C-2

TID-6056

HEALTH AND SAFETY

SHOCK TUBE STUDIES OF THE EFFECTS OF SHARP-RISING, LONG-DURATION OVERPRESSURES ON BIOLOGICAL SYSTEMS

Progress Report

By

D. R. Richmond M. B. Wetherbe
R. V. Taborelli R. T. Sanchez
F. Sherping V. C. Goldizen
C. S. White

March 10, 1959

The Lovelace Foundation for Medical Education
and Research
Albuquerque, New Mexico

UNITED STATES ATOMIC ENERGY COMMISSION
Office of Technical Information

Printed in USA. Price $0.75. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

USAEC Office of Technical Information Extension, Oak Ridge, Tennessee

TID-6056

SHOCK TUBE STUDIES OF THE EFFECTS OF SHARP-RISING, LONG-DURATION OVERPRESSURES ON BIOLOGICAL SYSTEMS

by

D. R. Richmond, R. V. Taborelli, F. Sherping,
M. B. Wetherbe, R. T. Sanchez, V. C. Goldizen,
and C. S. White

Atomic Energy Commission Project

Progress Report

AEC Contract No. AT(29-1)-1242

Presented at the Third Shock Tube Symposium,
Sponsored by the Air Force Special Weapons Center, KAFB, N. M.,
Fort Monroe, Virginia, March 9-11,
1959

March 10, 1959

The Lovelace Foundation for Medical Education and Research
Albuquerque, New Mexico

SHOCK TUBE STUDIES OF THE EFFECTS OF SHARP-RISING, LONG-DURATION OVERPRESSURES ON BIOLOGICAL SYSTEMS*

D. R. Richmond, R. V. Taborelli, F. Sherping, M. B. Wetherbe,
R. T. Sanchez, V. C. Goldizen, and C. S. White
Lovelace Foundation for Medical Education and Research
Albuquerque, New Mexico

INTRODUCTION

Shock tubes have been used successfully by a number of investigators to study the biological effects of variations in environmental pressures (1, 2, 3). Recently an unusually versatile laboratory pressurization source became available with the capability of consistently reproducing a wide variety of pressure-time phenomena of durations equal to and well beyond those associated with the detonation of nuclear devices (4). Thus it became possible to supplement costly full-scale field research in blast biology carried out at the Nevada Test Site (5, 6) by using an economical yet realistic laboratory tool. In one exploratory study employing pressure pulses of 5 to 10 sec duration wherein the times to max overpressure and the magnitudes of the overpressures were varied, a relatively high tolerance of biological media to pressures well over 150 psi was demonstrated (7). In contrast, the present paper will describe the relatively high biological susceptibility to long duration overpressures in which the pressure rises occurred in single and double fast-rising steps.

METHODS

Shock Tube

The shock tube used to achieve variations in the pressure environment has been described in detail elsewhere (4, 8). In brief, however, the apparatus consisted of a cylindrical pressure chamber 40.5 in. in diameter and 17 ft 5 in. long separated by a frangible diaphragm (Dupont Mylar) from an expansion chamber made up of sections of steel pipe 23-1/2 in. in diameter and 25 ft long. The reduction in diameter from 40-1/2 to 23-1/2 in. occurred over

---

*This work was supported by contract with the Division of Biology and Medicine of the Atomic Energy Commission, and was carried out at the AEC-Lovelace Foundation Blast Tube Facility, Sandia Base, Albuquerque, New Mexico.

a 3 ft long transition section upstream of the diaphragm station. The downstream portion of the shock tube was closed with a steel plate bolted to the end of the expansion chamber. See Figure 1. Following pressurization of the expansion chamber, which was accomplished by initiating rupture of the diaphragm with a .22 caliber bullet fired at an angle from a pistol mounted downstream of the diaphragm, high-pressure gas escaped through openings in the wall of the shock tube and thus determined the rate of pressure fall.

Animals and Cages

Four species of animals were exposed in metal-mesh cages having the dimensions noted in Table 1. The cages, shown in Figs. 2, 3, 4 and 5, were carefully sized to fit the animals snuggly and thus served to minimize possible damage from displacement. The cages were either bolted against the inside of the end-plate of the shock tube or were fixed at varying distances away from the end-plate, e.g., 1, 2, 3, 6 and 12 in.

Instrumentation

Pressure-time data were obtained using Wiancko pressure transducers and piezoelectric gauges appropriately integrated with amplifying equipment and recorders. The latter consisted of Consolidated galvanometers and an oscillograph for Wiancko data and a Tektronix cathode ray oscilloscope mounting a camera to photograph the piezo gauge results.

Pressure-time Environment

Pressure gauges were located in the end-plate, face-on to the advancing shock front and side-on in the wall of the shock tube 1 and 11 ft from the end-plate. The upper portion of Figure 6 shows a face-on pressure-time trace. The reader will note that the incident and reflected wave almost instantaneously activated the pressure transducer giving a sharp, fast-rising pressure pulse followed by a slow-rising crown. In contrast, the middle and lower records of Figure 6 taken with gauges located at 1 and 11 ft from the end-plate of the tube, respectively, show two fast-rising steps in the pressure pulse followed by a crown. The first step was due to the incident shock, whereas the second was caused by the pressure reflection from the end of the tube. All overpressures were from 6 to 8 sec in duration.

Pressures to be reported later were read from the peak of the vertically rising portion of the record. The crown following the reflected shock

Table 1—DIMENSIONS OF THE ANIMAL CAGES

Species	Dimensions of individual cage (in.)	Number of compartments	Division of openings in wire mesh (in.)
Mouse	1-1/2x1-1/2x3-1/4 1.5 x 1.5 x 3.25	5	1/4x3/4
Rat	2x2-1/4x8 2 x 2.25 x 8	5	1/4x3/4
Guinea Pig	3x3x8-1/2 3 x 3 x 8.5	3	1/4x3/4*
Rabbit	5x5x14 5 x 5 x 14	2	3/4x1-3/4**

*Approximately 60 per cent open area (diamond-shaped)

**Approximately 75 per cent open area (diamond-shaped)

Mouse	1.5/.8 =	1.88	1.5/1 =	1.5
Rat	2/1.74	1.15	2.0/1.5	1.3
GP	3/2.29	1.31	3/2	1.5
Rab	5/3.61	1.38	5/4	1.25

represented only a small additional and slow rise over the pressure in the reflected shock and was considered unimportant biologically.

The secondary reflections in the latter portions of the traces in Fig. 6 were eliminated in some of the experiments by using the arrangement shown in Fig. 7. As shown in the figure, the secondary pressure reflections were absent and, as will be indicated later, they were probably of no biological importance as far as the present study was concerned.

RESULTS

1. Animals Exposed Side-on Against the End-plate of the Shock Tube

Four species of animals, listed in Table 2 showing their numbers and body weights, were exposed side-on in cages bolted against the end-plate of the shock tube to reflected pressures of increasing magnitude. The mortality noted at 1 hr or less after exposure is detailed in Table 3, and plotted in Fig. 8. The latter shows typical sigmoid shaped mortality curves. The probit analysis of Finney (9) was applied to the data.

Figure 9 shows a probit plot of the results and sets forth the reflected pressure in psi associated with 50 per cent mortality in each species (LD_{50}). As can be seen from the figure, the LD_{50} values arranged in ascending order were 29.8 (±1.1), 33.4 (±1.2), 36.7 (±0.7), and 38.7 (±0.6) psi for the mouse, rabbit, guinea pig, and rat, respectively. The standard errors of the means noted in parentheses above were encouragingly small.

Statistical tests showed that the LD_{50} value for the rat was significantly higher than those for the rabbit and the mouse, but not for the guinea pig. Though there was a significant difference between the guinea pig and the mouse, such was not the case when comparing the rabbit and the mouse or rabbit and guinea pig. Also, tests indicated the regression lines for the rat, guinea pig and rabbit were essentially parallel, but the slope of the regression line for the mouse was significantly different than those for the other three species of animals.

As previously mentioned, the multiple reflections returning secondarily from the compression chamber did not add to the mortality rate. For example, a group of 30 guinea pigs were exposed against the end-plate to the pressure pulse that lacked the repeated reflections (Fig. 7). Fifty-seven per cent mortality was obtained with reflected shocks that averaged 39 psi. In

$m^{1/3}/W$

Table 2—NUMBER AND SPECIES OF ANIMALS USED IN THIS STUDY

Species	Body weight (Mean, SE)	Age (mos.)	Width (in.)	Number of Animals Exposed against end-plate	at various distances from end-plate
Mouse (F) (Webster Strain)	2,645 18.5 ± 0.15 g	1 - 1/2	(2.645) 1	115	78
Rat (F) (Sprague Dawley)	5.769 192.0 ± 1.51 g	2 - 2-1/2	2.18 (3.846) 1-1/2	145	80
Guinea Pig (M & F) (English Breed)	7.588 436.7 ± 3.3 g	3-1/2 - 4	2.87 (3.794) 2	140	446
Rabbit (F) (New Zealand White)	12.00 1732 ± 35.8 g	2-1/2 - 3	4.54 (3.00) 4	55	38

$\left(\frac{m^{1/3}}{w}\right)_{ave} = 3.32$ $\frac{1}{3.32} = .3012$

	wt	$m^{1/3}$	width		
Mouse	18.5	2.645	.80 in	(1.0)	.8
Rat	192	5.769	1.74	(1.5)	1.16
GP	437	7.588	2.29	(2)	1.14
Rab.	1730	12.0	3.61	(4)	.90

$\frac{m^{1/3}}{3.32}$

Table 3—MORTALITY* AS RELATED TO THE MAGNITUDE OF THE REFLECTED SHOCK FOR ANIMALS EXPOSED SIDE-ON AGAINST THE CLOSED END OF A SHOCK TUBE

Overpressure in reflected shock (psi)	Number killed / Total	Percent Mortality
Mouse:		
19.50	0/15	0
24.50	0/15	0
29.70	17/25	68.0
34.80	19/25	76.0
37.12	18/20	90.0
38.8	14/15	93.0
Rat:		
21.2	0/10	0
31.0	0/20	0
34.0	2/25	20.0
37.6	8/25	32.0
39.0	12/20	60.0
40.2	14/20	70.0
46.0	13/15	86.7
53.5	10/10	100
Guinea Pig:		
16.3	0/15	0
20.7	0/15	0
29.3	1/20	5.0
36.3	8/20	40.0
39.6	19/25	76.0
42.0	13/15	86.7
46.7	15/15	100
55.3	15/15	100
Rabbit:		
25.5	0/8	0
29.2	1/6	16.7
32.9	4/8	50.0
35.0	8/15	53.3
37.6	7/8	87.5
39.3	4/4	100
52.7	6/6	100

*Mortality at 1 hr or less.

the other arrangement where multiple peaks occurred (Fig. 6), initial reflected shocks of 38 psi produced 60 per cent mortality. The difference in mortality between the two groups was not significant.

2. Animals Exposed to Varying Distances from the End-plate of the Shock Tube

Guinea Pigs

Experiments similar to those described above were performed using guinea pigs except that the cages were located 1, 2, 3, 6 and 12 in. from the end-plate of the shock tube at the time of exposure. Mortality data for the several groups of animals are summarized in Table 4 which, for comparison, also includes results for animals exposed against the end-plate.

Probit analysis was performed on the data shown in Table 4. Mortality regression lines and the reflected pressures associated with 50 per cent mortality for the different cage positions are shown in Fig. 10. Attention is directed to the results which clearly indicate a rise in the LD_{50} values as the animals were moved away from the end of the tube being 36.7 ± 0.7 psi against the end-plate and 40.8 ± 2.1, 48.3 ± 1.3, 52.8 ± 1.9, 58.6 ± 1.6 and 57.1 ± 1.1 psi for cage positions at 1, 2, 3, 6 and 12 in. from the reflecting surface, respectively. The reader will note that there was no essential difference in the results obtained at the 6 and 12 in. cage positions and that the rather large increase in pressure tolerance occurred at the 1 and 2 in. cage locations.

This somewhat remarkable finding occurred even though the time between the arrival of the initial incident pressure at the animal position and the subsequent reflected pressure was by measurement close to 1.4 msec for the 12 in. position and was much less at stations closer to the end-plate. Apparently the biological system can and does distinguish surprisingly short time intervals when stepwise pressure "loading" occurs with sharp-rising segments of the pressure pulse.

Mouse, Rat, Rabbit

To further explore the biological effects of step-loading, the experiments performed on guinea pigs described above were repeated using mice, rats, and rabbits with two alterations in procedure, namely, (1) a series with animals exposed against the end-plate was included, and (2) the tube was

Table 4—MORTALITY AS RELATED TO THE MAGNITUDE OF THE REFLECTED SHOCK FRONT FOR GUINEA PIGS EXPOSED SIDE-ON AT VARIOUS DISTANCES FROM THE END-PLATE

Distance of cage from end-plate (in.)	Number of animals	Reflected overpressure (psi)	Mortality* (per cent)
0	15	16.3	0
	15	20.7	0
	20	29.3	5
	20	36.3	40
	25	39.6	76
	15	42.0	86.7
	15	46.7	100.0
	15	55.3	100.0
1	21	31.1	14.3
	15	37.0	13.3
	15	42.0	40.0
	12	45.9	83.3
	12	52.0	100.0
2	12	39.3	8.3
	12	42.9	25
	18	48.8	55.6
	12	52.0	66.7
	9	58.0	77.8
	6	71.0	100.0
	9	77.3	100.0
3	9	37.7	0
	12	48.1	25
	15	50.6	26.7
	15	52.6	53.3
	9	56.7	77.8
	15	60.8	86.7
	12	73.5	91.7

Table 4—MORTALITY AS RELATED TO THE MAGNITUDE OF THE REFLECTED SHOCK FRONT FOR GUINEA PIGS EXPOSED SIDE-ON AT VARIOUS DISTANCES FROM THE END-PLATE (Continued)

Distance of cage from end-plate (in.)	Number of animals	Reflected overpressure (psi)	Mortality* (per cent)
6	9	35	0
	12	38	0
	18	47	5.56
	21	52.1	23.8
	15	59.2	60.0
	6	63.5	66.7
	9	68	77.8
	9	72.3	88.9
12	3	33	0
	6	37	0
	19	47.4	10.5
	9	52	22.2
	9	55.7	22.2
	9	58	55.6
	9	60	66.7
	15	62	80.0
	9	67.7	88.9
	12	72.5	100.0
	9	84	100.0

*Mortality at 1 hr or less

operated at near constant compression chamber pressures of 58 psi. The latter yielded reflected pressures, which proved fatal for all animals exposed against the end-plate (which averaged 53 psi with a range from 48 to 56 psi).

Results obtained are tabulated in Table 5 in which are also included appropriate portions of the guinea pig data described in the previous section. A graphic presentation of the results are shown in Fig. 11. From a study of the figure at least two results are apparent. First, all animal species show a decrease in mortality with increasing distance from the reflecting surface, i.e., with increasing time between arrival of the incident and reflected waves. Secondly, the rate of decrease of mortality with increasing distance from the end-plate is greater for the smaller than the larger animals. Actually, the exploratory nature of the data do not justify further comment beyond pointing out that (1) only a trend in the "behavior" of biologic systems has been demonstrated, (2) the animals against the end-plate were "over-shot", meaning that the reflected pressures were well above those required for 100 per cent mortality, and (3) lastly, the number of animals used to define each point were small, particularly in the case of the rabbit experiments.

DISCUSSION

General

From the practical point of view, when considering biological tolerance to overpressures of long duration, it is very important to distinguish between the incident and reflected pressures, the rate of pressure rise, the character of the rising portions of the pressure pulse and the geometry of exposure as it is interrelated with the above blast parameters. This is so because nuclear weapon effects data as presented in manuals showing the scaling laws for blast usually report the incident pressure (10) and say that 30 psi, when referring to the incident pressure, is a "safe" pressure for man. Such statements can have at least two inaccuracies. First, 30 psi incident in an appropriate geometry of exposure may result in sudden application of a reflected overpressure of 90 - 120 psi to a biologic target. Such reflected pressures of long duration applied as a single step would no doubt be fatal to man. Secondly, a 30 psi incident overpressure in another geometry of exposure might rise in two or more steep steps due to reflection, or might rise slowly to less than 30 psi in a time measured in several tens of milliseconds and produce no significant

Table 5—THE RELATION BETWEEN THE MAGNITUDE OF THE REFLECTED SHOCK AND MORTALITY FOR SMALL ANIMALS EXPOSED SIDE-ON AT VARIOUS DISTANCES FROM THE END-PLATE

Species	Number of animals	Distance of cage from end-plate (in.)	Overpressure in reflected shock (psi)*	Mortality (percent)
Mouse (5 per shot)	20	0	52 (52-52)	100
	24	1/2	55 (53-56)	63
	24	1	55 (54-56)	29
	15	2	54 (54-54)	0
	15	3	54 (54-56)	7
Rat (5 per shot)	15	0	52 (48-55)	100
	10	1/2	53 (52-55)	100
	15	1	52 (50-53)	80
	15	2	52 (49-54)	13
	15	3	50 (48-52)	0
	15	6	48 (48-49)	0
	5	12	55 (55)	0
Guinea Pig (3 per shot)	20	0	48 (46-52)	100
	15	1	51 (49-53)	100
	18	2	51 (50-54)	72
	30	3	52 (50-54)	37
	21	6	52 (50-53)	24
	15	12	53 (50-54)	25
Rabbit (2 per shot)	12	0	42 (38-53)	100
	4	1	53 (52-53)	100
	8	2	54 (53-55)	88
	8	3	55 (53-56)	63
	6	6	52 (51-53)	17
	2	12	55 (55)	0

*Mean and range

24
avg 52.1
incident 17.2

damage whatsoever. The point is that tolerance to pressure variations is a complex matter and considerable care must be observed in specifying safety criteria and in the design of protective structures.

Mortality from Single, Sharp-rising Overpressures

To turn now to more specifically consider the data comprising the present study, a few comments regarding tolerance to single, fast-rising pressure pulses will be set forth.

First, in spite of large weight range there was little difference in the LD_{50} figures for the four species studied ranging from about 30 psi for the mouse to near 39 psi for the rat, with the rabbit and guinea pig in between.

Secondly, the range of the reflected pressure associated with 10 and 90 per cent mortality was quite small in the order of ± 7 to 12 psi on either side of the LD_{50} reflected pressure. What this can mean in terms of the incident pressure is indirectly illustrated by the data in Table 6 showing the relation between the incident (P_s) and reflected (P_f) overpressures as they occurred in the present study. The table shows that there is approximately a ratio of 3 between the P_s and the P_f which means that a variation of about ±7 to 12 psi in the P_f would require only a variation of near ±2 to 4 psi in the P_s. Apparently the biological system is responding in what might be called an "all-or-none" manner to fast-rising overpressures. At least the range between near zero and 100 per cent mortality is small and those interested in protection should take careful note of this fact.

Thirdly, by way of speculation, it is doubtful that the LD_{50} reflected overpressures for fast-rising pulses of long duration applicable to the dog and to man are likely to be much above 40 - 45 psi if indeed they are that high. Though the present study supports such a guess, let it be clear that as yet there are no empirical data on which to base a firm opinion.

Animals Exposed at Varying Distances from the End-plate of the Shock Tube

It is now useful to note the relationships between the incident and reflected pressures that were associated with 50 per cent mortality of the guinea pigs exposed against and at various distances from the end-plate of the shock tube. Table 7 details the data.

Table 6—REFLECTED AND INCIDENT OVERPRESSURES ASSOCIATED WITH 50 PER CENT MORTALITY FOR ANIMALS EXPOSED AGAINST THE END-PLATE OF THE SHOCK TUBE

Animal Species	Overpressure in psi		Ratio
	reflected (P_f)	incident (P_s)	P_f/P_s
Mouse	29.8	10.0	2.90
Rabbit	33.4	11.3	2.95
Guinea pig	36.7	12.1	3.03
Rat	38.7	12.6	3.07

avg 34.65

Table 7—REFLECTED AND INCIDENT OVERPRESSURES ASSOCIATED WITH 50 PER CENT MORTALITY OF GUINEA PIGS EXPOSED AGAINST AND AT VARIOUS DISTANCES FROM THE END-PLATE OF THE SHOCK TUBE

Distance from end-plate (in.)	Incident overpressure (P_s) (psi)	Reflected overpressure (P_f) (LD_{50}) (psi)	Difference in psi (P_r)	Time between steps msec
0	12.1	36.7	24.6	~0
1	13.4	40.8	27.4	0.10*
2	15.6	48.3	32.7	0.20
3	16.9	52.8	35.9	0.30
6	18.7	58.6	39.9	0.63
12	18.2	57.1	38.9	1.36

*Estimated

The next to the last column of the table shows the difference between the incident and reflected pressures associated with equal biological response (50 per cent mortality). The last column shows the time between arrival of the incident and reflected pressures at the animal stations. When the incident and reflected pressures were applied almost simultaneously, a single, fast-rising increase in pressure of 36.7 psi was required for the LD_{50}. In contrast, progressively higher total reflected pressures were associated with the LD_{50} at increasing distances from the end of the tube up to the 6 in. position. At the same time, the magnitudes of the incident pressures for all groups were not near the LD_{50} value for a single pulse. Likewise, neither were the magnitudes of the second pressure steps applicable to the 1, 2, and 3 in. positions all near the single step LD_{50} figure (see the difference column in Table 7). One is forced to conclude that neither the incident nor reflected pulse alone was responsible for the mortality, rather that both were contributing.

In the case of the 6 and 12 in. stations, however, a comparison of Tables 6 and 7 show that the magnitude of the second stepwise rises in pressure — being about 39 - 40 psi — were above the single-step figure of near 37 psi associated with 50 per cent mortality. Were the second step alone producing death, a slightly higher mortality should have been obtained. That such was not noted, indicates that the presence of the initial shocks and associated pressures were giving the animals some protection from the second shocks and accompanying pressure rises through some adaptive mechanism not completely understood at the present time.

That such protection is very real is confirmed by Fig. 11 and Table 8 which was prepared from the guinea pig data given in Table 5 referable to mortality noted at different exposure positions with near constant reflected pressures. The actual incident and reflected pressures are shown, and in the last column are noted the mortalities that might be expected from the second step rise in pressure were they acting as single steps and alone responsible for the mortality. Comparing the figures noted in the last column with those in the second giving the observed mortality, shows that for positions 0, 1 and 2 in. the observed mortality was higher than that expected on a single-rise basis. Therefore, the first and second steps were both contributing to the deaths noted. In contrast, for the 6 and 12 in. positions,

Table 8—MORTALITY VARIATIONS AS A FUNCTION OF EXPOSURE POSITION FOR GUINEA PIGS EXPOSED TO A NEAR CONSTANT REFLECTED PRESSURE BUT SHOWING THE INCIDENT AND REFLECTED PRESSURE DATA FOR EACH GROUP (Data from Table 5)

Distance from end-plate (in.)	Mortality in per cent	Incident overpressure (P_s) (psi)	Reflected overpressure (P_f) (psi)	Magnitude second step (P_f-P_s) psi	Time between steps msec	Mortality expected from 2nd step alone
0	100	15.5	48	32.5	~0	
1	100	16.4	51	34.6		40
2	72	16.4	51	34.6	0.20	40
3	37	16.7	52	35.3	0.30	46
6	24	16.7	52	35.3	0.63	44
12	25	17.0	53	36.0	1.36	48

the expected mortalities were well above those actually found, indicating that the initial pressure had existed long enough to allow the animal to "adapt" in a way that lent protection against the second rise in pressure.

While the problem is under study, it is not possible to offer any clear cut explanation to explain the facts noted above. In all probability, however, the pressure differentials which exist at various times between the air-containing lung and the external pressure are of critical importance. At least three factors could influence magnitude of the environment-lung pressure difference with time, e.g., (1) air could flow into the lung, (2) the volume of air-containing lung could change because the external pressure pushed the chest walls inward and the abdominal wall and diaphragm in and upward, respectively, and (3) fluid (blood and lymph) might migrate into the thorax and serve to reduce the air volume and hence reduce the pressure differential. Certainly, the speed with which these three "adaptations" could occur will vary, and in the absence of applicable experimental data, one can only remark that while the second possibility noted above looks the more attractive for the time intervals set forth in Tables 7 and 8, none the less all three factors no doubt contribute some to the adaptations which take place with overpressures of long duration.

SUMMARY

A closed-end shock tube was used to study the effects of single and stepwise, fast-rising overpressures of long duration on four species of experimental animals.

For animals exposed side-on against the end-plate to single, sharp-rising pressure pulses, the reflected pressures necessary to kill 50 per cent (LD_{50}) were as follows: for the mouse - 29.8 ± 1.1; rabbit - 33.4 ± 1.2; guinea pig - 36.7 ± 0.7; and the rat - 38.7 ± 0.6 psi.

Animals located at short distances away from the end-plate were loaded in a two-step manner. The steps corresponded to the incident and reflected shock fronts. With stepwise increases in pressure, animals tolerated much higher reflected overpressures than when the pressure load consisted of a single, sharp-rising pulse.

The importance of the time interval between step loads was pointed out and briefly discussed.

REFERENCES

1. B. Cassen, L. Curtis and K. Kistler, Initial Studies of the Effect of Laboratory Produced Air Blast on Animals, J. Aviat. Medicine, 21: 38-47 (1950).
2. H. Celander, C. Clemedson, U. Ericsson, and H. Hultman, The Use of Compressed-air-operated Shock Tube for Physiological Blast Research, Acta Physiol. Scand., 32: 6-13 (1955).
3. H. Schardin and O. Wünsche, Versuche an Kleintieren zur Bestimmung der Druckstosstödlichkeitsgrenze, Bericht V 17, Deutsche Versuchsanstalt für Luftfahrt E. V., January 1958.
4. D. R. Richmond and R. V. Taborelli, Some Results of a Shock Tube for Biomedical Investigation, pp. 56-69, 'Proceedings of Second Shock Tube Symposium , Report SWR-TM-58-3, Air Force Special Weapons Center, March 5-6, 1958.
5. C. S. White, T. L. Chiffelle, D. R. Richmond, W. H. Lockyear, I. G. Bowen, V. C. Goldizen, H. W. Merideth, D. E. Kilgore, B. B. Longwell, J. T. Parker, F. Sherping, and M. E. Cribb, The Biological Effects of Pressure Phenomena Occurring Inside Protective Shelters Following Nuclear Detonation, Operation Teapot Report, WT-1179, October 1956.
6. D. R. Richmond, R. V. Taborelli, I. G. Bowen, T. L. Chiffelle, F. G. Hirsch, B. B. Longwell, J. G. Riley, C. S. White, F. Sherping, V. C. Goldizen, J. D. Ward, M. B. Wetherbe, V. R. Clare, M. L. Kuhn and R. T. Sanchez, Blast Biology — A Study of the Primary and Tertiary Effects of Blast in Open Underground Protective Shelters, Operation Plumbbob Report, ITR-1467, September 1957.
7. D. R. Richmond, M. B Wetherbe, R. V. Taborelli, T. L. Chiffelle, and C. S. White, The Biologic Response to Overpressure. I. Effects on Dogs of Five to Ten-second Duration Overpressures Having Various Times of Pressure Rise, J. Aviat. Medicine, 28: 447-460 (1957).
8. D. R. Richmond, The Biologic Response to Sharp-rising Pressures of Long Duration, presented before the meeting of the AEC AD HOC Task Unit on Blast Biology, August 5, 1958, Albuquerque, N. M.
9. D. J. Finney, "Probit Analysis. A Statistical Treatment of the Sigmoid Response Curve," 2nd ed., Cambridge University Press, New York, 1952.

10. Armed Forces Special Weapons Project, Department of Defense, "The Effects of Nuclear Weapons," edited by Samuel Glasstone, U.S. Government Printing Office, Washington 25, D.C., June 1957.

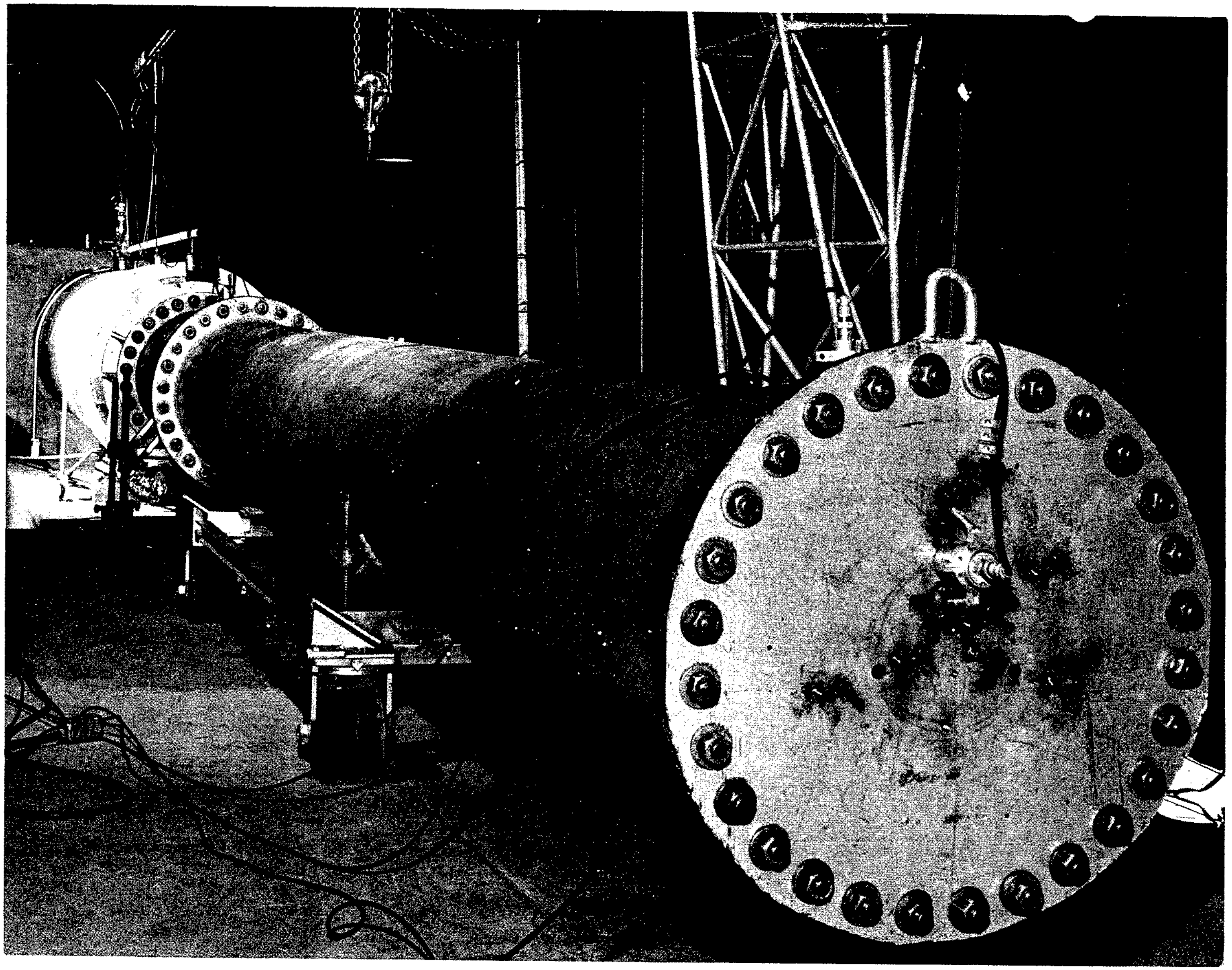


Figure 1. Shock Tube Viewed from the Closed End of the Expansion Chamber.

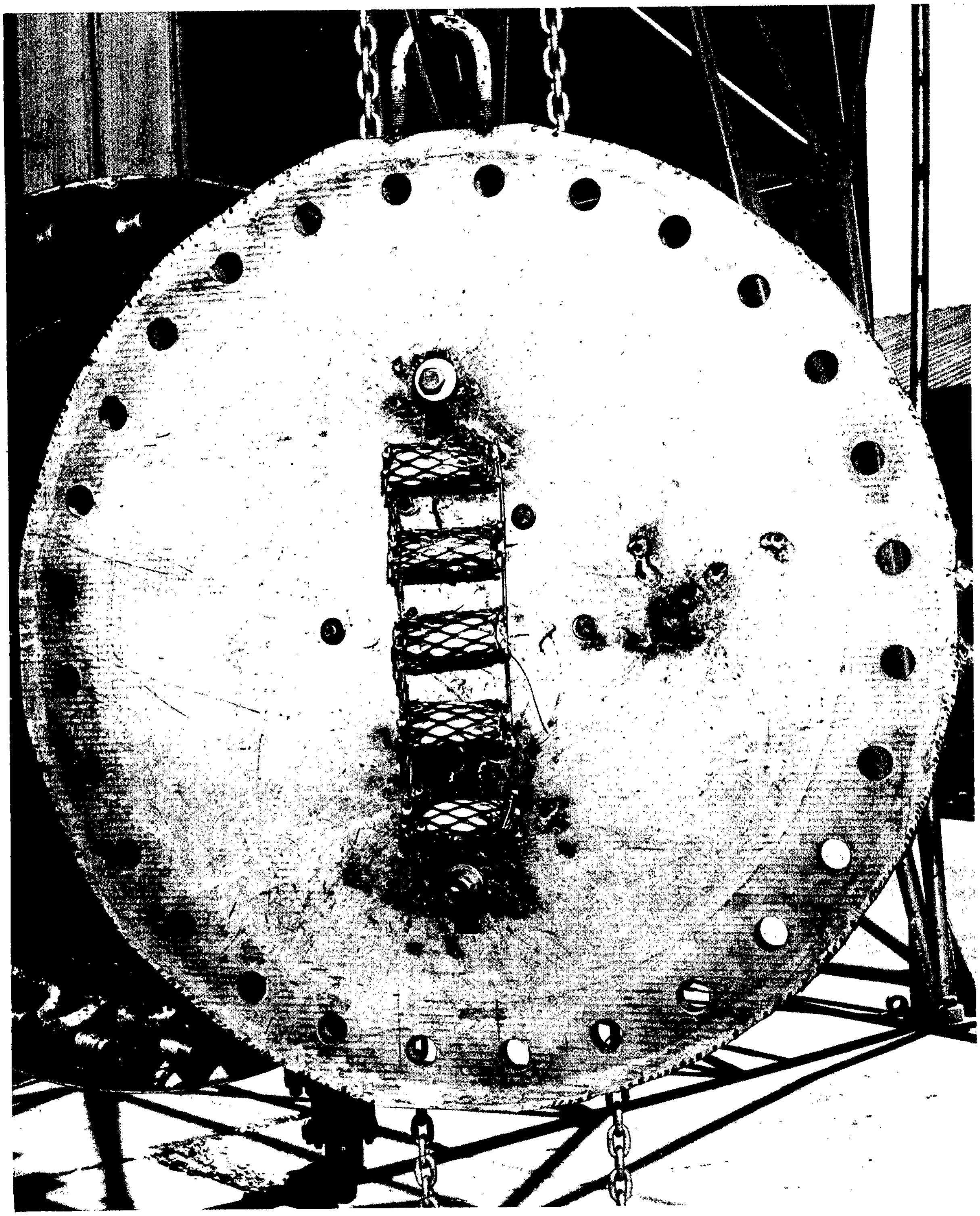


Figure 2. Mouse Cage Mounted Against the End-plate of the Shock Tube.

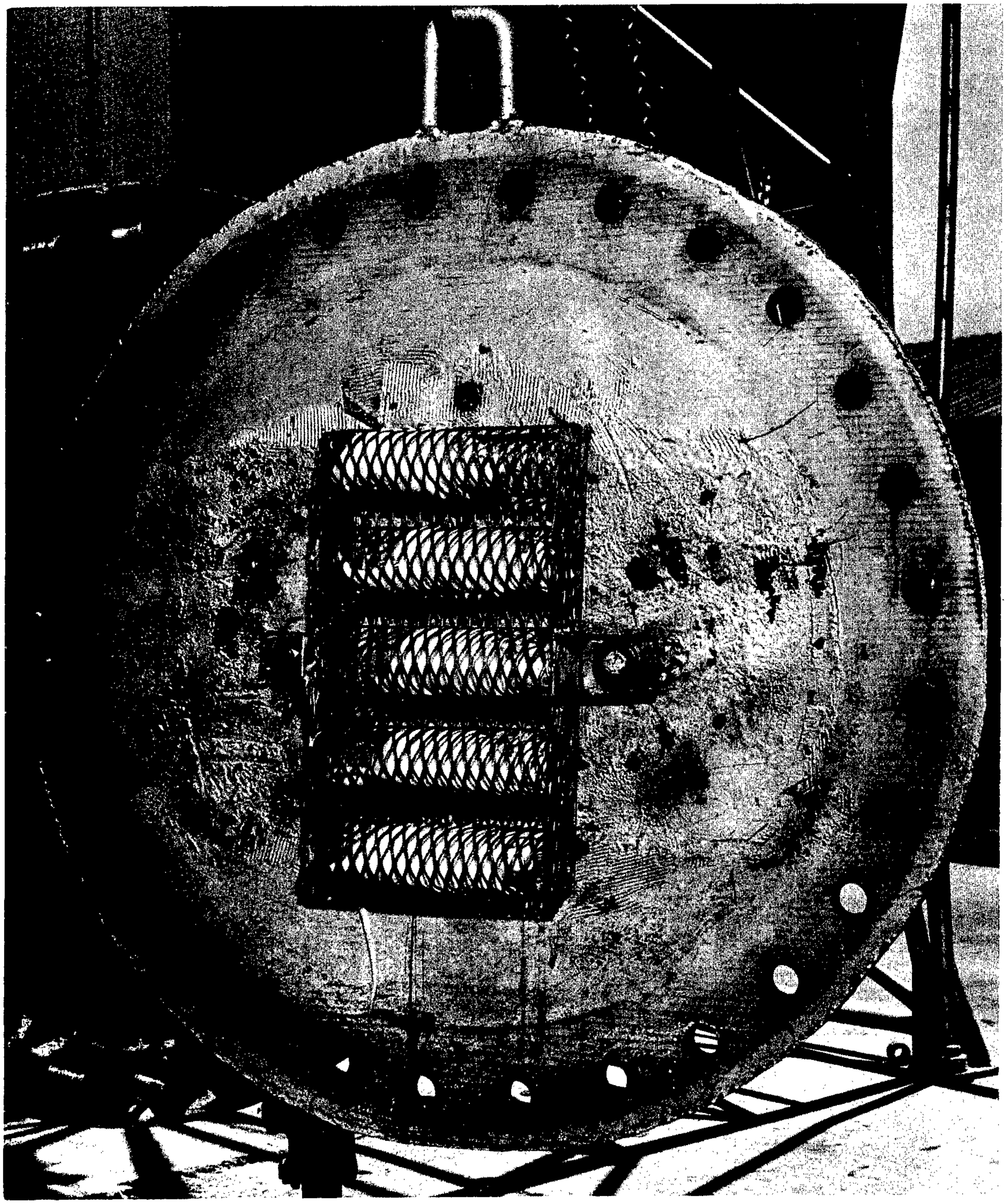


Figure 3. Rat Cage Mounted Against the End-plate of the Shock Tube.

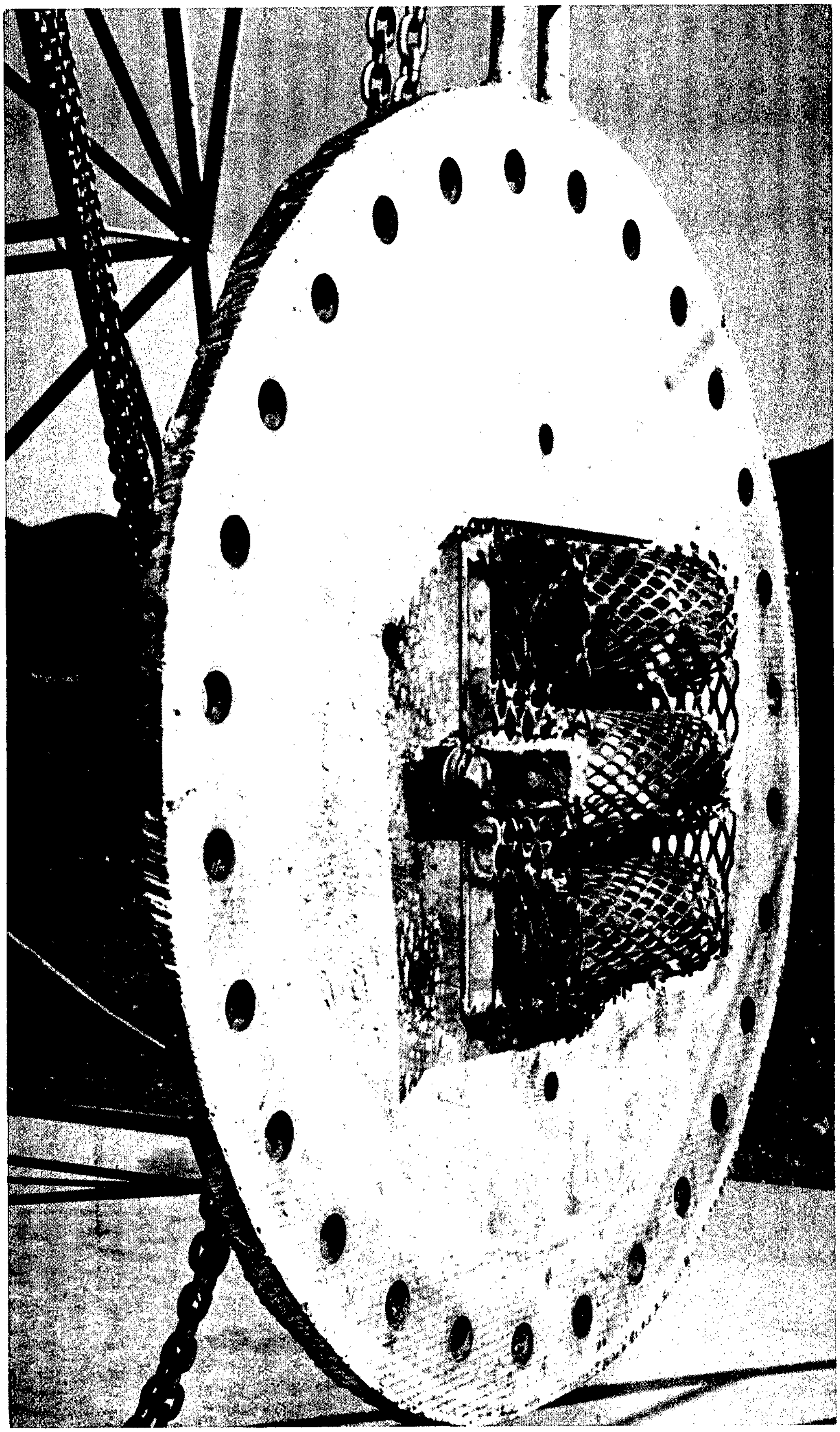


Figure 4. Guinea Pig Cage Mounted Against the End-plate of the Shock Tube.

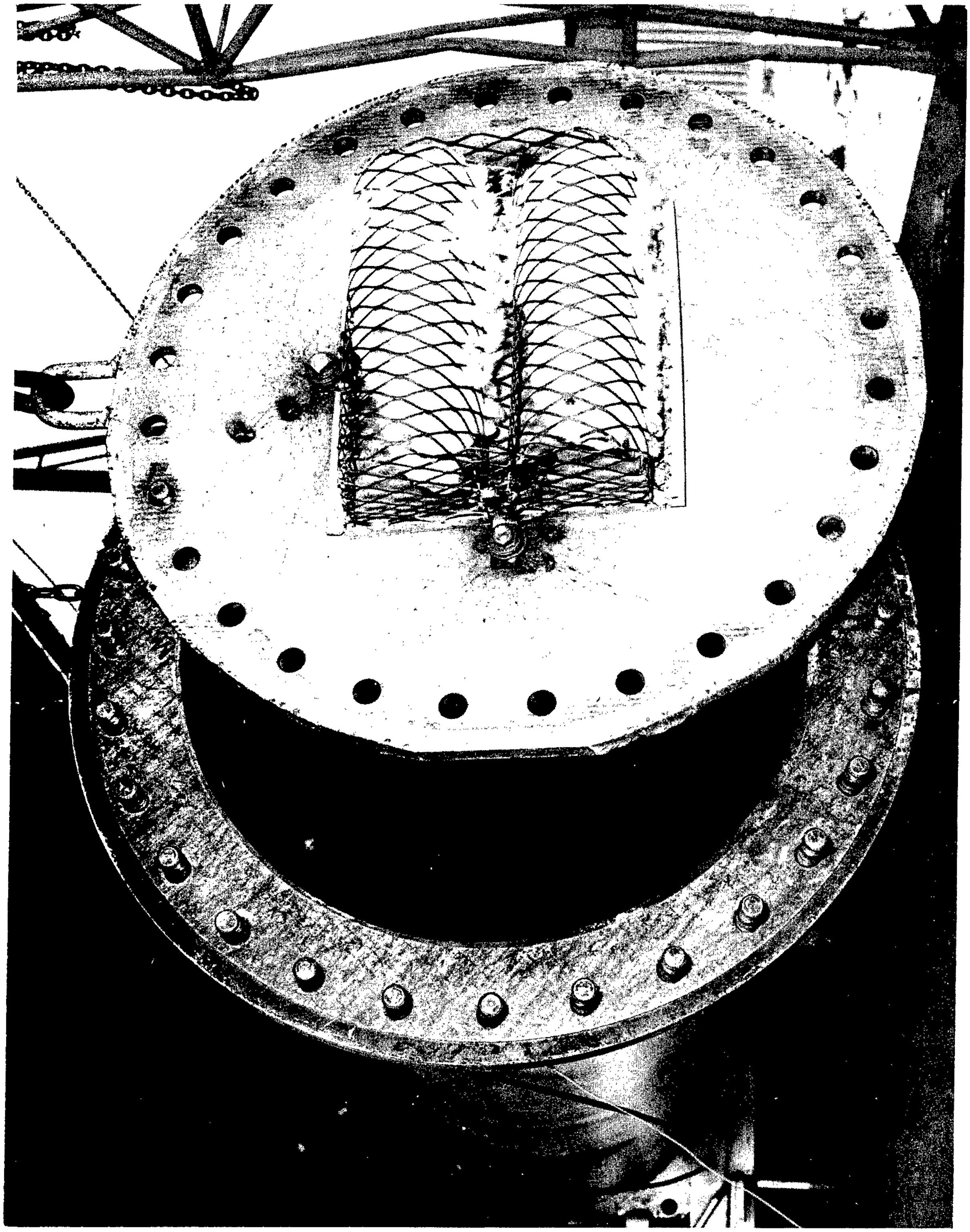


Figure 5. Rabbit Cage Mounted Against the End-plate of the Shock Tube.

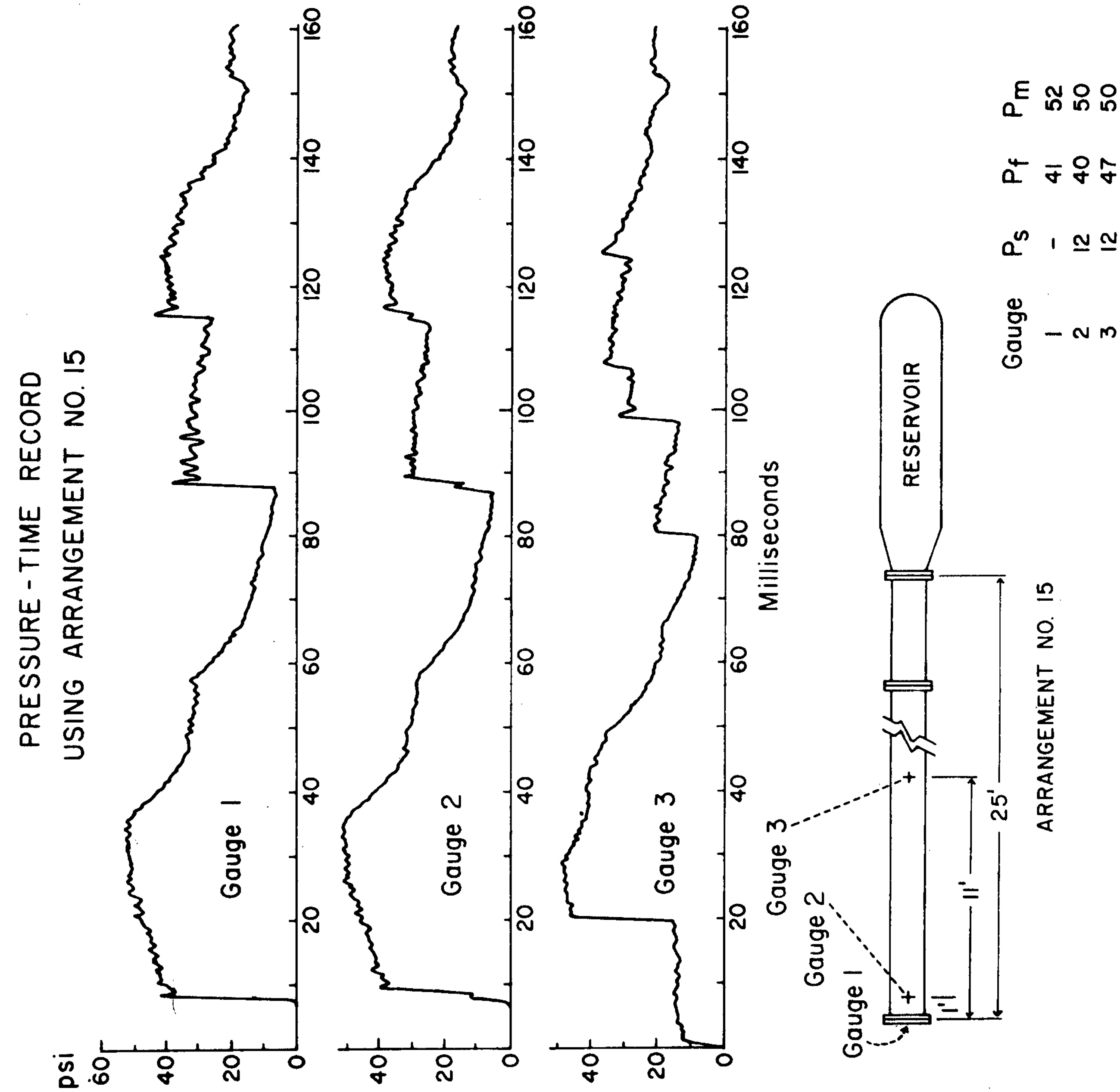


Figure 6. Records of Pressure-time Along Closed Tube: Multiple Reflections.

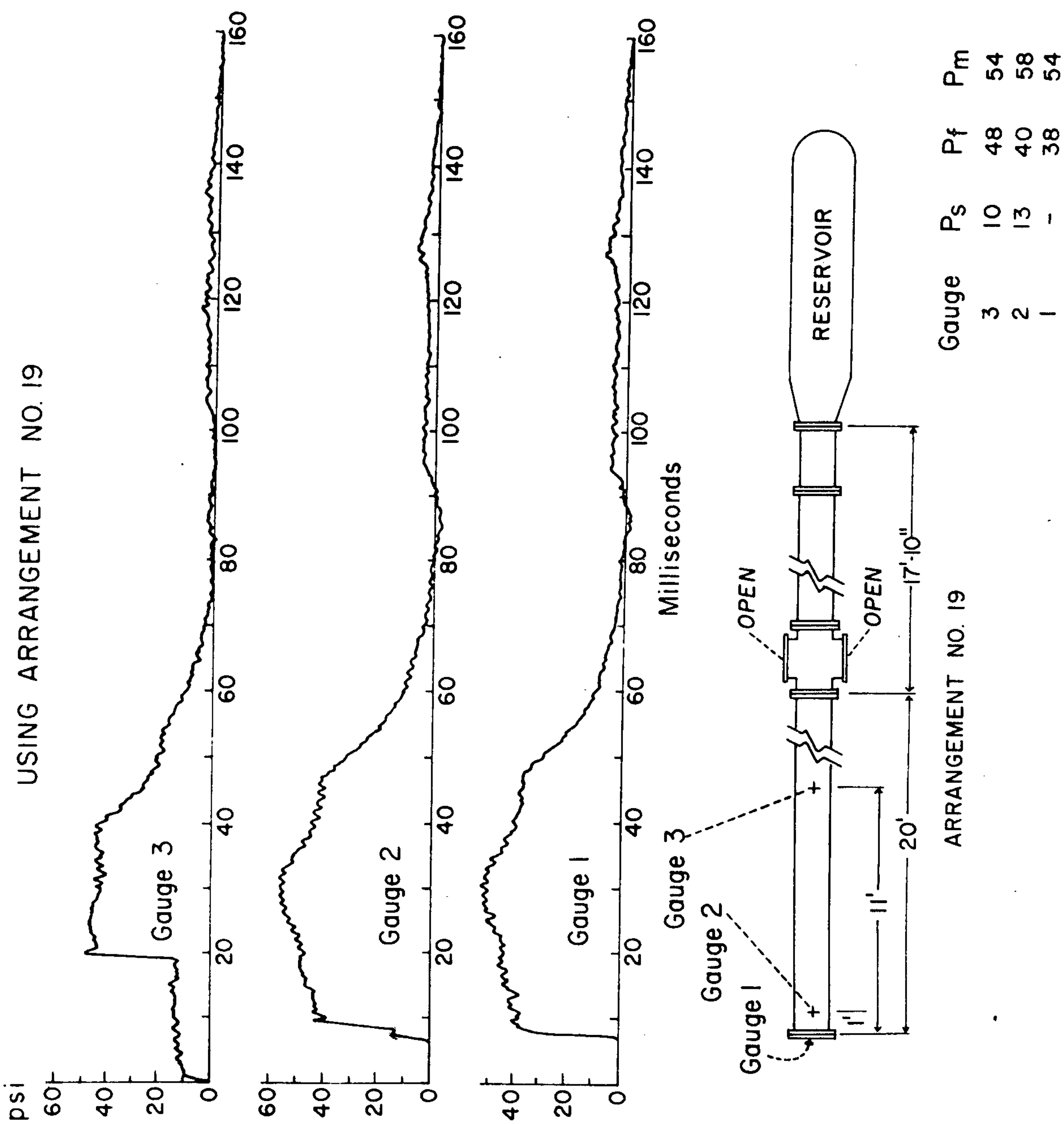


Figure 7. Records of Pressure-time Along Tube with Lateral Parts Open: Single Reflection.

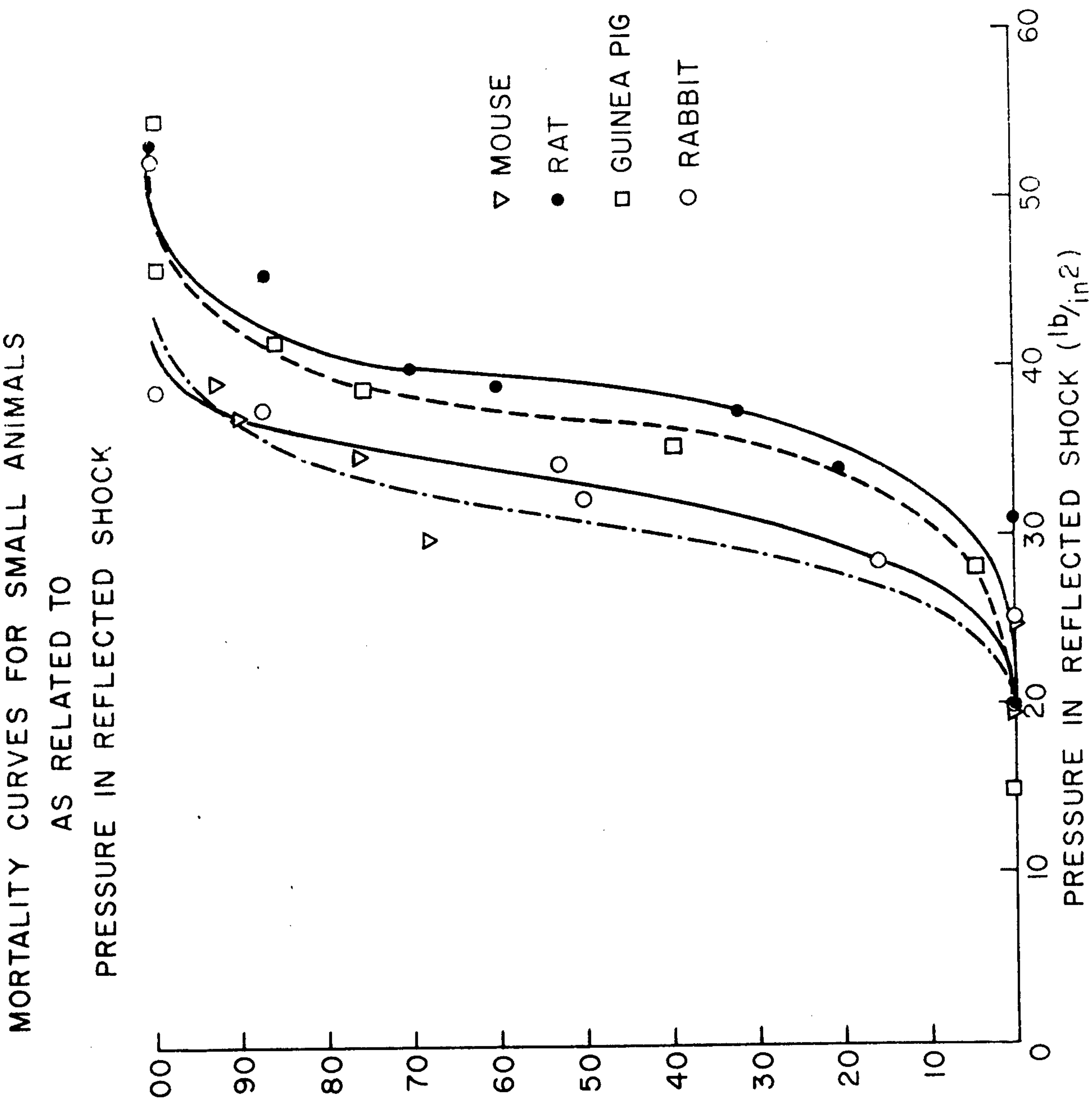
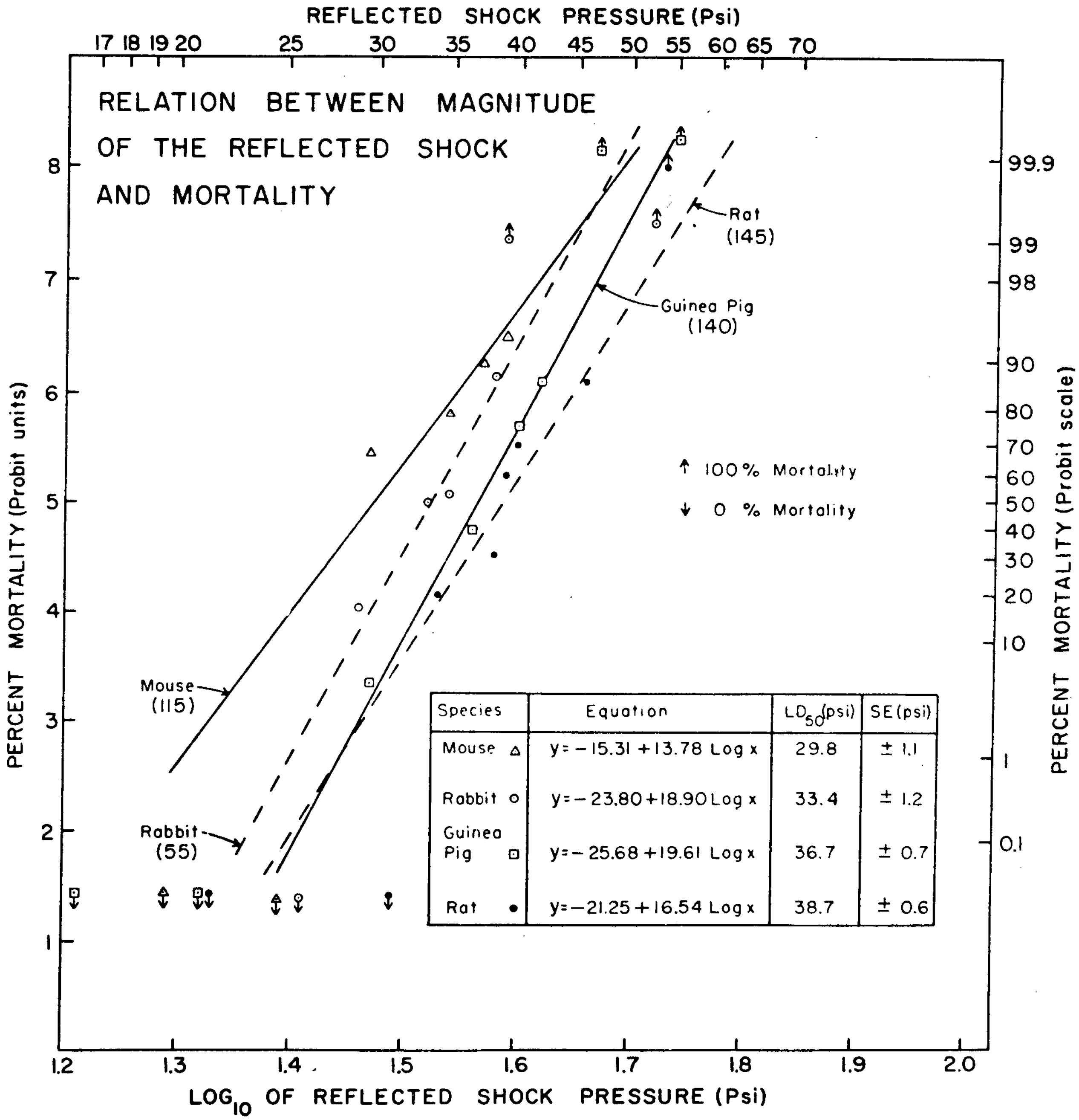


Figure 8. Mortality for Small Animal Species Exposed Against the End-plate of the Shock Tube as Related to the Pressure in the Reflected Shock.



Species	Equation	LD_{50} (psi)	SE (psi)
Mouse △	$y = -15.31 + 13.78 \text{ Log } x$	29.8	± 1.1
Rabbit ○	$y = -23.80 + 18.90 \text{ Log } x$	33.4	± 1.2
Guinea Pig □	$y = -25.68 + 19.61 \text{ Log } x$	36.7	± 0.7
Rat ●	$y = -21.25 + 16.54 \text{ Log } x$	38.7	± 0.6

Figure 9. Probit Regression Lines Relating Mortality for Animals Exposed Against the End-plate to the Reflected Shock Pressure.

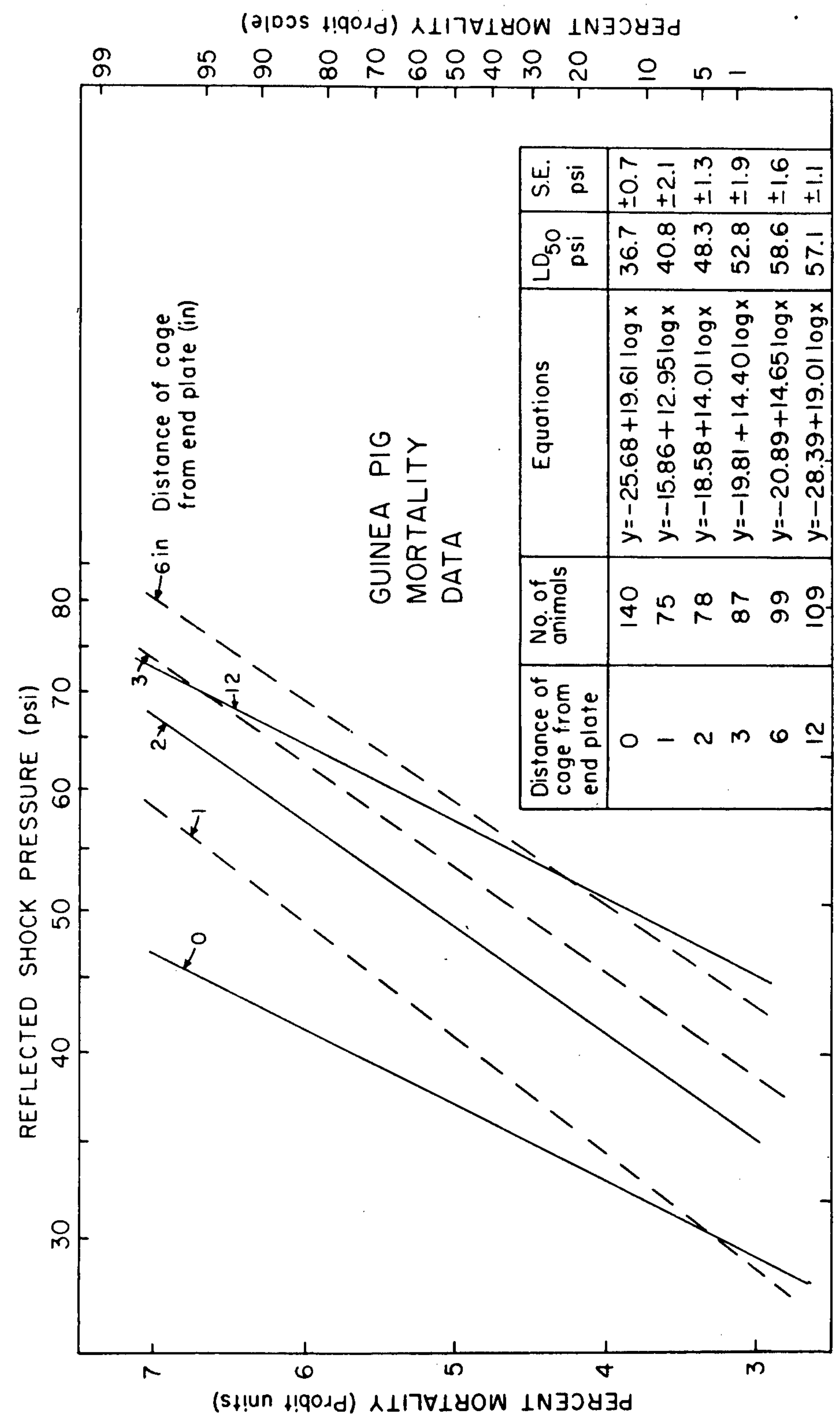


Figure 10. Probit Regression Lines Relating Guinea Pig Mortality at Various Distances from the End-plate to the Magnitude of the Reflected Shock.

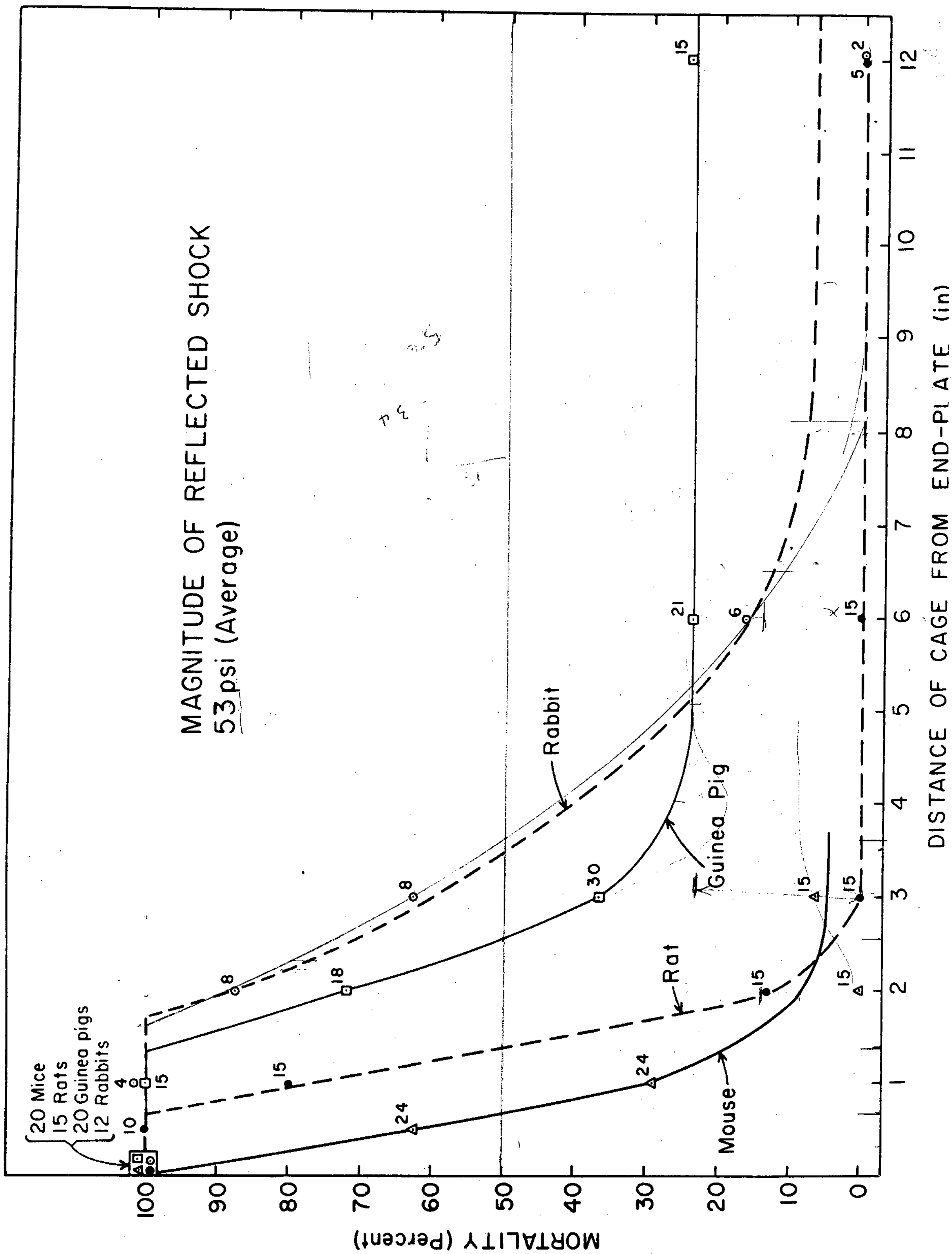


Figure 11. Mortality for Small Animals Located at Various Distances from the End-plate for Reflected Shocks Averaging 53 psi.