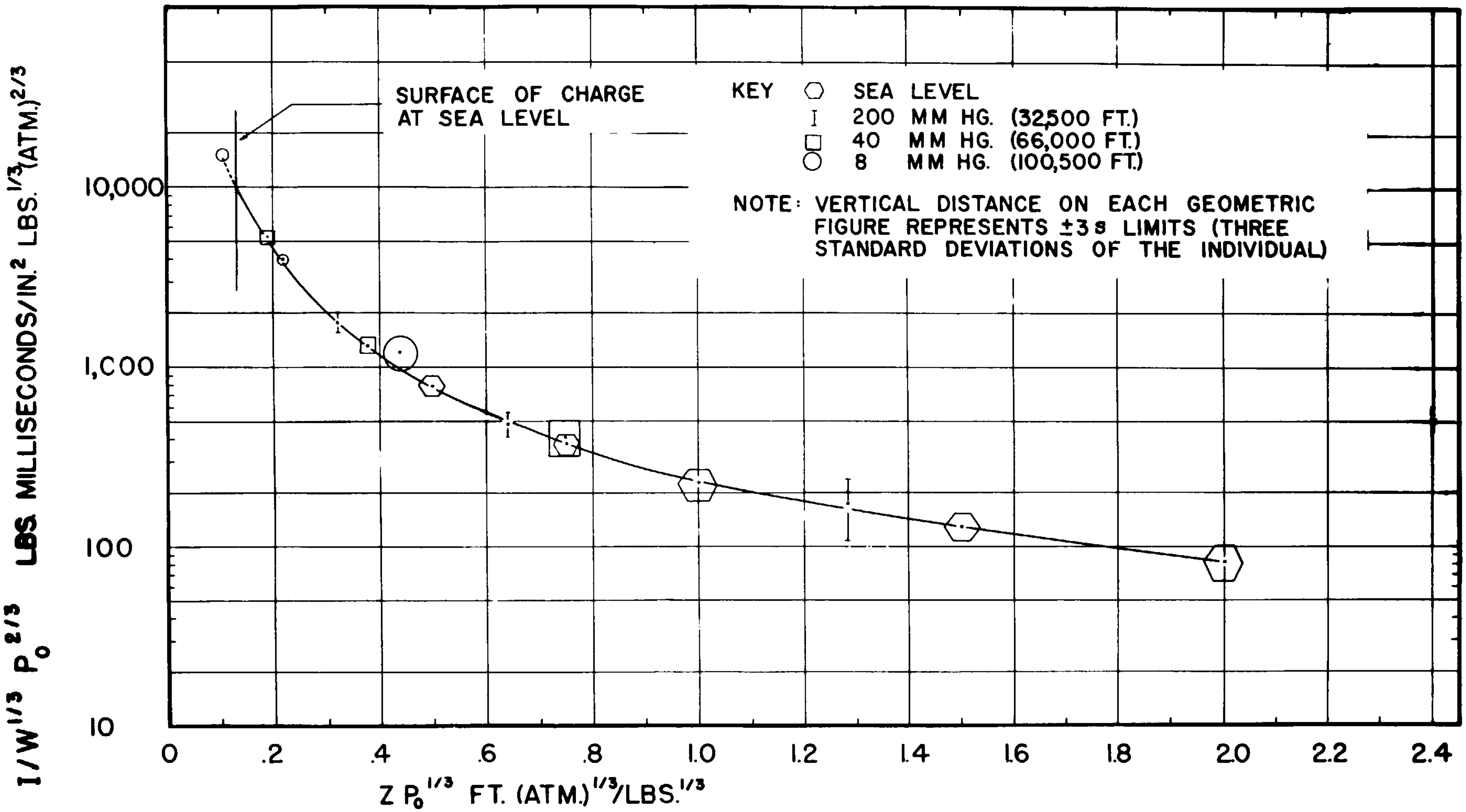

Fig. 3 Scaled Impulse vs. Scaled Distance at Different Atmospheric Pressure.
(Scaled According to Sachs' Scaling).

TABLE III

Altitude-Scaled Positive Impulse

Simulated Altitude	Geometric Scaling			Sach's Altitude Scaling		
	$Z = R/W^{1/3}$, $ft/lb^{1/3}$	Ave. Pos. Imp. $I/W^{1/3}$, $\frac{\text{psi millisec}}{lb^{1/3}}$	St. Dev. of Ind., s	$Z\ p_o^{1/3}$, $\frac{ft\ (atmos)^{1/3}}{lb^{1/3}}$	Ave. Pos. Imp.* $I\sqrt{\frac{T_o}{T_n}}/W^{1/3}\ p_o^{2/3}$, $\frac{\text{psi millisec}}{lb^{1/3}\ (atmos)^{2/3}}$	St. Dev. s
32,500 ft 200 mm Hg	2.0 1.0 0.5	71.4 200.3 733.0	9.2 10.7 31.8	1.282 0.641 0.320	173.8 487.8 1785.	22.4 26.0 77.3
66,00 ft 40 mm Hg	2.0 1.0 0.5	58.1 187.5 738.9	4.2 6.4 20.8	0.750 0.375 0.187	413.3 1335. 5261.	26.4 45.5 148.
100,500 ft 8 mm Hg	2.0 1.0 0.5	58.1 190.1 734.1	4.2 4.4 20.5	0.438 0.219 0.110	1209. 3958. 15280.	86.8 91.8 427.

* Temperature at altitude for these tests was equal to outside sea level temperature

DISCUSSION

The data reported herein are in general consistent with both geometric and Sachs' scaling. The altitude data are all significantly lower than the sea level data, as can be seen from Figure 2, but yield a single curve consistent with all the data when scaled according to Sachs' law (Figure 3).

The precision of measurements made under altitude conditions was quite high, exceeding the precision of the sea level data for nearly every datum point.

An anomaly is apparent in Figure 3 which indicates that Sachs' law must have its limitations, even though apparently verified by the experiments reported herein. One of the datum points appears to fall within the explosive charge itself, when scaled according to Sachs' law. This is, of course, a physical impossibility and serves to indicate that one should still view this scaling law with caution where small scale distances are involved.

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APPENDIX

Simulated Altitude 32,500 Ft. (200 mm Hg)

Rd. No.	Exp. Wt. W_e lbs	Plug Wt. W_p lbs	Film Time Δt_f Sec	Counter Δt_c Time Sec	Film Geometric Scaled Imp. $I/W^{1/3}$	Counter Geometric Scaled Imp. $I/W^{1/3}$	Base Line for Film (X_1-X_2), in
	Charge Distance 2.04 Ft				Nominal Scaled Distance 2.0 ft/lb$^{1/3}$		
61	1.040	.0732	.0335	.11177	69.9	80.6	12-24
62	1.041	"	.0316	.09049	74.7	101.8*	12-24
63	1.051	"	--	.14791	--	57.9	--
64	1.054	"	.0329	.10818	71.2	83.3	12-24
65	1.060	"	.0368	--	62.1	--	12-24
Ave	(film + Counter)				71.4		
S	(Standard Dev. of Ind.)				9.2		
	Charge Distance 1.023 Ft				Nominal Scaled Distance 1.0 ft/lb$^{1/3}$		
66	1.059	.0732	.0075	--	189.4	--	18-25
67	1.060	.0728	.0058	--	317.7*	--	21-27
68	1.061	.0728	.0070	.03332	234.9*	282.5*	19-26
69	1.065	.0728	.0128	--	191.5	--	15-27
70	1.045	.0728	.0127	.02947	194.9	321.4*	12-24
78	1.062	.0723	.0112	--	219.0	--	12-24
79	1.068	.0723	.0117	--	209.1	--	12-24
80	1.056	.0723	.0121	.04769	202.9	195.5	12-24
Ave					200.3		
S					10.7		
	Charge Distance .512 Ft				Nominal Scaled Distance 0.5 ft/lb$^{1/3}$		
72	1.062	.0732	.00350	.01297	714.6	733.5	12-24
73	1.066	.0725	.00332	--	745.2	--	--
74	1.051	.0725	.00325	--	765.0	--	--
75	1.061	.0725	.00325	.00617	762.7	1529.0*	12-24
76	1.061	.0723	.00335	--	737.6	--	--
77	1.050	.0723	.00338	.00704	672.6	1345.3*	12-24
Ave					733.0		
S					31.8		

* rejected as outlying observation
-- no reading could be made

Simulated Altitude 66,000 Ft. (40 mm Hg)

Rd. No.	Exp. Wt. W_e lbs	Plug Wt. W_p lbs	Film Time Δt_f Sec	Counter Δt_c Time Sec	Film Geometric Scaled Imp. $I/W^{1/3}$	Counter Geometric Scaled Imp. $I/W^{1/3}$	Base Line for Film (X_1-X_2), in
	Charge Distance 2.04 Ft.				Nominal Scaled Distance 2.0 ft/lb$^{1/3}$		
29	1.063	.0732	.0371	.14331	61.5	59.9	12-24
30	1.069	"	.0377	.14629	60.3	58.3	12-24
31	1.072	"	.0384	.14835	59.0	57.2	12-24
32	1.058	"	.0369	.14142	62.1	61.0	12-24
33	1.050	"	.0440	.16256	50.0	51.4	12-24
Ave					58.1		
S					4.2		
	Charge Distance 1.023 Ft.				Nominal Scaled Distance 1.0 ft/lb$^{1/3}$		
50	1.042	.0734	.0134	.05015	186.3	189.2	12-24
51	1.046	.0730	.0133	--	186.6	--	12-24
52	1.050	.0730	.0130	.04941	190.6	190.6	12-24
53	1.054	.0730	.0138	.05249	179.1	178.8	12-24
54	1.056	.0730	.0133	.05009	186.1	187.6	12-24
Ave					186.1		
S					4.4		
	Charge Distance .807 Ft.				Nominal Scaled Distance 1.0 ft/lb$^{1/3}$		
81	.519	.0721	.0167	.06478	184.1	180.1	12-24
82	.520	.0721	.0165	.06314	186.9	184.8	12-24
83	.523	.0723	.0149	.05831	207.2	201.0	12-24
84	.523	.0723	.0166	.06097	185.8	191.2	12-24
85	.524	.0723	.0162	.06213	190.6	188.0	12-24
Ave					189.9		
S					8.3		
86	.257	.0723	.0199	.07765	195.0	188.7	12-24
87	.255	.0721	.0210	--	184.1	--	12-24
88	.256	.0721	.0210	.05933	183.4	249.6*	12-24
89	.256	.0721	.0210	.08142	183.8	179.1	12-24
90	.255	.0721	.0207	--	186.5	--	12-24
Ave					185.8		
S					5.0		
	Charge Distance .512 Ft.				Nominal Scaled Distance 0.5 ft/lb$^{1/3}$		
55	1.062	.0730	.00315	--	725.4	--	12-24
56	1.064	.0730	.00350	--	711.6	--	15-26
57	1.065	.0730	.00330	.01288	758.1	734.3	12-24
58	1.065	.0730	.00335	.01257	742.1	752.4	12-24
59	1.073	.0730	.00320	.01288	776.2	733.5	12-24
60	1.037	.0730	--	.01339	--	716.1	12-24
Ave					738.9		
S					20.8		

APPENDIX

Simulated Altitude 100,500 ft (8 mm Hg)

Rd. No.	Exp. Wt. W_e lbs	Plug Wt. W_p lbs	Film Time Δt_f Sec	Counter Δt_c Time Sec	Film Geometric Scaled Imp. $I/W^{1/3}$	Counter Geometric Scaled Imp. $I/W^{1/3}$	Base Line for Film (X_1-X_2), in
	Charge Distance 2.04 ft				Nominal Scaled Distance 2.0 ft/lb$^{1/3}$		
24	1.059	.0732	.0367	.23450	62.5	87.5*	12-24
26	1.057	.0732	.0396	.10588	56.9	107.9*	12-24
27	1.060	.0732	.0394	--	57.2	--	12-24
28	1.062	.0732	.0392	--	57.7	--	12-24
34	1.063	.0732	.0417	.16087	53.3	51.9	12-24
35	1.069	.0732	.0364	.13927	63.0	62.1	12-24
Ave					58.1		
S					4.2		
	Charge Distance .023 ft				Nominal Scaled Distance 1.0 ft/lb$^{1/3}$		
40	1.068	.0734	.0107	.04969	193.0	189.5	14-24
41	1.069	.0734	.0101	.02632	102.7*	368.9*	16-24
42	1.071	.0734	.0111	.05076	185.7	185.3	14-24
43	1.072	.0734	.0123	.04922	199.2	190.1	24-36
44	1.072	.0734	.0128	.04952	192.3	190.1	24-36
45	1.064	.0734	.0111	--	185.8		15-25
Ave					190.1		
S					4.4		
	Charge Distance .512 ft				Nominal Scaled Distance 0.5 ft/lb$^{1/3}$		
38	1.060	.0732	Plug	.01308	--	727.3	--
46	1.067	.0734	Obscured	--	--	--	--
47	1.075	.0730	by	.01277	--	739.9	--
48	1.036	.0724	explosion	.01354	--	710.3	--
49	1.040	.0734	Gases	.01266	--	759.0	--
Ave						734.1	
S						20.5	

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W. C. Olson, J. D. Patterson, II, J. S. Williams

BRLM Report No. 1241 January 1960

DA Proj No. 5B03-04-002, ORD Proj No. TB3-0112
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