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A Shock Tube Utilized to Produce Sharp-rising Overpressures of 400 Milliseconds Duration and Its Employment in Biomedical Experimentation

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Lovelace Foundation for Medical Education and Research
Albuquerque, New Mexico

April 7, 1961

A Shock Tube Utilized to Produce Sharp-rising Overpressures of 400 Milliseconds Duration and Its Employment in Biomedical Experimentation

FORWORD

The purpose of the present study is two-fold; namely, (1) to describe "long-duration" pressure pulses simulating those produced by nuclear explosions, and (2) to present the result of an interspecies animal study when the data on six different animals are extrapolated to a biologic target the size of man.

The results are limited to single-pulses of overpressure which rise almost instantaneously to a maximum and endure for about 400 msec. As far as man is concerned, these results do not apply to very short duration overpressures (50 msec or less), to pressures having a slow or step-wise rise to a maximum, and to oscillating pressures of considerable magnitude. Also the data apply to overpressure injury under circumstances in which displacement from blast pressures and winds is minimized and blast-energized missiles do not occur. The findings are applicable to military and industrial situations involving potential exposure to explosive phenomena, e.g., nuclear weapons, high explosives, tanks containing gases or liquids under high pressure, etc.

The interspecies study is a part of research carried on since 1952 aimed at better understanding human response to the several environmental variations produced by low and high yield explosives.

ABSTRACT

A shock tube employed for blast biology studies is described along with the results of one series of experiments.

The shock tube is air-driven and utilizes Mylar plastic diaphragms. The compression chamber is 17.5 ft in length and 40.5 in. I.D.; it reduces in diameter to 23.5 in. over a 3-ft-long transition section just upstream of the diaphragm station. The expansion chamber consists of 30 ft of 23.5 in. I.D. tubing followed by 22 ft of 40.5 in. I.D. tubing. It is closed distally by a steel end-plate to generate high pressures from the reflected shock. Three vents in the expansion side of the system serve to control the duration of the overpressure and to eliminate multiple reflections by bleeding off the reflected shock as it travels upstream.

An interspecies correlation is presented based on mortality data from six species of experimental animals with an extrapolation to a 70 kg animal.

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INTRODUCTION

The shock tube has proven to be a valuable tool in studying the biological effects of air blast.[1-5] By appropriate modifications, the device can be made to generate a wide variety of wave forms some of which closely resemble those recorded inside structures exposed to full-scale nuclear detonations.[6-7] The capability of creating and reproducing at will a desired variation in environmental pressure has made it possible to initiate comparative interspecies experimentation without which there can be no clear understanding of hazardous and non-hazardous wave forms. In this light, it is well to emphasize that the air-driven shock tube has an unusual versatility and offers many other advantages. For example, it has become possible to achieve the precision in performance that is quite critical for biological experimentation. Too, with proper care, there need be no complications due to secondary missiles, hot gases, and toxic fumes which often plague explosive-driven tubes. Finally, pressure-time recording instruments, as well as those employed to monitor pathophysiological processes, can be mounted just outside the test chamber in close proximity to the animal under study.

It is well now to turn to the two main purposes of this paper; namely, first to describe a shock tube assembled to produce single pressure pulses that rise almost instantaneously to a maximum and endure for about 400 msec, which is a wave form quite comparable to those produced under certain circumstances by nuclear detonations; and second, to present mortality data on six species of animals all exposed in a similar geometry to similar pressure-time phenomena that varied among the species mostly with respect to the magnitude of the overpressure.

METHODS

Geometry of the Shock Tube

Figure 1 presents a diagram of the blast tube. The over-all length is approximately 70 ft. The compression chamber measures 17 ft 5 in. and has an internal diameter of 40.5 in. The driver reduces in diameter from 40.5 in. to 23.5 in. over a 3-ft long transition section at its diaphragm end. The expansion chamber is 53 ft 4 in. in length, of which 30 ft is 23.5 in. I.D. tubing followed by 22 ft of 40.5 in. I.D. tubing. The increase in diameter of the expansion chamber from 23.5 in. to 40.5 in. occurs rather abruptly over a span of little over 1 ft.

As noted in Fig. 1, the driver is stationary since it is "nested" in a massive reinforced concrete back-stop. Consequently, the various components on the expansion side are on casters to facilitate diaphragm replacement. The end of the tube is closed by a 2-in. thick steel plate — the end-plate.

Three vents, each 10x14x8 in., are located at the upstream end of the 40.5 in. tubing of the expansion chamber. These vents serve to "tailor" the wave form and will be discussed later.

The diaphragms employed are 40x40 in. sheets of polyester plastic film (Dupont Mylar). They have holes pre-drilled to match the bolt holes in the flanges. For their insertion they are simply bolted between the appropriate flanges. Mylar sheets of 0.010 and 0.0075 in. thickness are employed, a predetermined number being used to hold a given pressure in the driver section.

Diaphragms are ruptured by lead pellets from a sawed-off 12-gauge shotgun mounted on the tube. The gun fires straight down through the tube, through holes appropriately placed in the top and bottom of the tube. The

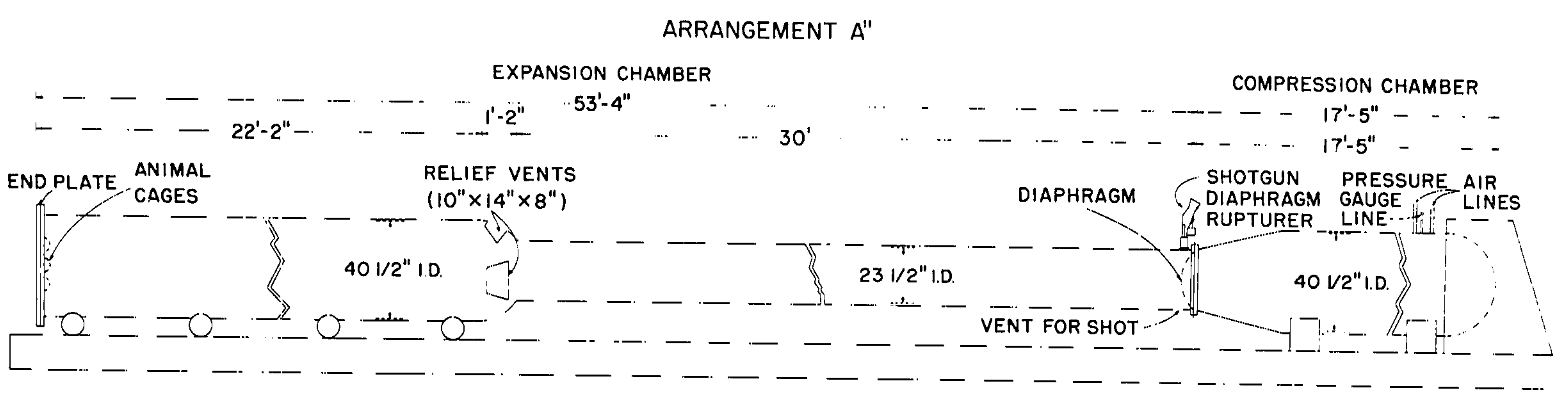
ARRANGEMENT A"
EXPANSION CHAMBER
53'-4"
COMPRESSION CHAMBER
22'-2"
1'-2"
30'
17'-5"
17'-5"
END PLATE
ANIMAL CAGES
RELIEF VENTS (10"×14"×8")
40 1/2" I.D.
23 1/2" I.D.
DIAPHRAGM
VENT FOR SHOT
SHOTGUN DIAPHRAGM RUPTURER
PRESSURE GAUGE LINE
AIR LINES
40 1/2" I.D.

Figure 1

diaphragms under pressure obligingly bow-out in the path of the shotgun blast. Since the shot passes out of the tube through the vent in the under side, it is not carried downstream where it might interfere with the test.

Photographic views taken of the blast tube are presented in Figs. 2, 3 and 4. As seen in Fig. 3 access into the end of the tube, for animal placement, is accomplished by separating the tube at the distal most 24 in. flanges.

The shack seen near the end-plate houses the pressure-time recording instruments and the equipment necessary to operate the shock tube.

Instrumentation

In these particular experiments pressure-time variations were measured by Quartz piezo-electric gauges (Model 401)* that were shock mounted flush with the inside of the tube. Gauges were routinely placed at the end-plate and at short distances upstream from the end-plate. The signal from a gauge was fed through low noise cable with an amplifier-calibrator* into an oscilloscope (Tektronix Model 535A) having a Type L or Type 53/54C pre-amplifier plug-in unit. This oscilloscope had a single sweep circuit which prevented retriggering after the desired trace was recorded.

In using the oscilloscope, the horizontal sweep was externally triggered by the signal from another "trigger gauge" of Barium Titanate** located just upstream of the recording gauge. Pre-triggering the sweep allowed a reference trace of base line to be photographed during the time the shock travelled from the "trigger gauge" to the recording gauge. To insure sufficient voltage to trigger reliably the oscilloscope sweep, the signal from the trigger gauge was amplified. A power supply (Type 105) with amplifiers** (Type 104A) was used for that purpose.

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*Purchased from Kistler Instrument Corporation, North Tonawanda, N.Y.
**Purchased from Atlantic Research Corporation, Alexandria, Va.

Figure 2

Figure 3

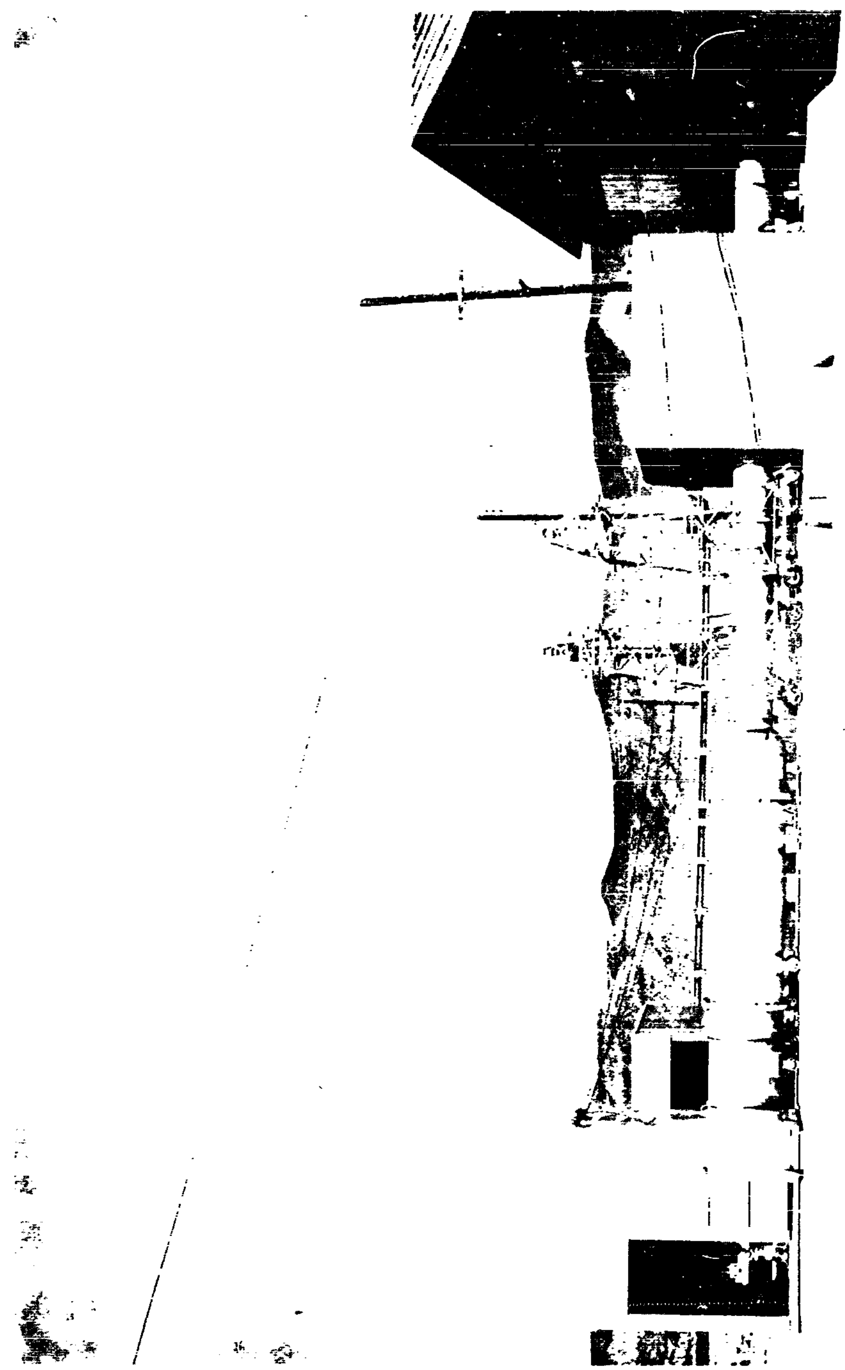


Figure 4

The sweep on the face of the oscilloscope was photographed for the permanent pressure-time record with a Polaroid Land Camera mounted in a periscope assembly. The components that make up a channel of instrumentation are shown in Fig. 5. Available at present are 8 channels of pressure-time measuring gear plus three channels for monitoring the pressures within biological systems.

Calibration of Gauges

The quartz piezo-electric gauges were statically calibrated using a small pressure vessel. Their dynamic performance was also checked on a 12-in.-diameter calibration shock tube. Barium titanate and lead zirconate crystal gauges were calibrated on the calibration shock tube by measuring their voltage out-put at various shock pressures. The latter were computed from measuring the speed of the shock with a Hewlett-Packard Electronic Counter that was started and stopped by gauges placed 18 in. apart.

Biological Material

Table 1 summarizes the number of animals from each of the 6 different species that were employed in this study, along with their body weights and ages. Of the total of 569 animals, 140 were mice; 164, rats; 96, guinea pigs; 104, rabbits; 35, dogs; and 30, goats. Their body weights ranged between 22 g for the mouse to 20 kg for the goat.

All animals were exposed to the overpressure against the end-plate. Except for a few of the mice and rats that managed to turn end-for-end in their cages, all animals were right-side-on to the incident shock front. The dogs and goats were restrained in harness — the mice, rats, guinea pigs, and rabbits in wire mesh cages as described in a previous study.[4]

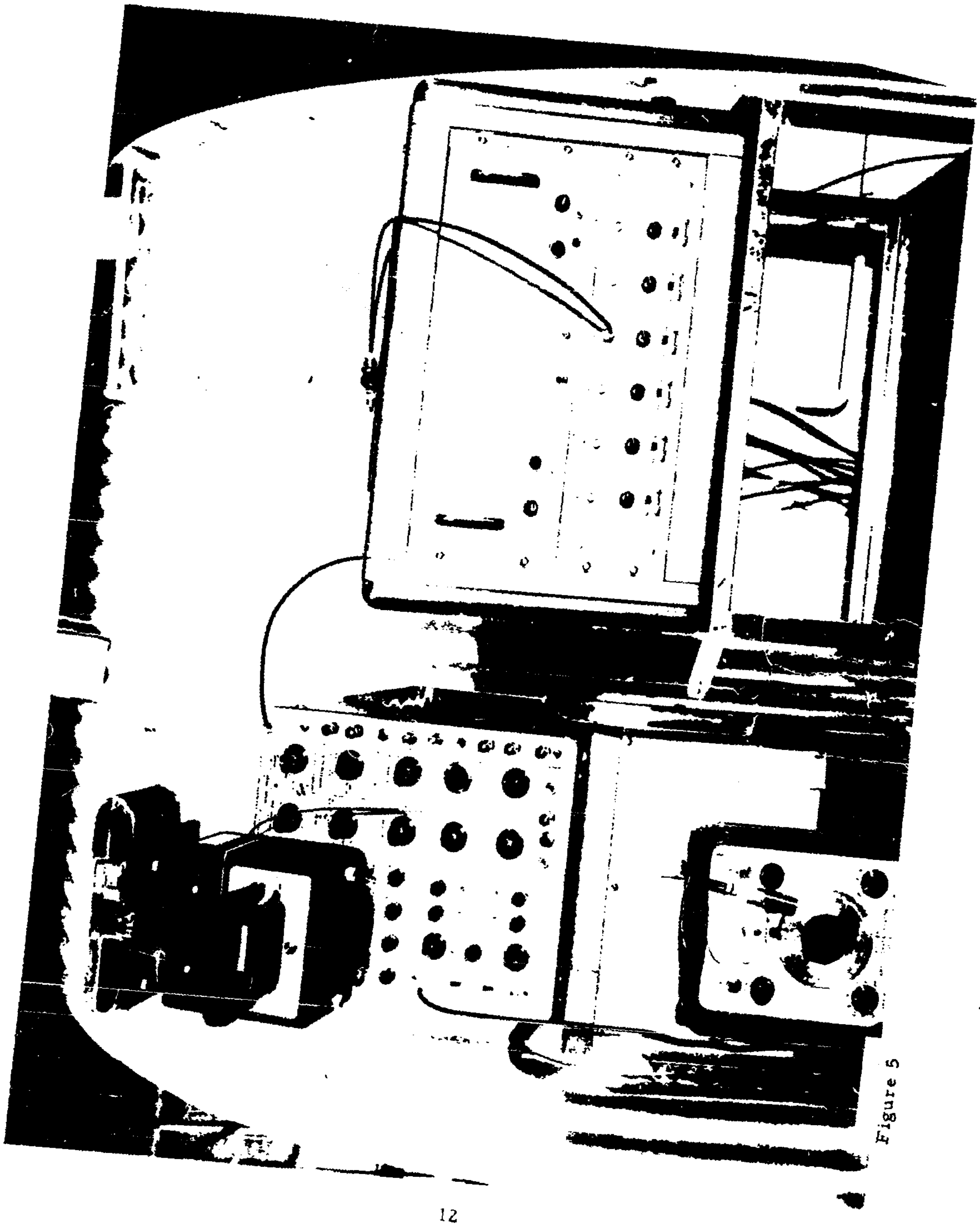


Figure 5

TABLE 1

ANIMALS USED IN THIS STUDY

Species	Number of animals	Body weight	Age, months
Mouse (Webster strain)	140	22 g ± 1.9*	1 - 1-1/2
Rat (Spraguc-Dawlcy)	164	192 g ± 25	2 - 2-1/2
Guinea pig (English short haired)	96	445 g ± 37	3-1/2 - 4
Rabbit (New Zealand White)	104	1.97 kg ± 0.26	2-1/2 - 3
Dog (Mongrel)	35	15.1 kg ± 3.1	—
Goat (Mixed breed)	30	20.5 kg ± 3.6	4 - 5

*Mean and standard deviation

RESULTS

Pressure-time Records

Illustration of four piezo-electric gauge records are presented in Fig. 6. The upper two records were from gauges 1 and 2 located face-on flush with the inside of the end-plate, while the lower two records were from gauges 3 and 4 side-on at 3 in. and 9 in. upstream from the end-plate. As seen in the figure, the face-on gauges see the incident and reflected shock pressures as one step, whereas those gauges side-on resolve the shocks as two pressure steps. It can also be noted from the record of gauge 2 that the rise time of the pressure on the end-plate was less than that of the gauge. The oscillations seen on the records to damp out rapidly were, of course, due to the natural frequencies of the quartz crystal gauges.

The duration of the overpressure (near 400 msec) can be read from the record of gauge 4 since the oscilloscope that recorded the out-put of that gauge was run at a fairly slow sweep-speed of 50 msec/cm.

The magnitude of the incident and reflected shock fronts obtained with a range of compression chamber pressures between 17 psi to 170 psi was plotted and is shown in Fig. 7. The reflected shock pressures from 25 psi to nearly 60 psi were sufficient for the compilation of the dose-response curves. The durations of the overpressures over that range of reflected pressures were between 350 to 412 msec.

Mortality

The 24-hr lethality obtained with the sample of animals exposed at the various driver pressures and the associated mean incident and reflected pressures are given in Table 2. Previous studies have shown that the mortality

PRESSURE-TIME RECORDS QUARTZ PIEZO GAUGES

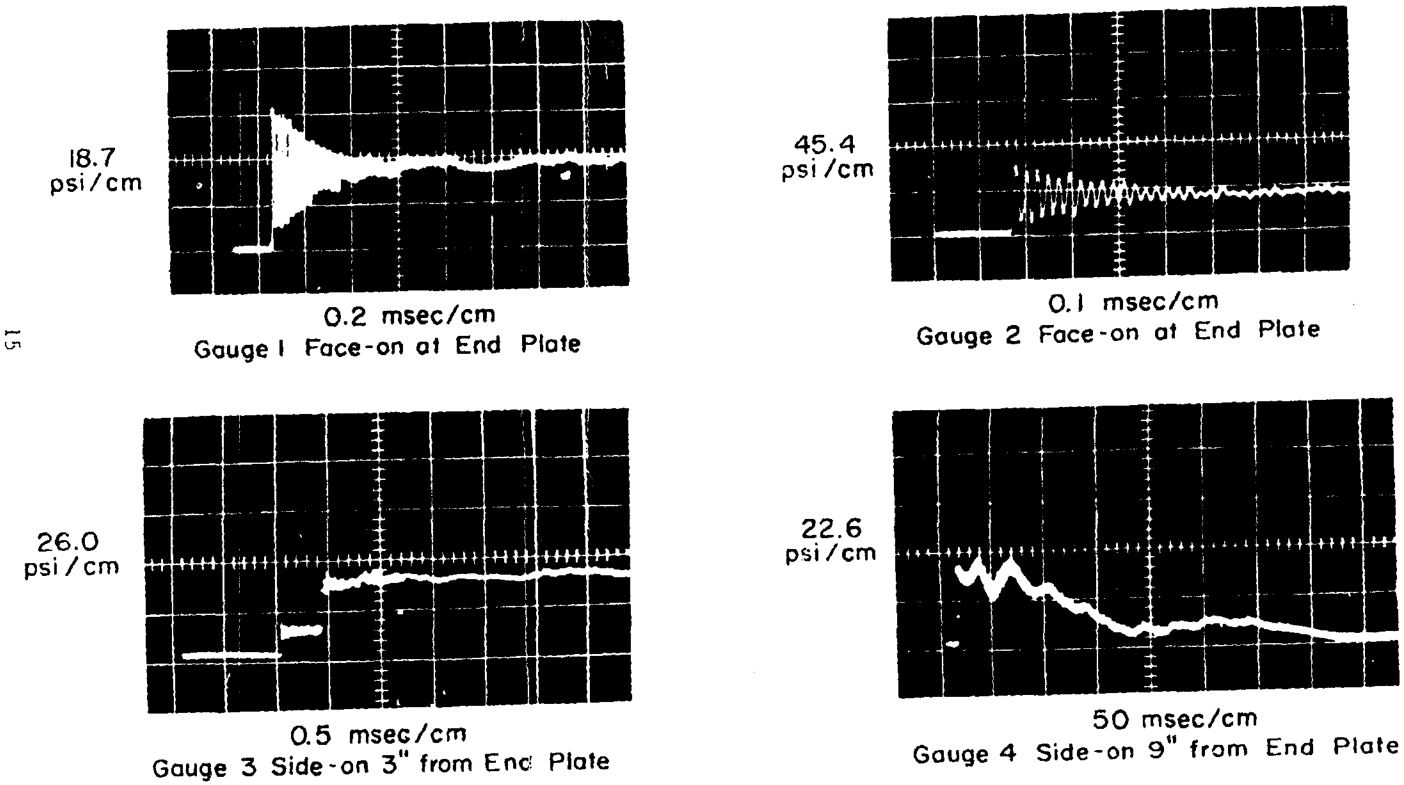
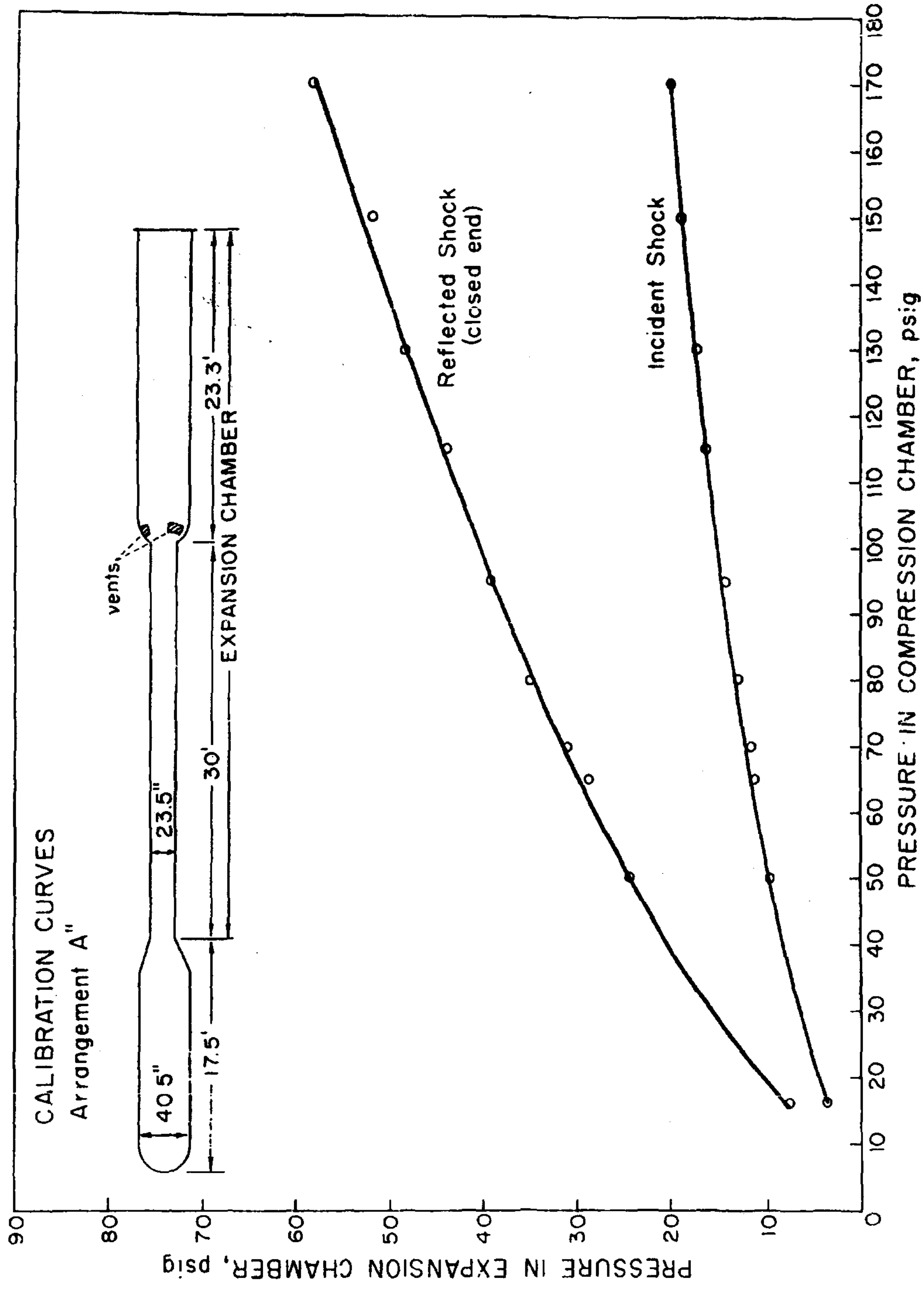


Figure 6



CALIBRATION CURVES
Arrangement A"
vents
40.5"
23.5"
17.5'
30'
23.3'
EXPANSION CHAMBER
Reflected Shock
(closed end)
Incident Shock
PRESSURE IN COMPRESSION CHAMBER, psig
PRESSURE IN EXPANSION CHAMBER, psig
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180

Figure 7

TABLE 2

MORTALITY AS RELATED TO THE MAGNITUDE OF THE INCIDENT AND REFLECTED SHOCK FRONTS

Compression chamber pressure psi	Incident shock psi	Reflected shock psi	Mortality	
			No. dead / Total	Per cent
Mice:				
58	10.2 (9.5-11.0)*	27.2 (25.4-27.9)*	7/40	17.5
65	11.2 (10.9-11.4)	28.9 (28.6-29.1)	8/30	26.7
70	10.9 (10.5-11.2)	31.6 (31.3-31.9)	18/30	60.0
80	13.3 (13.2-13.4)	35.6 (34.7-36.6)	18/20	90.0
130	18.0 (17.5-18.5)	50.8 (49.5-52.2)	20/20	100.0
Rats:				
70	11.4 (10.9-11.9)	30.4 (30.0-30.8)	2/30	6.7
80	13.8 (13.4-14.1)	34.4 (33.8-34.7)	12/34	35.3
95	13.6 (12.7-14.0)	38.6 (37.9-39.6)	35/50	70.0
105	15.4 (15.0-15.8)	42.2 (40.3-43.2)	35/40	87.5
130	18.0 (17.5-18.5)	50.8 (49.5-52.2)	10/10	100.0
Guinea pigs:				
65	10.9 (10.6-11.0)	29.0 (28.6-29.8)	1/24	4.2
80	12.0 (11.0-12.4)	33.9 (33.2-34.3)	9/24	37.5
80	13.4 (12.8-14.0)	35.8 (35.5-36.5)	18/24	75.0
95	13.5 (11.3-14.7)	39.9 (38.1-41.0)	21/24	87.5
Rabbits:				
48	9.2 (8.7-9.8)	22.8 (20.0-24.7)	1/20	5.0
58	10.5 (9.6-10.9)	26.9 (25.0-29.1)	10/28	35.7
75	12.2 (11.5-13.6)	32.6 (30.5-34.6)	16/24	66.7
80	13.1 (12.5-13.6)	36.6 (35.2-38.3)	17/20	85.0
95	14.3 (14.0-14.7)	40.5 (40.4-40.5)	12/12	100.0
Dogs:				
95	14.7 (13.9-15.1)	39.2 (39.0-39.4)	0/5	0
115	16.6 (16.0-17.4)	44.1 (42.2-44.9)	1/10	10.0
130	17.7 (16.9-18.4)	48.1 (46.8-49.6)	6/10	60.0
150	19.0 (18.2-19.9)	53.0 (50.0-55.3)	9/10	90.0
Goats:				
130	16.7 (15.8-17.8)	44.9 (44.0-46.2)	2/10	20.0
150	18.2 (16.2-19.3)	51.4 (47.3-56.2)	4/10	40.0
170	19.4 (19.0-20.1)	56.9 (56.6-57.4)	3/5	60.0
170	20.3 (20.0-20.7)	59.3 (58.7-60.1)	4/5	80.0

Computed LD_{50}'s: Mice, 30.7 psi; rats, 36.3 psi; guinea pigs, 34.5 psi; rabbits, 29.6 psi; dogs, 47.8 psi; goats, 53.0 psi.

*Mean and range.

was best correlated with the reflected shock pressures.[4] Since plotting the per cent mortality against the reflected pressure produced a sigmoid curve, the probit analysis was applied to the data which transforms it into a straight line.[8] The general form of the probit equation of this type was:

$$Y = a + b \log X$$

when Y was the per cent mortality in probit units, X was the reflected shock pressure, and a and b were the intercept and slope constants, respectively. The LD_{50} (the pressure associated with 50 per cent mortality) was obtained by substituting the probit value of 5 (equal to 50 per cent mortality) for Y in the appropriate probit equation and solving for X. The LD_{50}'s obtained in this manner, the standard errors of the LD_{50}'s and the probit regression line equations are listed in Table 3. The LD_{50}'s in order of increasing species weights were as follows: mouse, 30.7; rat, 36.3; guinea pig, 34.5; rabbit, 29.6; dog, 47.8; and goat, 53.0 psi. The trend was for the LD_{50}'s to increase with the species size. The probit regression lines with the data points are presented graphically in Fig. 8.

The LD_{50}'s fell into three groups according to statistical tests that compared them for significant differences. The mouse and rabbit were not significantly different from one another at the 95 per cent confidence level; neither were the guinea pig and rat, nor the dog and goat. However, each pair, as grouped above, were different statistically from one another. That is, the mouse and rabbit were significantly below the rat and guinea pig who were below the dog and goat.

Appropriate statistical tests that compared the slopes of the six probit mortality curves revealed that they were essentially parallel at the 95 per cent

TABLE 3

SUMMARY OF THE RESULTS FROM THE PROBIT ANALYSIS

Species	LD_{50} psi	Standard error of the LD_{50}, psi	Probit equation constants intercept, a	slope, b
Mouse	30.7	± 0.56	-23.63	19.25
Rat	36.3	± 0.61	-23.82	18.48
Guinea pig	34.5	± 0.64	-28.50	21.78
Rabbit	29.6	± 0.90	-13.63	12.67
Dog	47.8	± 1.06	-49.47	32.43
Goat	53.0	± 2.79	-16.68	12.57

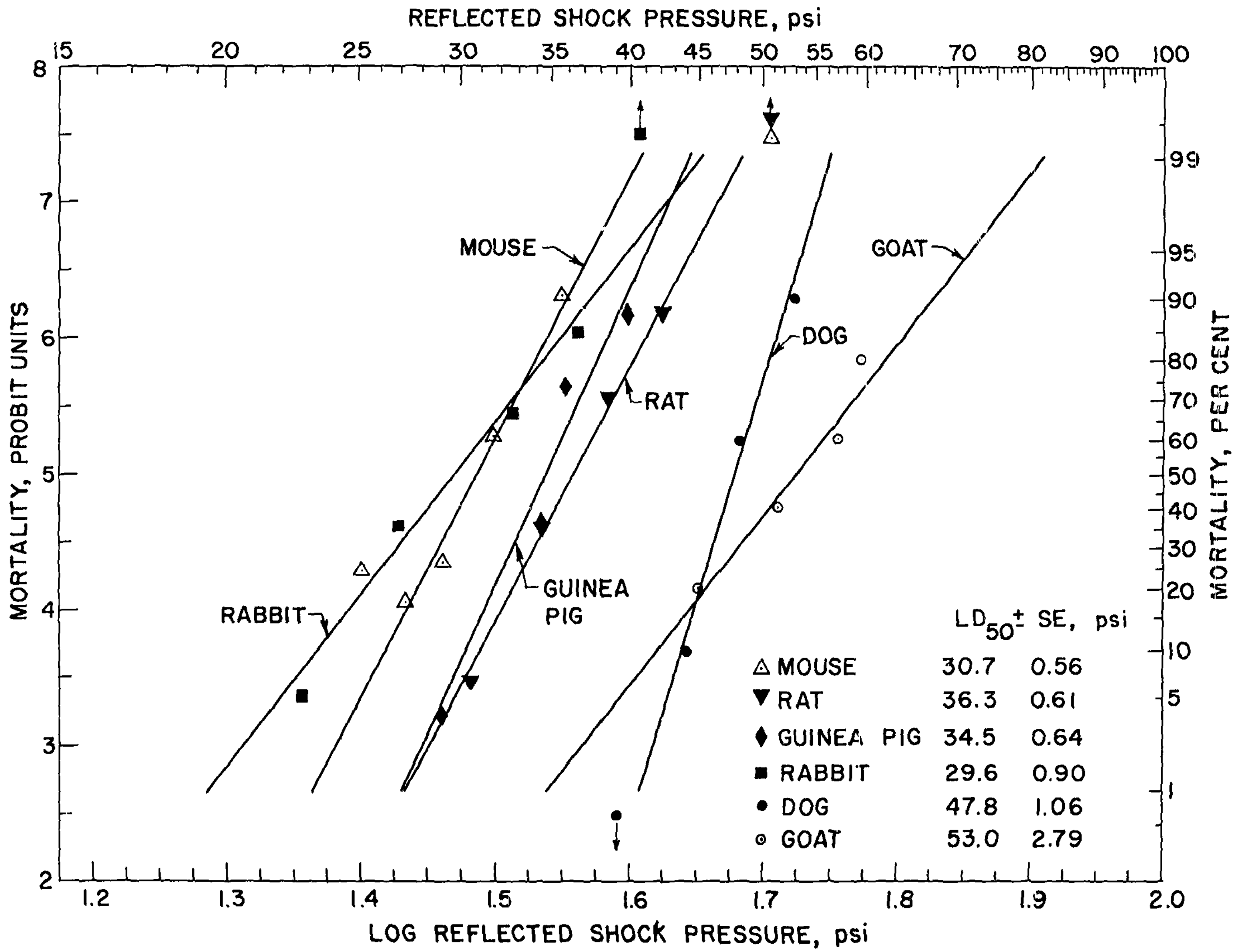

REFLECTED SHOCK PRESSURE, psi
MORTALITY, PROBIT UNITS
MORTALITY, PER CENT
LOG REFLECTED SHOCK PRESSURE, psi
MOUSE
RAT
GUINEA PIG
RABBIT
DOG
GOAT
LD50 ± SE, psi
△ MOUSE 30.7 0.56
▼ RAT 36.3 0.61
♦ GUINEA PIG 34.5 0.64
■ RABBIT 29.6 0.90
● DOG 47.8 1.06
⊙ GOAT 53.0 2.79

Figure 8

confidence level. This may be interpreted to mean that the same type of stimulus was instrumental in killing the animals from each species.[8]

Interspecies Correlation Between LD_{50} Reflected Pressures and Species Weight

A log-log plot of the LD_{50}'s versus the mean body weight of each species appears in Fig. 9. The regression line equation, calculated by the method of least squares that best fit the data, was:

$$\text{Log } LD_{50} = 1.3673 + 0.06939 \log BW$$

where

LD_{50} = the reflected pressure required for 50 per cent lethality, psi

BW = mean body weight of the species, grams

1.3673 = the intercept constant

0.06939 = the slope constant

According to Fig. 9 there is fair agreement between the calculated line and the measured points save for the rabbit whose point was noticeably low for its weight. The standard error of the regression estimate was 0.0602 log units or 13.9 per cent.

Included in Fig. 9 is the calculated point for a 70 kg animal. It was obtained by simply solving the regression equation for a body weight of 70,000 g. In other words, this predicts 50.5 psi to be the LD_{50} reflected pressure for a large animal the size of man exposed against a reflecting surface to a single-pulse overpressure rising almost instantaneously to near a maximum and enduring for about 400 msec.

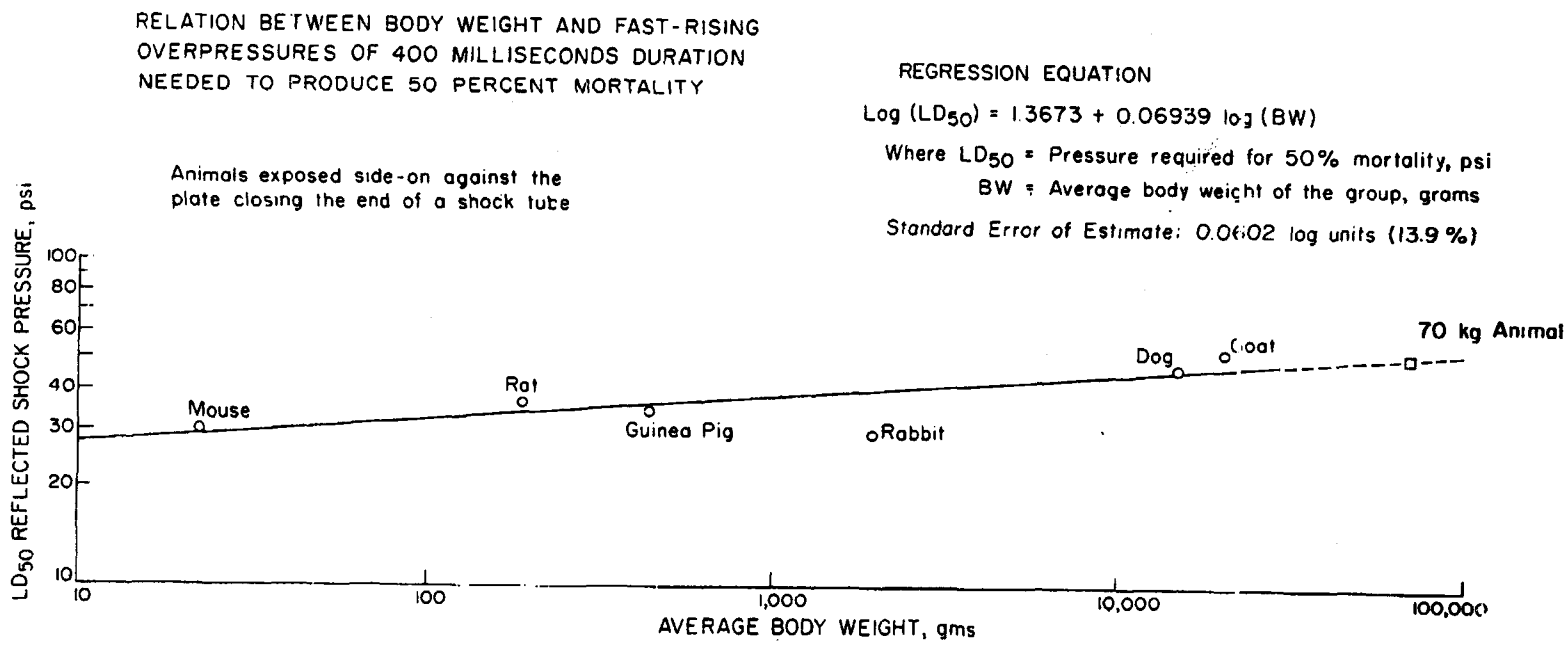

RELATION BETWEEN BODY WEIGHT AND FAST-RISING
OVERPRESSURES OF 400 MILLISECONDS DURATION
NEEDED TO PRODUCE 50 PERCENT MORTALITY
Animals exposed side-on against the
plate closing the end of a shock tube
REGRESSION EQUATION
Log (LD50) = 1.3673 + 0.06939 log (BW)
Where LD50 = Pressure required for 50% mortality, psi
BW = Average body weight of the group, grams
Standard Error of Estimate: 0.0602 log units (13.9%)
70 kg Animal
Mouse
Rat
Guinea Pig
Rabbit
Dog
Goat
LD50 REFLECTED SHOCK PRESSURE, psi
100
80
60
40
30
20
10
10
100
1,000
10,000
100,000
AVERAGE BODY WEIGHT, gms

Figure 9

DISCUSSION

By way of discussion, remarks in three areas are indicated; i.e., (a) the general behavior of the pressure source, (b) the wave form achieved using the shock-tube hardware described, and (c) the biological implications of the data.

The General Behavior of the Pressure Source

A study of Table 2, which gives the mean and range of the incident and reflected shock overpressures for the several experiments, shows that the pressure source utilized did not function perfectly as far as reproductibility of overpressures were concerned. For example, the variation in incident shocks for the different pressure groupings ranged from a few tenths of a psi to a maximum of 3.4 psi (see the guinea pig data for 95 psi compression chamber pressure). In the latter case the mean incident shock pressure was 13.5 psi with a minimum 2.2 psi below and a maximum 1.2 psi above the mean, respectively. Variability for reflected shocks, as could be expected, was somewhat greater, but only ranged from a few tenths of a psi to a maximum of 8.9 psi for the goat exposure involving a compression chamber pressure of 150 psi. The maximum reflected shock was 4.1 psi above the mean while the minimum was 4.1 psi below the mean of 51.4 psi. Though this last variability represents a performance about ±10 per cent from the mean pressure, it is indeed the maximal "misbehavior" of the shock tube. In most cases, the variability was much less as a study of the data in Table 2 will show. In fact, judging from earlier experience, the reproductibility performance noted in the present study is considered quite good indeed.

The Wave Form Achieved

Before the vent holes were added to the distal section of the shock tube, the wave form had many undesirable characteristics: first, the duration of the overpressure was longer than desired; second, there was considerable "crowning" of the overpressure after the development of the reflected shock, that is, the maximal pressure developed was considerably above the reflected shock pressure; third, marked oscillations in the overpressure occurred during the falling phase of the pulse. These were many in number and the amplitude of the oscillations was high.

After addition of the vents, all of these untoward characteristics were improved, though the wave form achieved is, from one point of view, still not exactly that desired. For example, attention is directed to the lower right-hand trace in Fig. 6 which shows the pressure pulse in its entirety on a somewhat compressed time scale. The reader will note that the maximal overpressure achieved is still somewhat above (about 5 psi) the reflected shock pressure of near 36 psi. Also, the pressure oscillations present represent a swing in pressure of about 19 psi, occurring in 20 msec; this involves a variation of about 1/2 the magnitude of the reflected shock pressure. Also, if 20 msec is taken for the half-cycle time, the frequency of this portion of the oscillation is 25 cps.

Thus, wave forms, having the characteristics of the pattern just discussed, raises uncertainties as regards assessing the biological implications of the pressure pulse, which uncertainties would be markedly lessened if the wave forms were "clean"; e.g., the crowning and pressure oscillations were absent. This point will be pursued later.

However this may be, it can be said from another point of view that the wave forms recorded in the present study are similar to some of those seen in full-scale operations in Nevada and are, therefore, quite desirable.[6] In truth, there is need for knowing the biology of both "clean" and "unclean" pressure pulses and in this light the present study contributes a great deal.

Biological Implications of the Data

At least two interesting questions arise in the biological area: first, what portions of the pressure pulse contribute to injury and second, what faith may or may not be put in extrapolating interspecies data to larger animals?

With regard to the first question, it is now clear that the animal poorly tolerates very "fast"-rising overpressures compared with "slow"-rising pressure pulses of the same magnitude.[4-6] This fact directs attention to the rising phase of the overpressure as critical and implies that damage is associated with shock loading. If indeed this is so and the animal suffers damage from the initial pressure rise, then any after-coming pressure variations might well enhance the injury. Also involved, of course, is the amplitude and frequency of the pressure oscillations, particularly as the latter may "match" the natural frequency of the thorax-abdominal system of a given species.

Also, if shock loading is one of the critical factors biologically, one would expect that any degrading of the average rate of pressure rise — all other factors being equal — would be associated with increased tolerance to overpressure. Such is the case empirically. Guinea pigs, for example, exposed at increasing distances from the end-plate of a shock tube show an increase in the P_{50} from 37 psi against the end-plate to 57 psi at 1 ft from the end-plate; e.g., the pressure rises in two rapid steps instead of one.[4] Likewise, dogs tolerate without fatality well over 150 psi if the time to Pmax is

30 msec or longer, even though the pulse duration is as long as 5 to 20 sec.[5]

Involved in the biological interpretation of the hazards of overpressure is the duration of a single, "fast"-rising overpressure. Data are at hand which indicate that, within limits, the duration of such a pulse of overpressure is significant; e.g., for the dog about 220 psi enduring for 1.8 msec is fatal, whereas only 75 psi is fatal when the duration is 11.8 msec; for smaller animals, duration is important only for shorter intervals like fractions of a millisecond to 1, 2, or 3 msec.[9]

Currently, data simply are not at hand to allow a more definitive and quantitative interpretation of those characteristics of pulses of overpressure which define hazard clearly. It remains for future work to systematically spell out the criticality of rates of pressure rise, overpressure duration, step loading with two or more shocks in the rising phase of a pulse, and finally the biological meaning of oscillating overpressures.

Last, there remains the question of extrapolating interspecies blast data to larger (or smaller) animals. There is little to be said except that one should approach the extrapolation of data to any given species, including man, with considerable caution. First, it should be noted that all the animals used in the work described here were mounted against a reflecting surface and any extrapolation should keep this fact in mind. Second, the shock overpressures related or correlated with the interspecies mortality were the reflected shock pressures and one should not confuse an incident or local static-free field pressure — corresponding to the incident pressures reported here — with the reflected shock. Third, exactly what the pressure reflection would be when an incident wave strikes an animal in the open is not currently clear to the authors and certainly the data presented do not bear upon this point.

Fourth, the extrapolation set forth in Fig. 9 applies strictly to the pulse form studied and to an overpressure duration of about 400 msec. Fifth, for these conditions, it is not known whether man is more or less tolerant than might be implied by the 70 kg point marked in Fig. 9. A few data do exist for the human case which relate 235 psi[9] and 450 psi[10] with human mortality, but these concern only high explosive-produced overpressures of a few msec duration and do not apply at all to the longer duration case. It would seem, therefore, that the extrapolation indicating that a 400 msec single, sharp-rising overpressure of 50.5 psi applies to as large an animal as man and might well be considered a tentative figure subject to all the conditions mentioned above. In the meantime, one must await the results of further experimental work to define more definitively man's tolerance to blast.

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