THE RELATION BETWEEN EARDRUM FAILURE AND BLAST-INDUCED PRESSURE VARIATIONS

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(Received 15 April, 1970)

Abstract. During a series of field and laboratory experiments designed to study overall blast effects, incidental observations were made of the ears of more than 490 animals to determine eardrum failures associated with exposure to 'atypical' and 'typical' blast wave forms. Animals positioned inside structures were exposed to a variety of 'atypical' blast waves, whereas those located inside shock tubes or in the open, when high explosives were detonated, were exposed to fairly 'typical' wave forms. When the incidence of eardrum rupture is related to the various elements of the measured pressure-time curves, the association is not the same for the two types of wave shapes. Besides suggesting that tolerance is higher for 'slow'- than for 'fast'-rising wave forms, the findings demonstrate a wide variability in the magnitude of the overpressures required to rupture the eardrum. Within the limits of the data available, the quantitative differences are noted and discussed with emphasis on the apparent wide variability in tolerance and a proposed explanation for this finding. Although the results are limited strictly to the mammalian species studied, it is likely that the eardrum of man also is sensitive to the shape and character, as well as the magnitude and duration of the blast wave. The data are useful to military and civilian physicians, industrial otologists and all other health and safety personnel including those who have research interests in establishing quantitative dose-response criteria for individuals exposed to blast-induced variations in pressure.

1. Introduction

Though perforation of the tympanic membrane may open the middle ear, mastoid air cells, and the Eustachian tube to the invasion of pathogens and other foreign materials via the external auditory meatus, traumatic failure of the eardrum is of medical interest for several other reasons. Not least of these is the fact that rupture of the membrane may help protect the ossicles and inner ear from overload when a single exposure to pressure variations associated with explosive events occurs. Also, the drum plays a role in the transfer of energy through the oval window to the organ of Corti via the ossicles and the endolymph when repetitive exposure to blast and high noise levels occurs. Thus the dynamic properties of the drum are of importance whether acute or chronic situations are involved, and it follows that any quantitative data relating the characteristics of the loading pulse to the magnitude of the membrane's response are of interest to the clinical and industrial otologist.

Some relevant observations, noted during field and laboratory experiments designed for other purposes, have been made periodically beginning as early as 1953 (Roberts *et al.*, 1953; Ruhl *et al.*, 1953; Mazzaros and Keefer, 1957; Vortman, 1957; Vortman *et al.*, 1957; White *et al.*, 1957, 1965; Richmond *et al.*, 1959, 1966a, b; Betz *et al.*, 1965; Gaylord *et al.*, 1965; Pratt *et al.*, 1965). These included notations of eardrum failure in animals exposed to 'typical' and 'atypical' blast-produced pressure pulses. The

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Space Life Sciences **2** (1970) 158–205.

findings have been reassessed to explore the possibility of there being a difference in response attributable to gross variation in the form of the pressure pulse loading the eardrum. The purpose of this paper is to review and summarize the data at hand, some of which imply that the tympanic membrane, like the animal as a whole, is indeed sensitive to the character as well as the magnitude of the blast wave.

2. Methods

A. GENERAL

The effects of blast-induced pressure variations were studied in several species of animals exposed in different instrumented locations during field and laboratory studies. All animals were preconditioned to harness or cages used to control and maintain position before and after exposure. Among the data reported were the pressure-time records and the incidence of eardrum rupture. These were obtained during field operations involving nuclear explosions at the Nevada Test Site in 1953, 1955, and 1957 and following a 500-ton TNT explosion in 1964 at the Suffield Experimental Station, Alberta, Canada. The laboratory results on the ear were obtained with a shock tube in Albuquerque, New Mexico, during the experiments to determine threshold injury to the lung.

In each instance, the pulse of overpressure was 'long' for all species involved, ranging from around 140 to over 1000 msec in some cases. Though details of the experimental conditions, the placement of pressure gauges in relation to the animals, the exposure geometry, the magnitude, character and duration of the measured overpressures, and the overall biomedical effects have been published elsewhere, pertinent information elucidating the different experimental arrangements will be noted below (Roberts *et al.*, 1953; White *et al.*, 1957, 1965, 1967; Richmond *et al.*, 1959, 1966a, b, c; Pratt *et al.*, 1965; Betz *et al.*, 1965; Gaylord *et al.*, 1965).

B. EXPOSURES TO 'ATYPICAL' AND 'NEAR-TYPICAL' WAVE FORMS

Exposure to a variety of 'atypical' wave forms occurred mostly inside a variety of structures, including foxholes of two designs situated at various ranges from full-scale nuclear or TNT detonations. In contrast, exposures to 'typical' or 'near-typical' pressure pulses involved two situations; namely, stations in the open with the animals positioned against a stout wire mesh or against a metal plate closing the end of a shock tube. In both instances, the orientation was side-on to the advancing blast waves.

1. *'Atypical' or Disturbed Wave Forms*

'Atypical' or disturbed wave forms occurred inside long tubular, square, and rectangular, below- or above-ground structures tested 'mostly open', but rarely 'mostly closed'.* Pressure gauges were flush mounted on the walls (or floors) and animals weie restrained at stations located nearby.

* 'Mostly open' implies tests in structures without roof or doors or with failure of windows and doors; 'mostly closed' is used to denote instances in which the blast wave entered through open ventilation ducts or leaked past cracks around unsealed, but blast-resistant, doors.

(a) *Cylindrical shelters.* In 1953 a total of 44 dogs, restrained at various stations inside two buried cylindrical structures (7 ft in diameter and 50 ft in length), with walk-down ramps of two configurations, were exposed to overpressures from two nuclear detonations (Roberts *et al.*, 1953; Ruhl *et al.*, 1953; White *et al.*, 1965). Plan views of the two structures are included in Figures 1 and 2 along with the location of the animals and the wall-mounted pressure gauges. Also the maximum pressure and the related duration are noted near each pickup from which a record was obtained.

Sample wave forms from 'slow' and 'fast' traces, as available for the three trans-

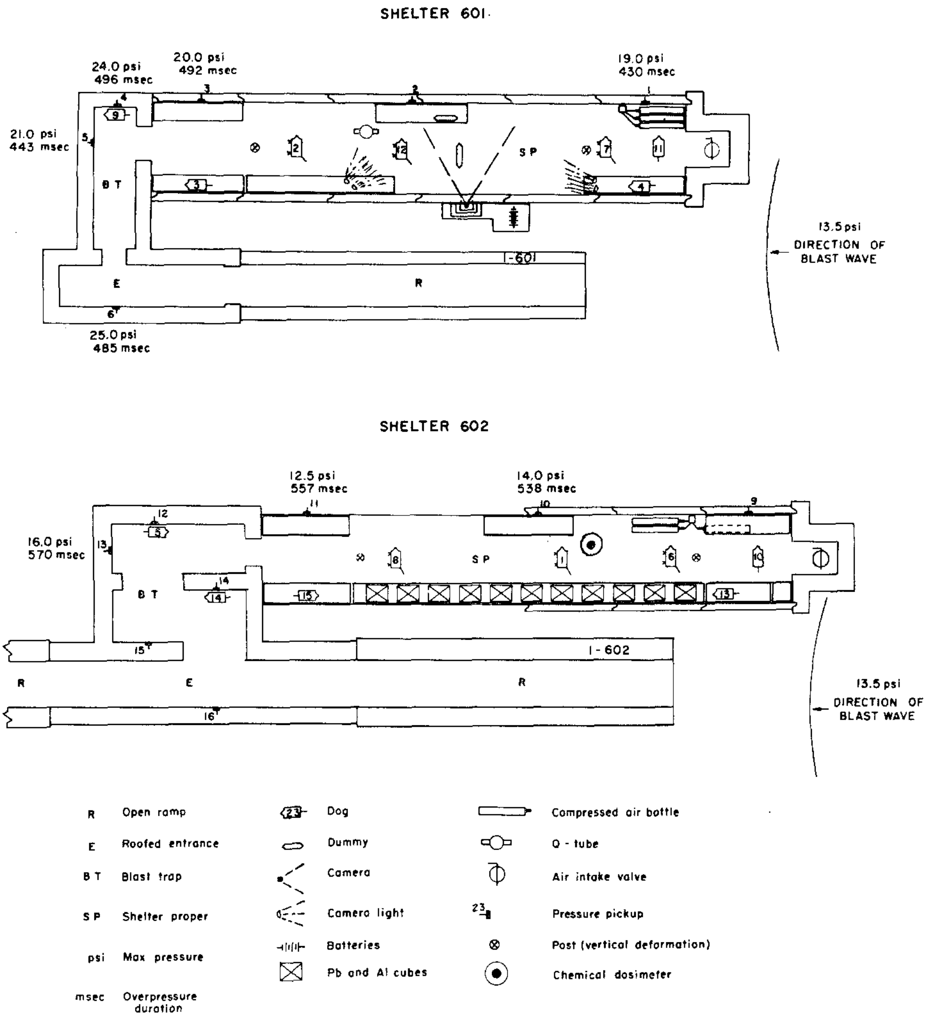


Fig. 1. Plan view of Shelters 601 and 602 and contents as used on Experiment I. Maximum recorded overpressures and their durations are also shown.
(Data from Roberts *et al.*, 1953 and White *et al.*, 1965.)

ducers numbered 1, 2, and 3 for Shelter 601 and 9, 10, and 11 for Shelter 602 are shown in Figures 3–6 (Ruhl *et al.*, 1953; White *et al.*, 1965).

In addition on another test of the 1953 series, there were four other dogs exposed inside, but near the open end of a blocked-off segment of a similar cylindrical shelter. The open end was entered by a slit trench with walk-down ramps at right angles to the axis of the shelter. Maximal pressures were recorded with floor-mounted mechanical gauges, but pressure traces were not obtained (Roberts *et al.*, 1953).

(b) *Square shelters.* In 1955 a total of 40 dogs were exposed inside 25 × 12 ft buried

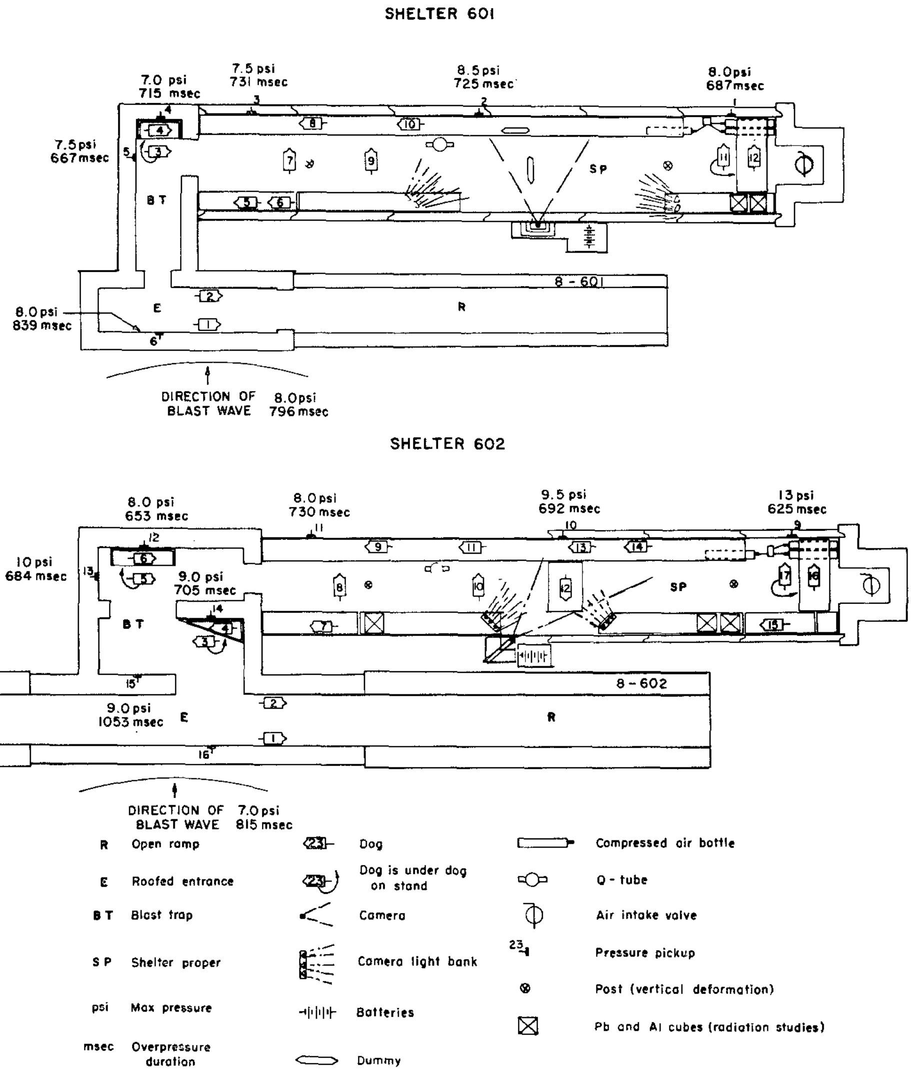


Fig. 2. Plan view of Shelters 601 and 602 and contents as used on Experiment II. Maximum recorded overpressures and their durations are also shown. (Data from Roberts *et al.*, 1953 and White *et al.*, 1965.)

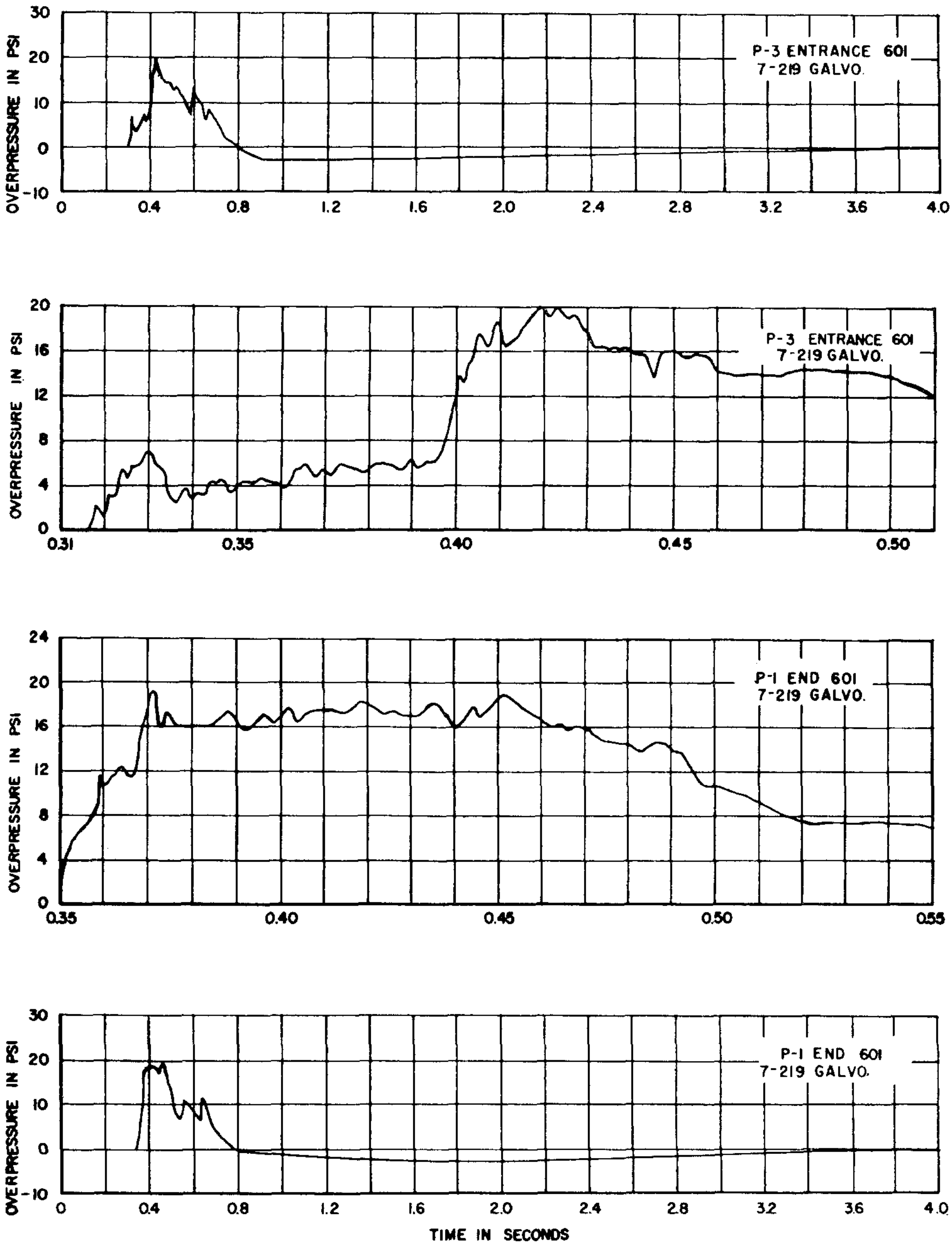


Fig. 3. Pressure-time records inside main room of Shelter 601 on Experiment I. (Data from Ruhl *et al.*, 1953 and White *et al.*, 1965.)

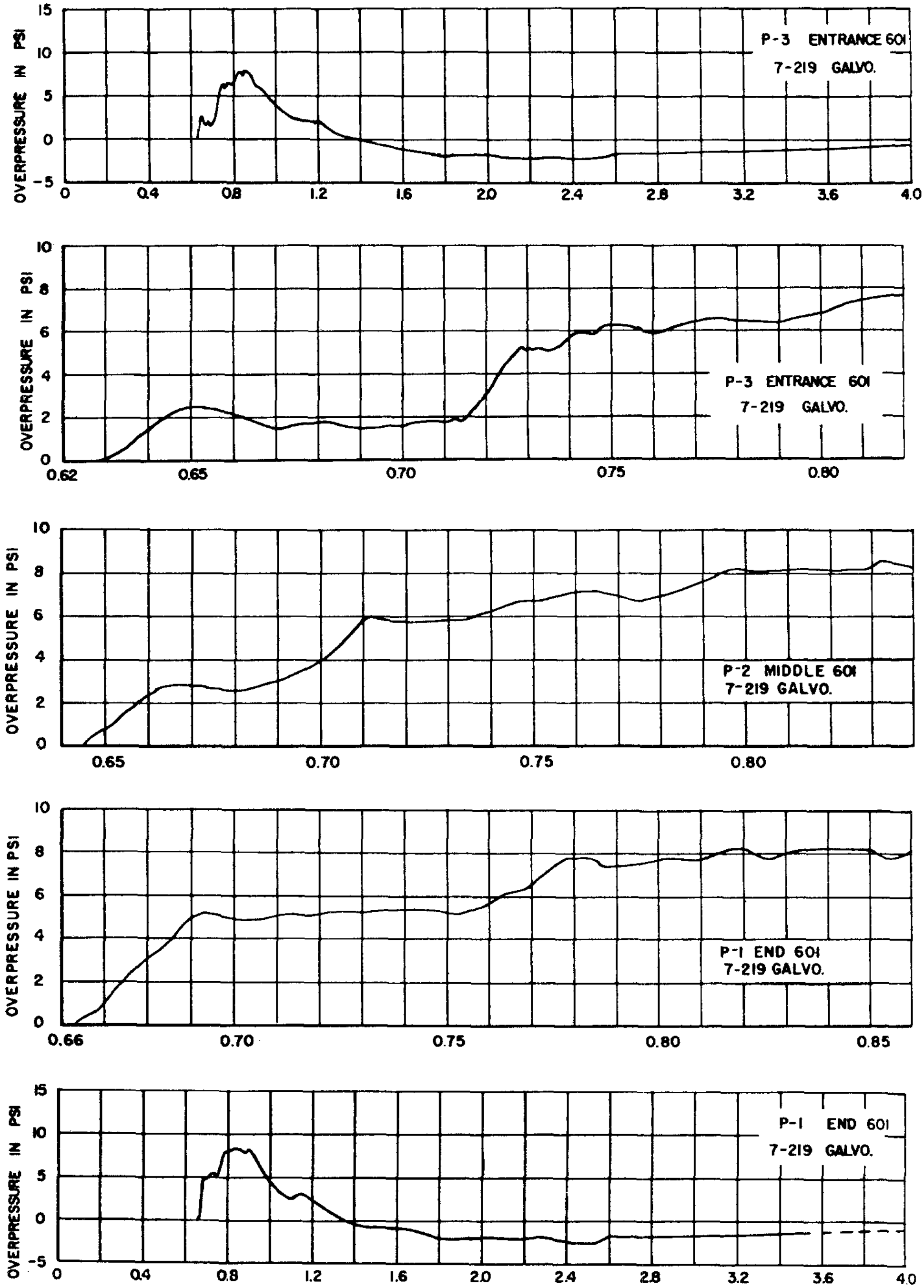


Fig. 4. Pressure-time records inside main room of Shelter 601 on Experiment II. (Data from Ruhl *et al.*, 1953 and White *et al.*, 1965.)

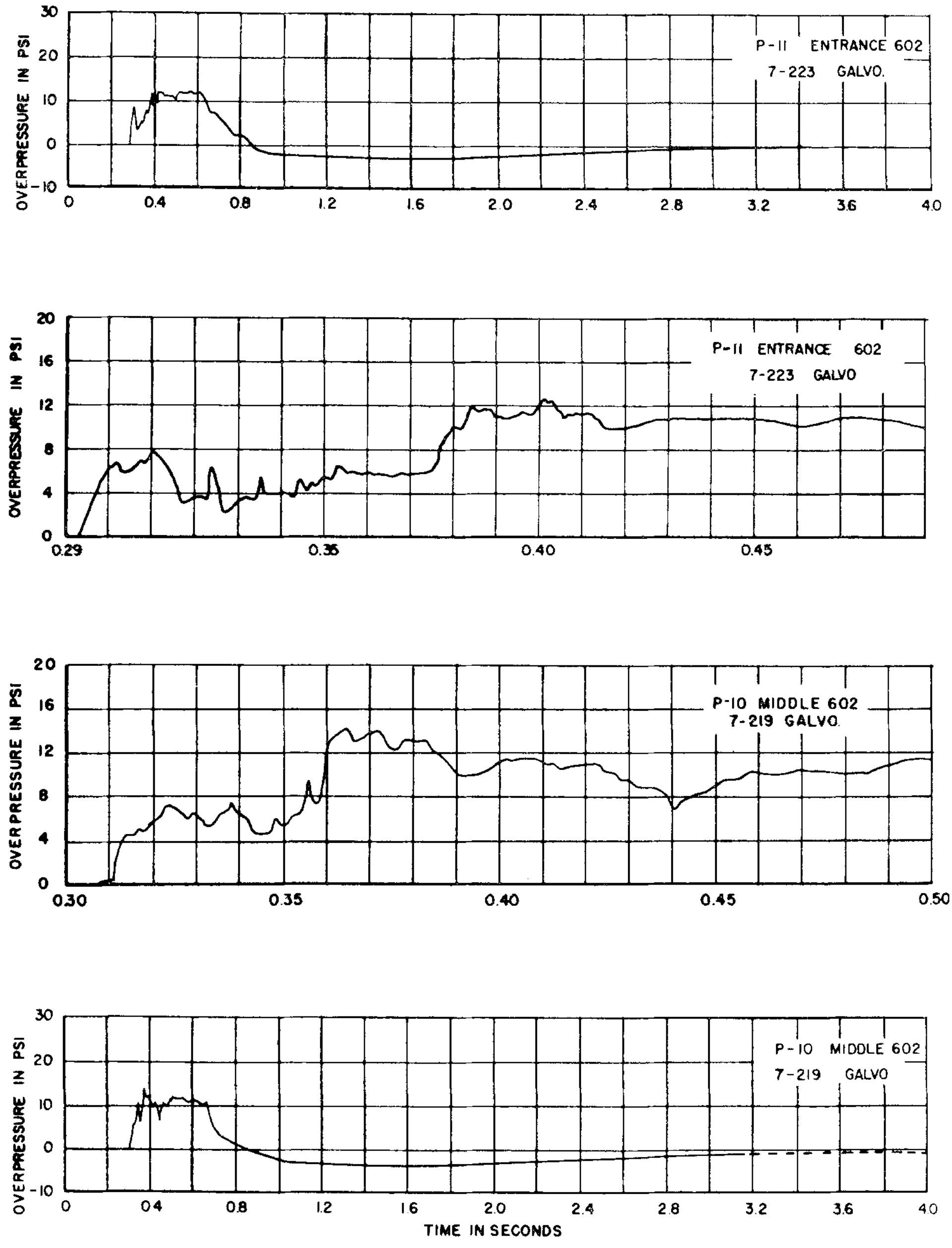


Fig. 5. Pressure-time records inside main room of Shelter 602 on Experiment I. (Data from Ruhl *et al.*, 1953 and White *et al.*, 1965.)

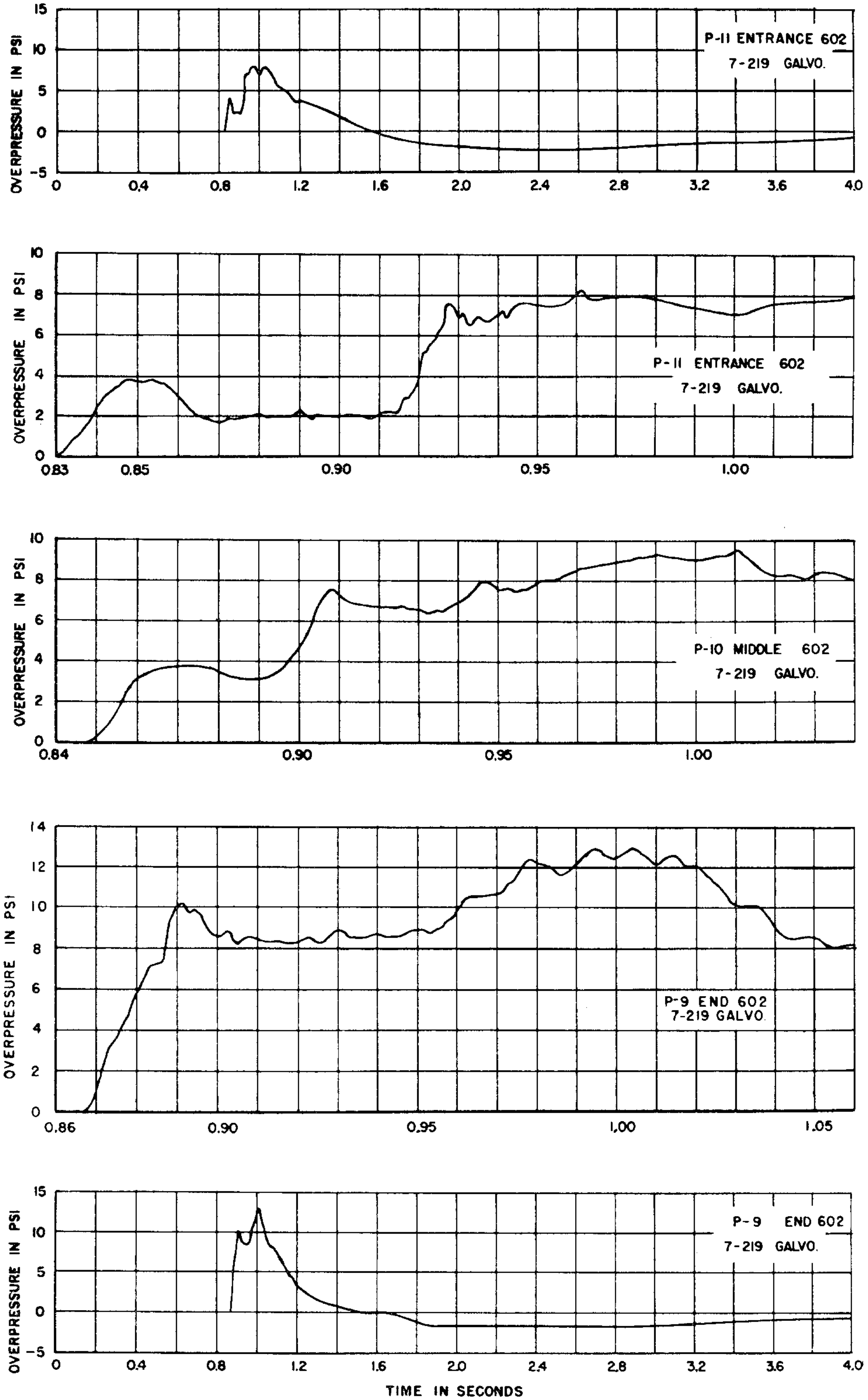


Fig. 6. Pressure-time records inside main room of Shelter 602 on Experiment II. (Data from Ruhl *et al.*, 1953 and White *et al.*, 1965.)

shelters partitioned to give two rooms each 12 × 12 ft with a ceiling height of 8 ft; see top of Figure 7 (White *et al.*, 1957). The bottom portion of Figure 7 shows the locations of pressure gauges and dogs on one of two series of experiments. In addition to the small animals shown on the table on the left side of the lower diagram in Figure 7, others were suspended in cages from the ceiling and still others in cages were placed below the benches on the right-hand side of the partition. Further details about the positions of small animals in Series I and II experiments in 1955 may be found in White *et al.* (1957).

The chamber shown in Figure 7 on the right-hand side of the partition received the blast through the main entryway that faced ground zero, all doors having been removed preshot. This was termed the 'fast-fill' side of the shelter in contrast with the 'slow-fill' side located on the left-hand side of the partition. The latter chamber received blast pressures and winds through a 3-ft square escape chimney which pierced the roof and ran vertically to ground level. The location of the escape hatch is shown with dotted lines in the upper left-hand corner of the views in Figure 7.

Pressure-time records obtained in 1955 from the gauges located inside the 'fast'- and 'slow-fill' sides of the shelters in Series I and II experiments are reproduced in Figures 8, 9, and 10. The incident pulses monitored outside each structure and having an early and delayed rising pulse are also shown for the Series I an II experiments at the bottom of Figures 8 and 10, respectively (White *et al.*, 1957; Vortman, 1957; White *et al.*, 1965).

In 1957, 24 dogs were exposed on two occasions in one of the 1955 shelters mentioned above (Richmond *et al.*, 1959). Exposure conditions including location of the pressure-time gauges are shown in Figure 11 for what were termed the 8001 and 8002 arrangements. Pressure-time curves recorded following each shot are depicted in Figures 12 and 13 (Richmond *et al.*, 1959; Mazzaros and Keefer, 1957).

(c) *Rectangular shelters.* Basement exit-type shelters, rectangular in shape as shown in the plan view of Figure 14, were tested 'mostly open' and 'mostly closed'* on two events in 1955 (White *et al.*, 1957). Six dogs were exposed in three shelters in the Series I experiment and eight in four shelters in the Series II experiment. The available pressure-time records inside and outside the shelters are included in Figures 15 and 16 (White *et al.*, 1957; Vortman, 1957; Vortman *et al.*, 1957).

(d) *The 'mostly closed' utility shelters.* Three utility shelters containing two dogs each were tested in the 1955 Series II experiment (White *et al.*, 1957). The roof of each shelter was pierced by a vent pipe 3 in. in diameter and the main entryway was protected by a heavy blast door though an ordinary door opening inward was also included. Figure 17(a) shows a plan view diagram of the shelter. The pressure-time curves recorded inside and outside the structures are shown in Figure 18 (White *et al.*,

* The 'mostly closed' shelters were pressurized through a 3-in. vent pipe piercing the roof and by leakage past four heavy doors closing the entryway. The 'mostly open' shelters were those tested without doors, with two rather than four doors, and the four-door arrangement when one or more doors failed.

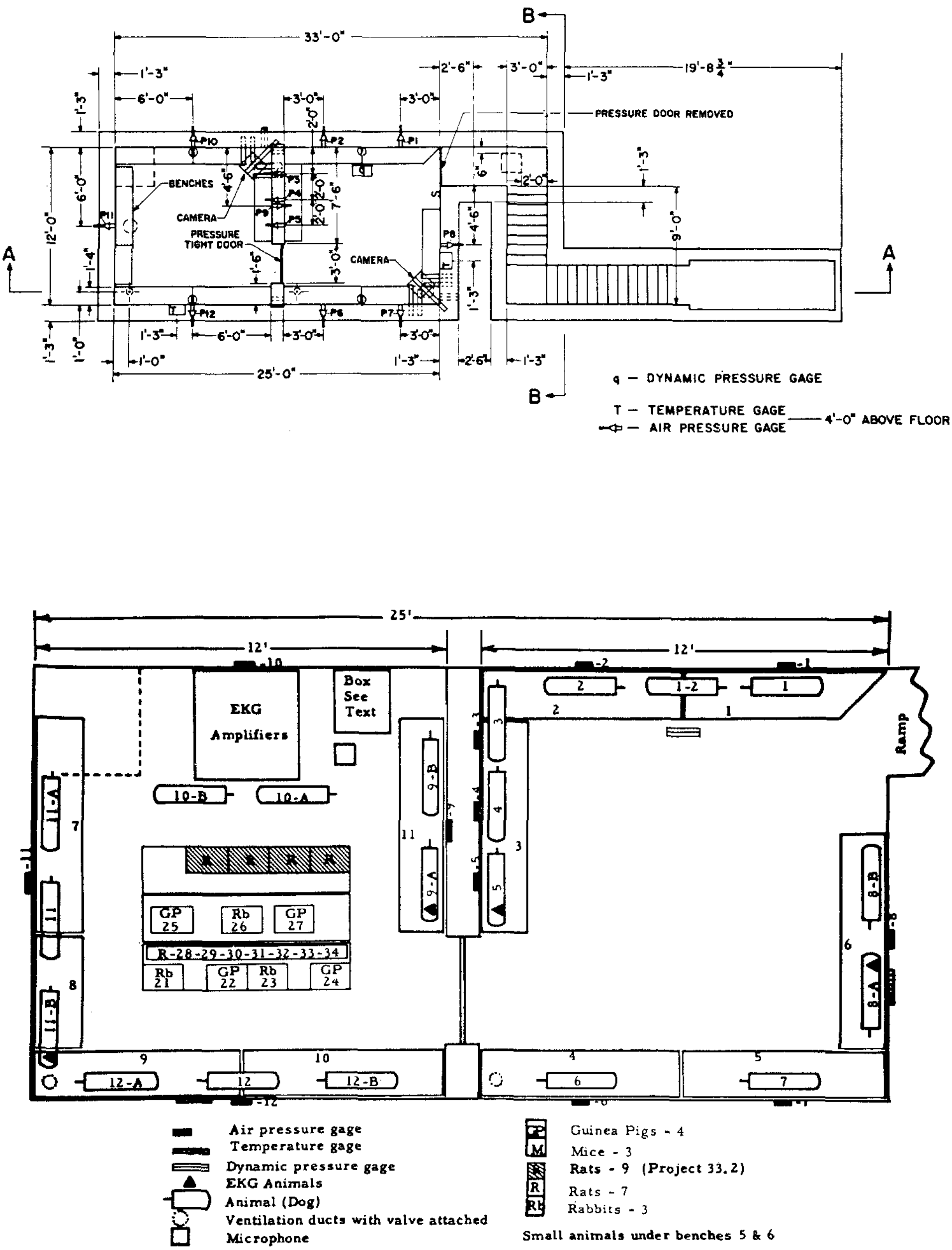


Fig. 7. Plan view of partitioned group (Blast Biology) shelter and partitioned group shelter. (Data from White *et al.*, 1957.)

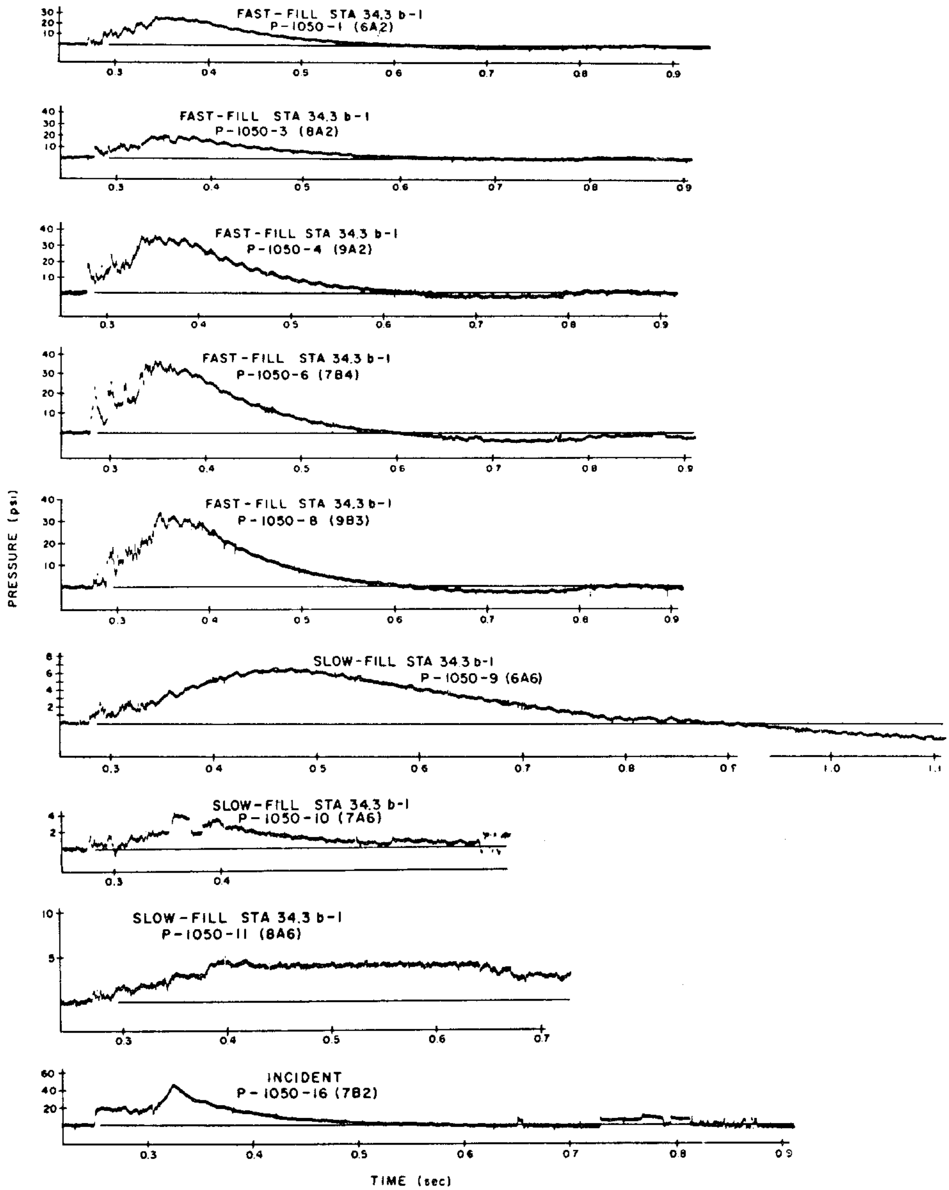


Fig. 8. Pressure-time records inside and outside (incident) the group shelter on Series I Experiment. (Data from Vortman, 1957; White *et al.*, 1957; and White *et al.*, 1965.)

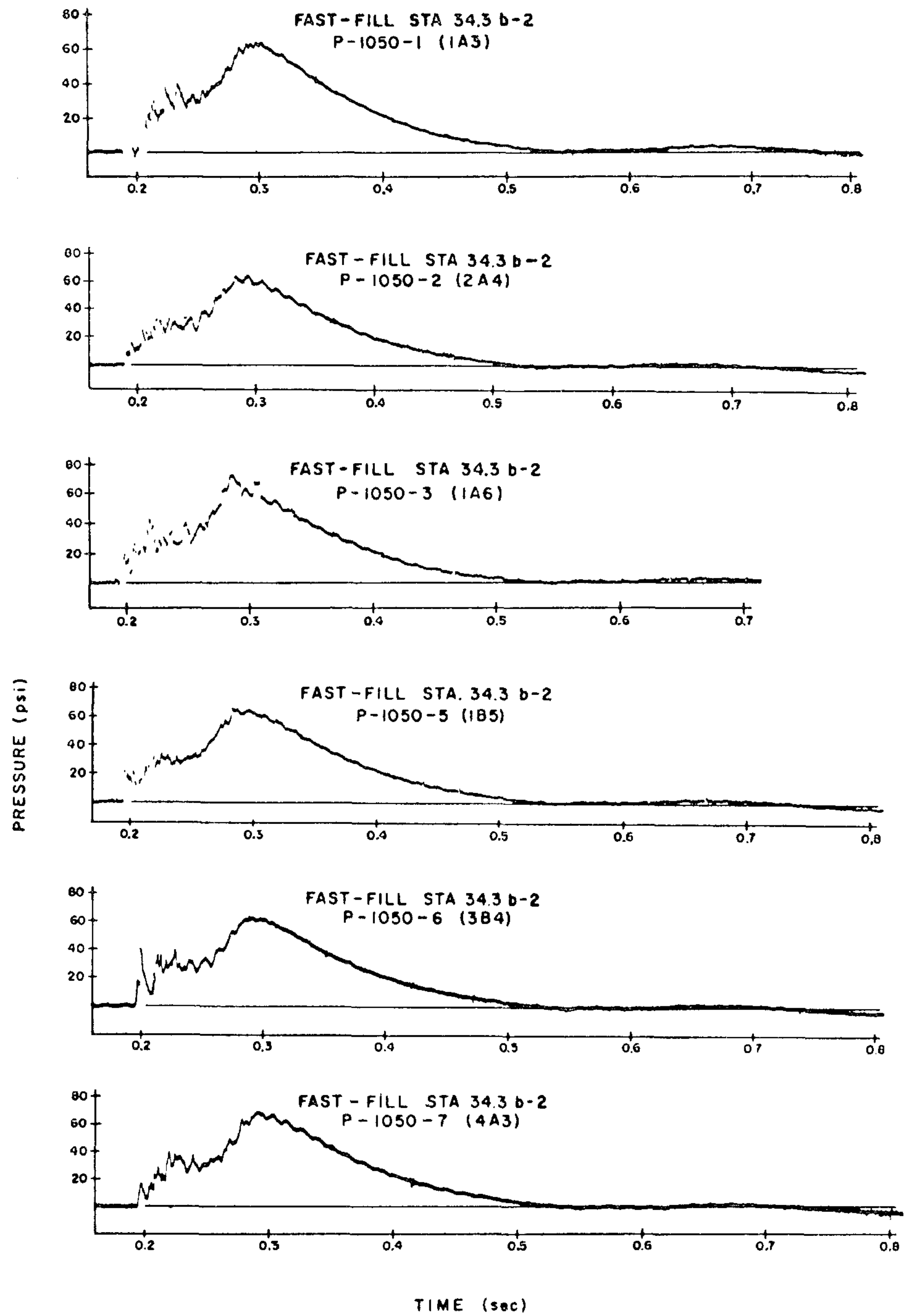


Fig. 9. Pressure-time records inside the 'fast-fill' sides of the group shelter on Series II Experiment. (Data from Vortman, 1957; White *et al.*, 1957; and White *et al.*, 1965.)

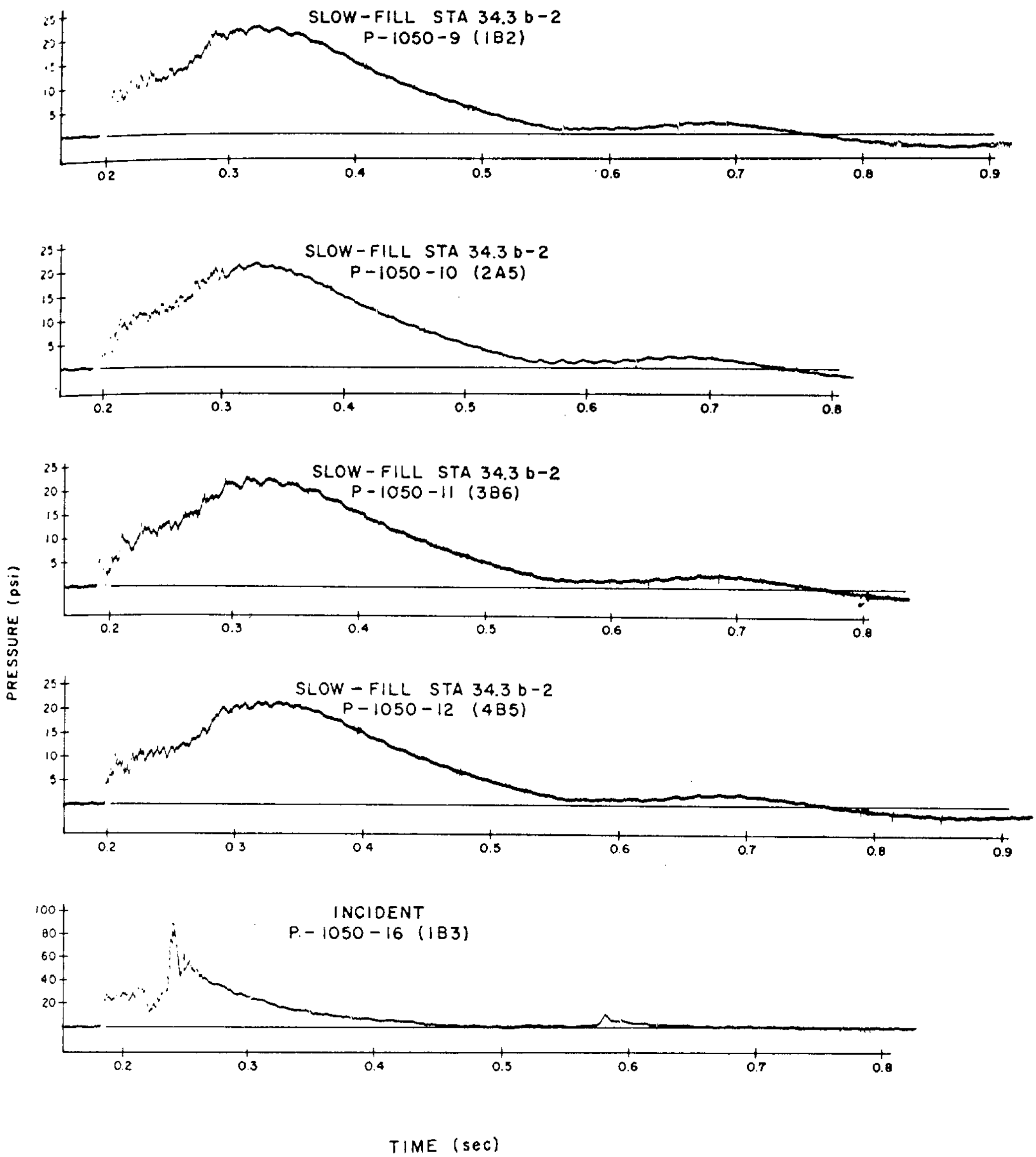
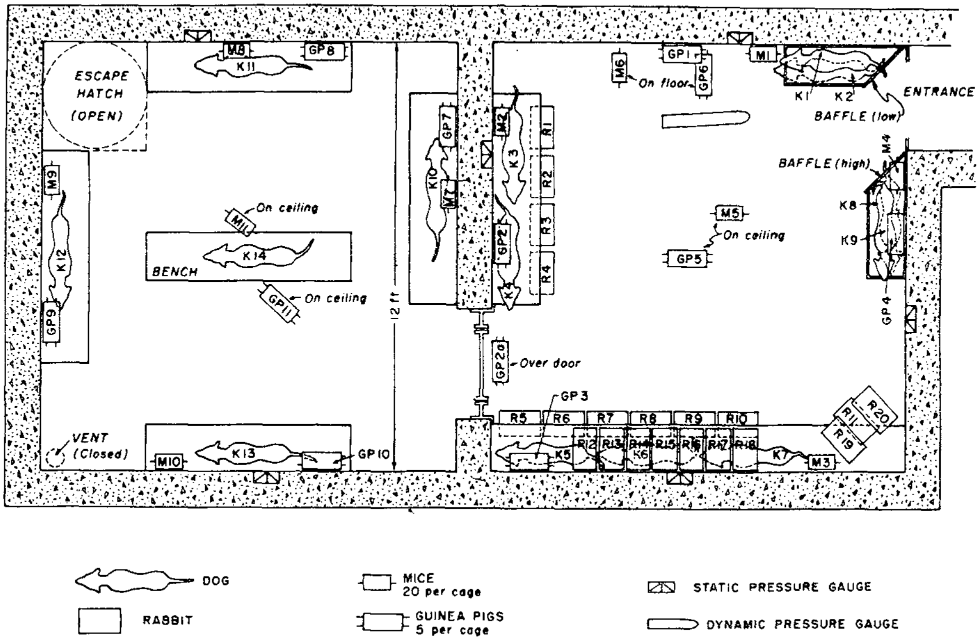
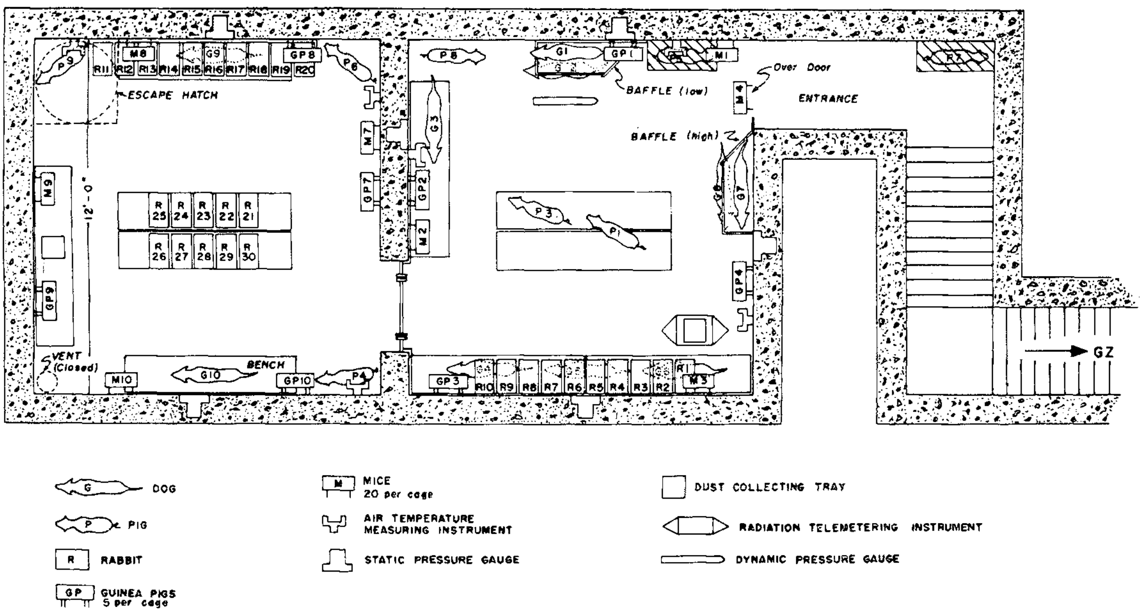


Fig. 10. Pressure-time records inside the 'slow-fill' and outside (incident) of the group shelter on Series II Experiment. (Data from Vortman, 1957; White *et al.*, 1957; and White *et al.*, 1965.)



Shelter 8001



Shelter 8002

Fig. 11. Location of animals and instruments in Shelters 8001 and 8002. (Data from Richmond *et al.*, 1957.)

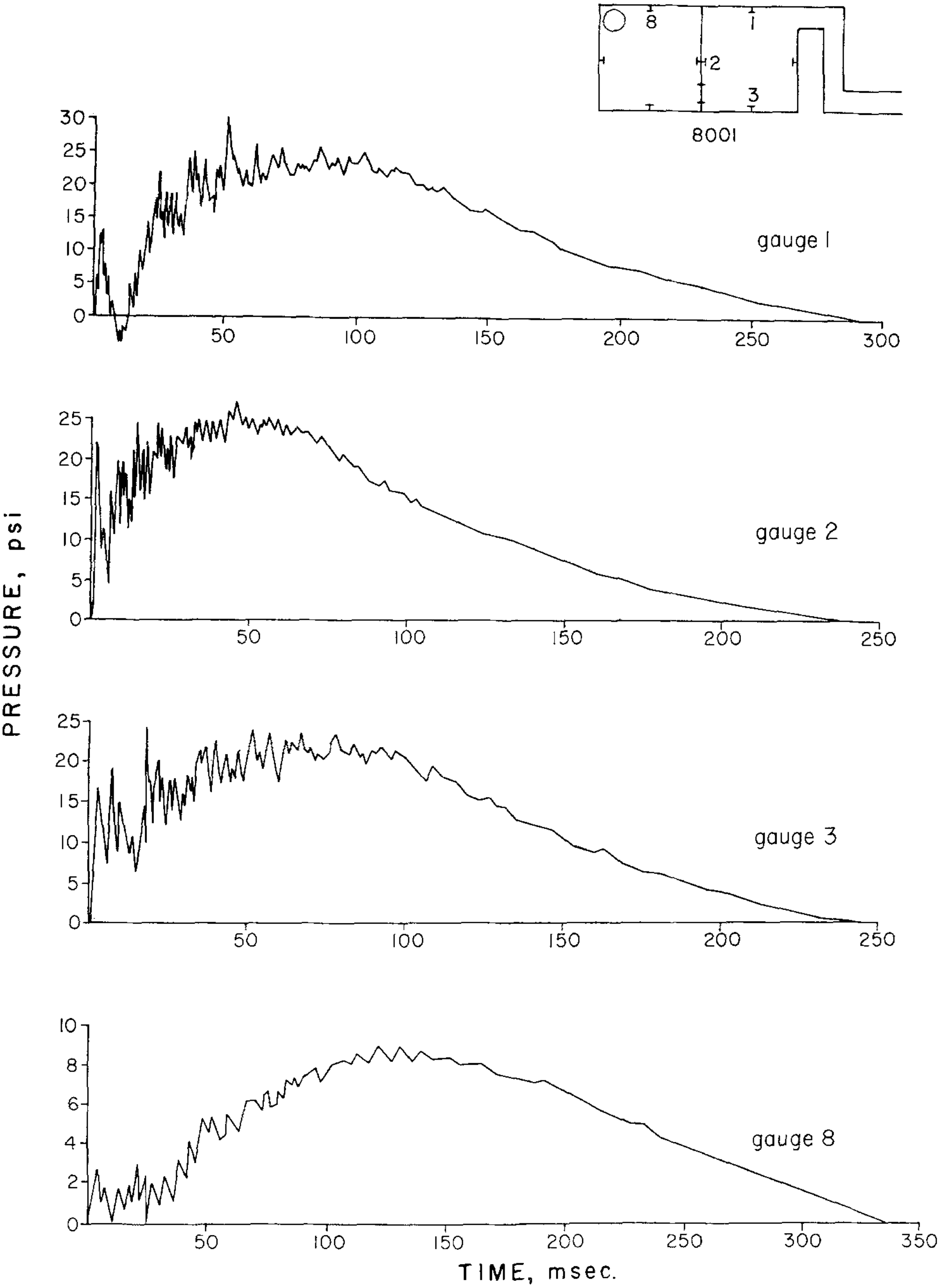


Fig. 12. Pressure-time curves as recorded inside Shelter 8001. (Data from Mazzaros and Keefer, 1957 and Richmond *et al.*, 1959.)

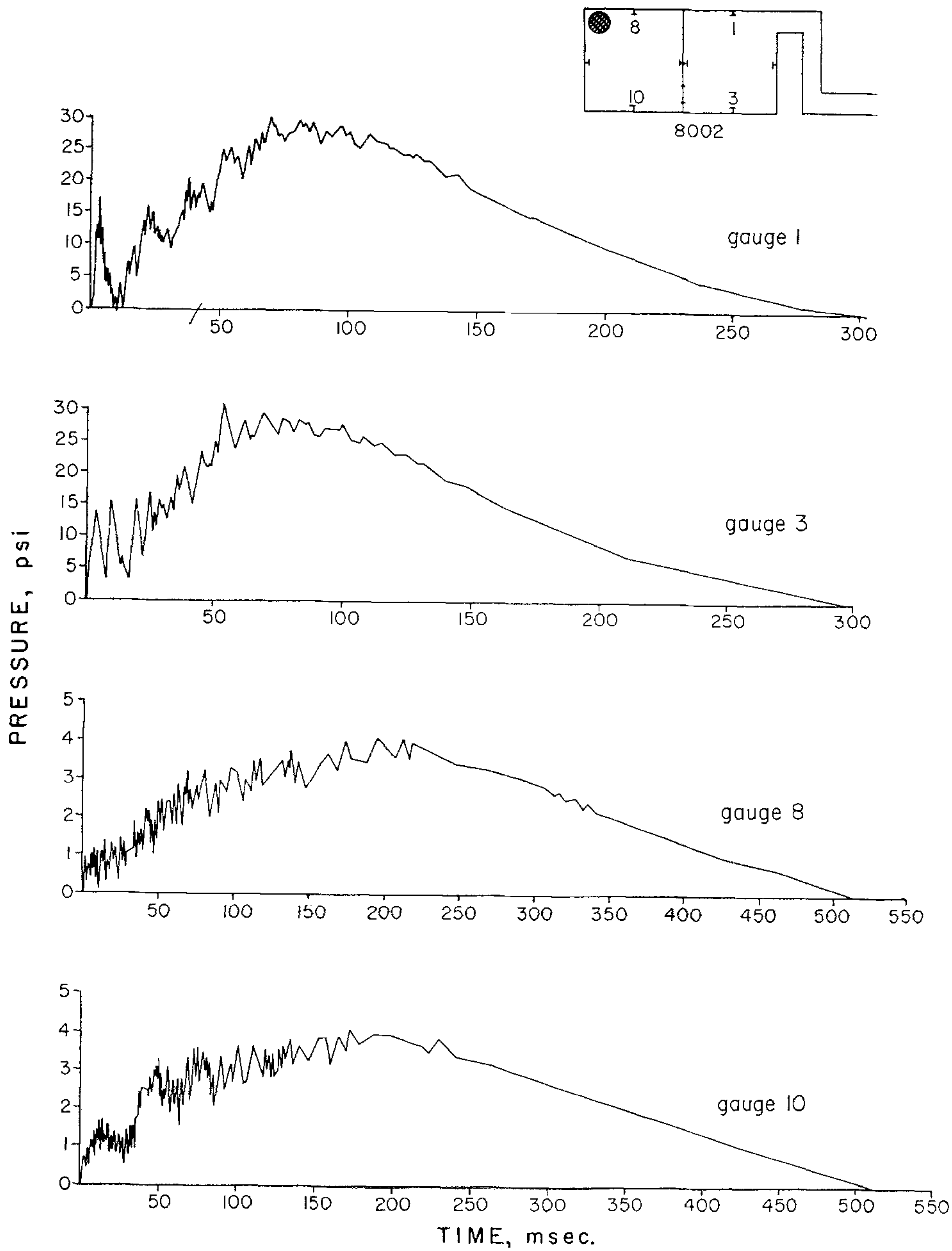


Fig. 13. Pressure-time curves as recorded inside Shelter 8002. (Data from Mazzaros and Keefer, 1957 and Richmond *et al.*, 1959.)

1957; Vortman, 1957). The forward shelter was overturned by the blast wave and no data were obtained from the wall gauge.

(e) *Other 'mostly open' and 'mostly closed' shelters.* Three other shelters, each housing two dogs, were also tested in the 1955 Series II experiment. Two of these, the basement corner room and the basement lean-to shelters, shown diagrammatically in Figures 17(b) and 17(c) were located in the basement of a house (White *et al.*, 1957). Neither shelter had doors. In contrast, the 'mostly closed' concrete bathroom shelter, shown in Figure 17(d) and containing two dogs, was located in a house, but the ordinary door and window were protected with a wooden blast door and shutter, respectively. The free-field, incident pressure-time record and those obtained inside the three shelters mentioned above are shown in Figure 19 (White *et al.*, 1957; Vortman, 1957; Vortman *et al.*, 1957).

(f) *Foxhole exposures.* In 1964 at the 500-ton test explosion at the Suffield Experimental Station, Ralston, Alberta, Canada, 18 goats were exposed, one each inside foxholes of two configurations placed at three ranges from ground zero (Gaylord *et al.*, 1965). A diagram of the deep foxhole, along with the pressure-time records obtained from instruments placed inside one foxhole at each range, is shown in Figure 20 (Gaylord *et al.*, 1965; Minor, 1964). Similar data are given in Figure 21 for the foxholes with an offset compartment inside which the goat was exposed lying down

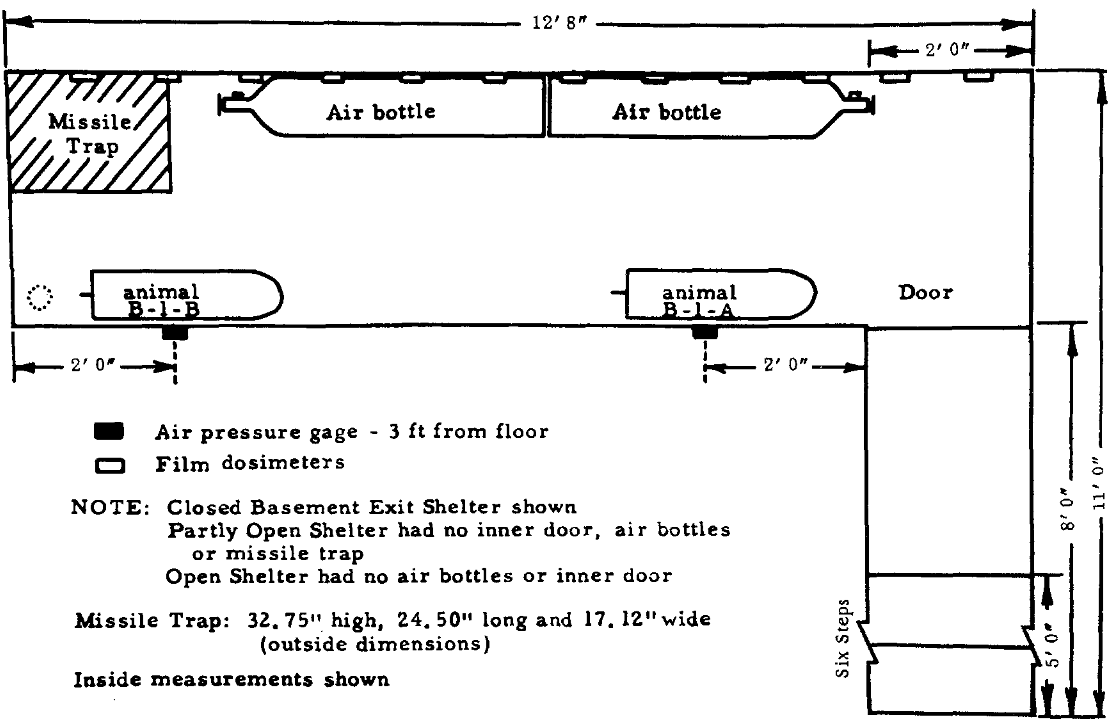


Fig. 14. Basement exit-type Shelter.
(Data from Vortman, 1957; Vortman *et al.*, 1957; and White *et al.*, 1957.)

(Gaylord *et al.*, 1965; Minor, 1964). The animals in the deep foxholes were standing.

To show the type of free-field incident wave forms recorded either at or near the same range as the foxholes, two tracings are included at the top of Figure 22 (Gaylord *et al.*, 1965; Minor, 1964).

2. *'Typical' or 'Near-Typical' Wave Forms*

Exposures of animals to 'typical' or 'near-typical' wave forms were accomplished in the open during the 500-ton trials mentioned above and in the laboratory with a shock tube.

(a) *Free-field exposures.* Goats, 55 in number, were tethered against stout screens to prevent displacement and exposed right side-on to the blast wave emanating from the 500-ton charge detonated in Canada (Pratt *et al.*, 1965; Betz *et al.*, 1965). A sketch of a screen and an animal is shown in the right portion of Figure 22. A sample free-field wave form recorded between the 10- and 15-psi stations where 10 goats each were located is shown at the bottom of the figure (Minor, 1964). Also, other animals were

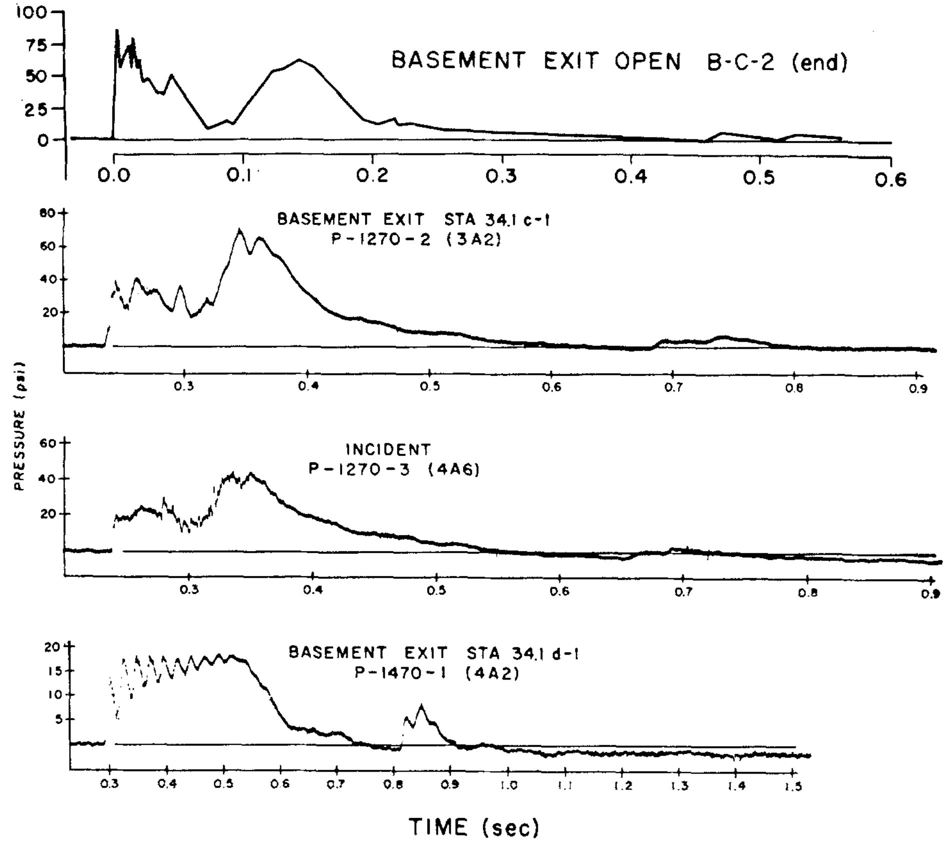


Fig. 15. Pressure-time records inside and outside (incident) basement exit shelters (ranges 1470 and 1270 ft). (Data from Vortman, 1957; Vortman *et al.*, 1957; and White *et al.*, 1957.)

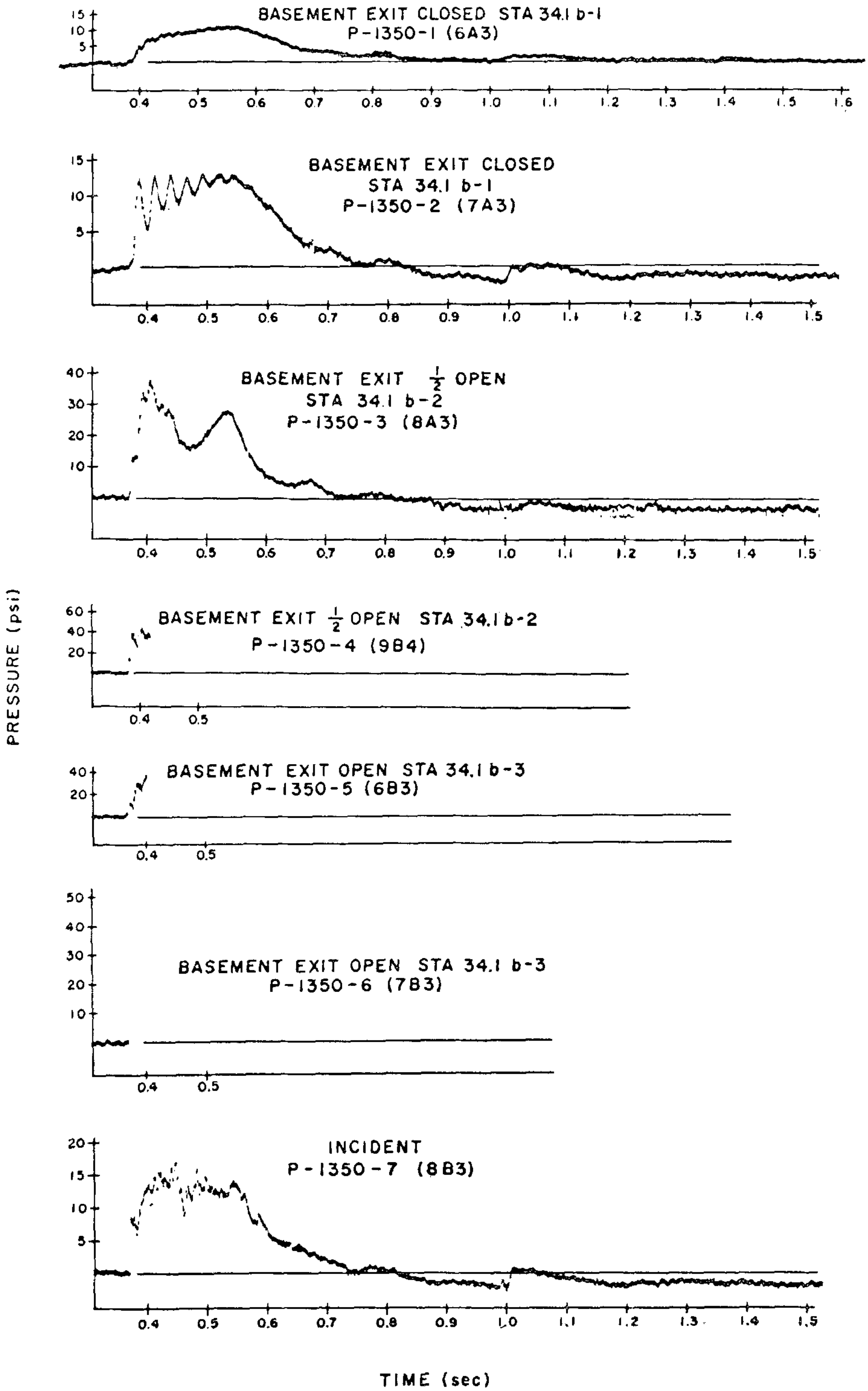


Fig. 16. Pressure-time records inside and outside (incident) basement exit shelters (range 1350 ft). (Data from Vortman, 1957; Vortman *et al.*, 1957; and White *et al.*, 1957.)

situated at 7 stations (5 at each station) spaced about 5 psi apart ranging from 30 to 60 psi (Betz *et al.*, 1965).

(b) *Shock tube exposures.* In experiments to study minimal blast lesion of the canine lung (White *et al.*, 1965, 1967; Richmond *et al.*, 1966a, 1968) 72 dogs weie exposed to 'fast'-rising overpressures enduring for approximately 400 msec. The equipment employed and a sample wave form achieved are illustrated in Figure 23 (Richmond *et al.*, 1966b). The animals were tethered in harness with the left side against the metal plate closing the end of the shock tube.

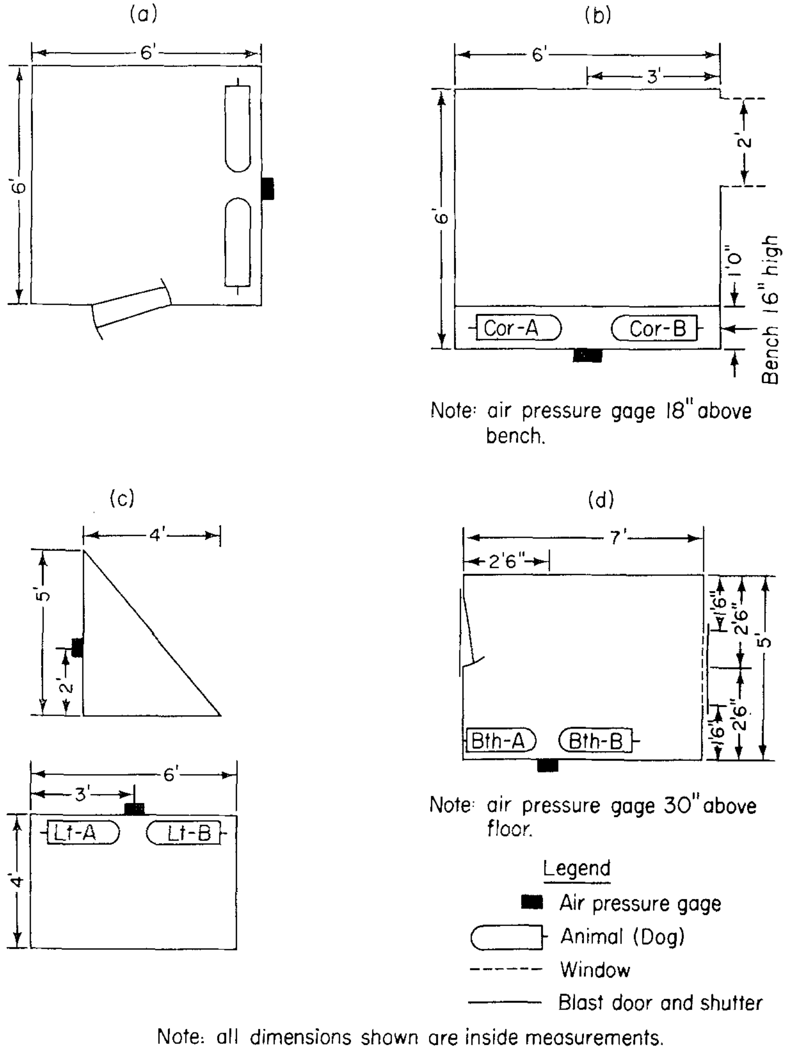


Fig. 17. 'Mostly open' and 'mostly closed' shelters used in Series II Experiment; (a) reinforced concrete utility room, (b) basement corner room, (c) basement lean-to and (d) concrete bathroom. (Data from Vortman, 1957; Vortman *et al.*, 1957; and White *et al.*, 1957.)

(c) *Data analysis.* The relationships between specified magnitudes of the overpressure pulses recorded by gauges located nearest the animal stations (or an average of several gauges in some instances) and the associated incidence of eardrum ruptures were explored in several ways. Initially, simple arithmetic plots were made from the tabulated data grouped and averaged in various ways. Subsequently, selected material was graphically compared using log-normal paper. Finally, the more significant

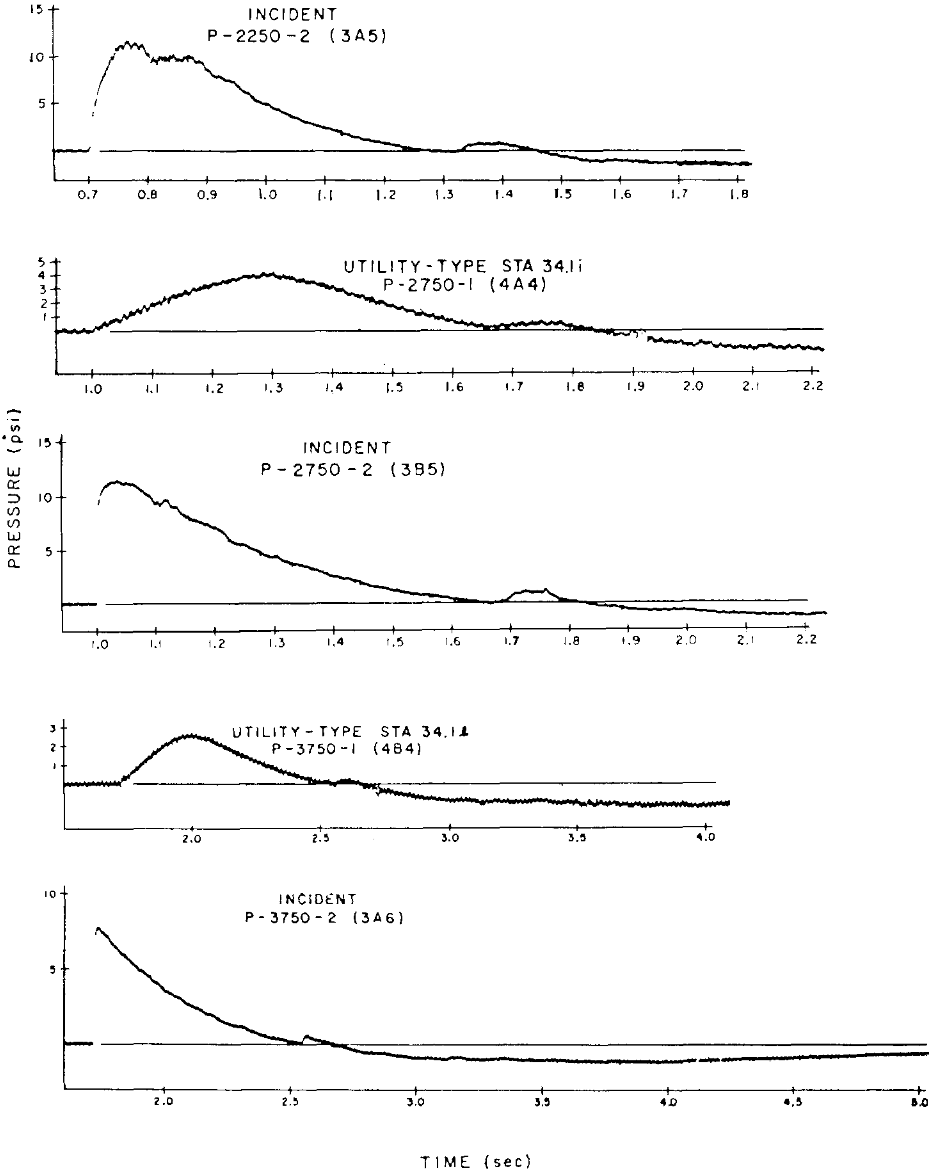


Fig. 18. Pressure-time curves inside and outside (incident) utility-type shelters. (Data from Vortman, 1957; Vortman *et al.*, 1957; and White *et al.*, 1957.)

relationships were analyzed by the probit technique of Finney (1952). Computations, including the probit curves and the 95% confidence limits, were programmed and completed using the Burroughs B5500 data processing system. Input data consisted of either 'small' or 'large' groups of data with the mean overpressure for each group expressed as the arithmetic averages or as the geometric means.

3. Results

A. GENERAL

Though the present study includes data based on guinea pigs, rabbits, dogs, goats and a few swine as detailed in Table I, most attention was directed to the dog and goat

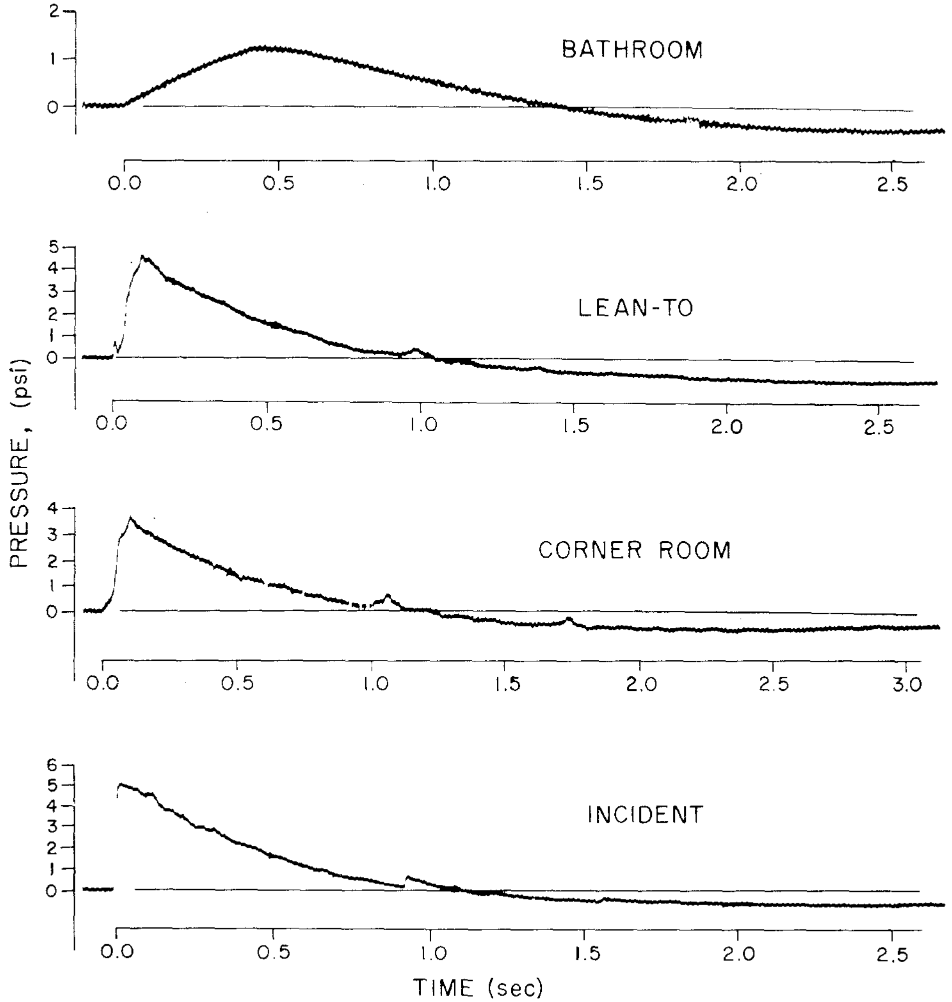


Fig. 19. Pressure-time curves obtained near a house (incident) and inside shelters situated in the house (bathroom – ground floor; lean-to and corner room – basement). (Data from Vortman, 1957; Vortman *et al.*, 1957; White *et al.*, 1957.)

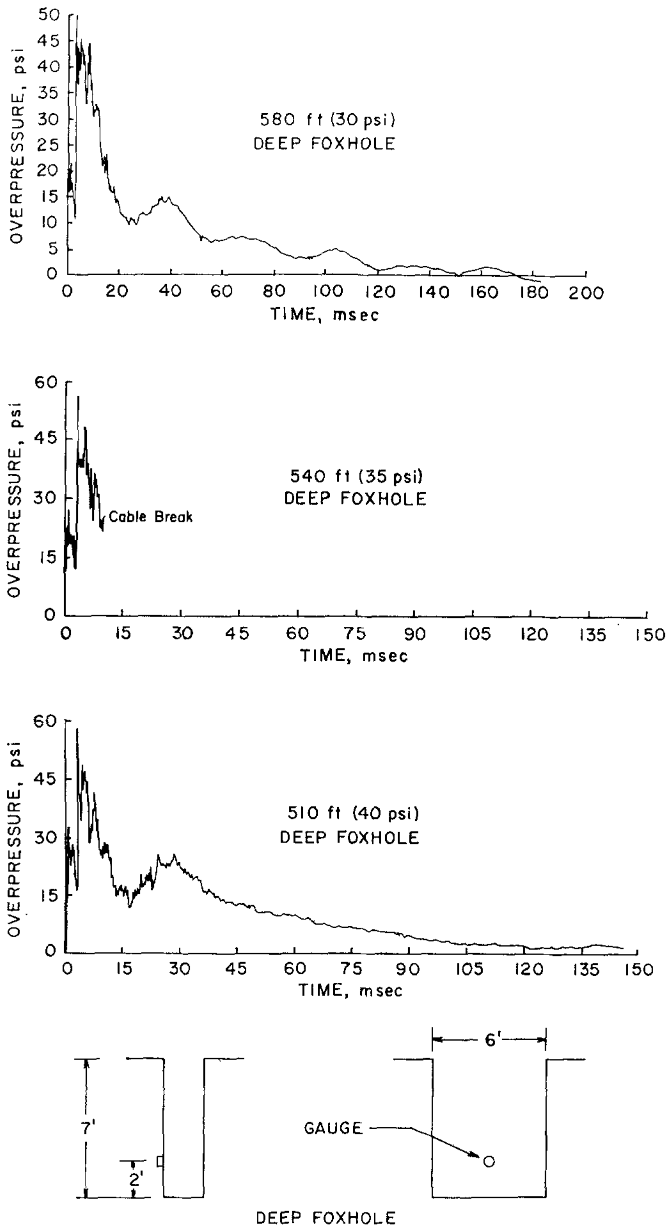


Fig. 20. Diagram of deep foxhole and pressure-time records obtained from instruments placed inside one foxhole at each range. (Data from Minor, 1964 and Gaylord *et al.*, 1965.)

analyses. After presentation of the tabular information, the 'large' and 'small' animal material will be considered more in detail.

B. TABULAR DATA

1. *Dogs*

(a) *'Atypical' wave forms.* Observations involving the rupture of the eardrums of 136 dogs exposed near instrumented locations of the Nevada Test Site in the 1953,

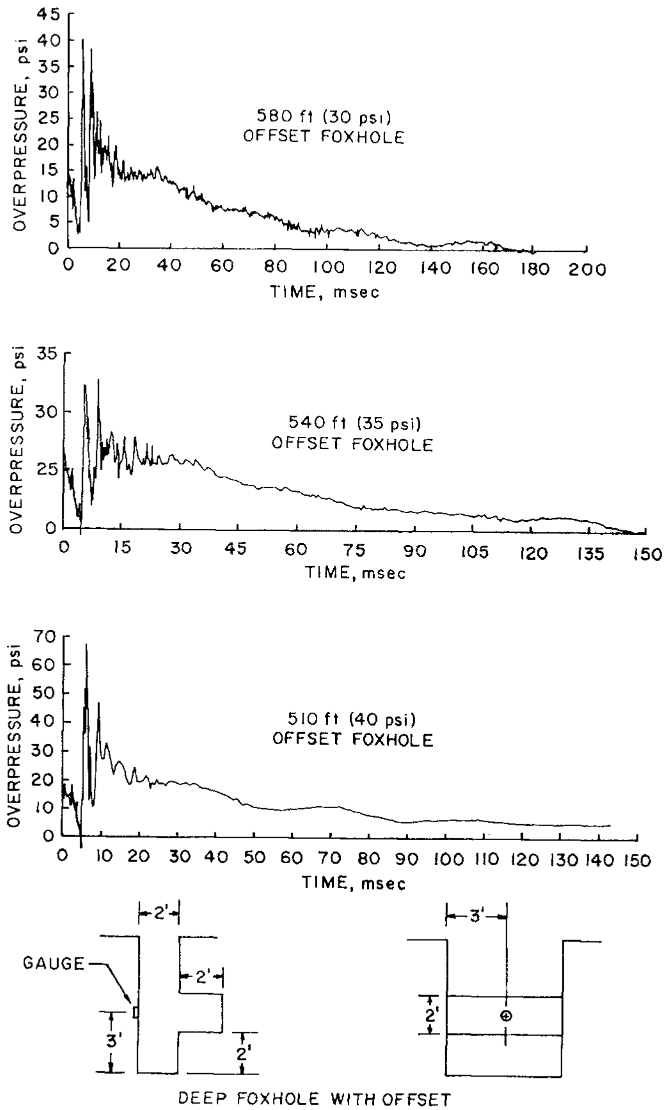


Fig. 21. Diagram of deep foxhole with offset and pressure-time records obtained from instruments placed inside one foxhole at each range. (Data from Minor, 1964 and Gaylord *et al.*, 1965.)

1955, and 1957 field operations are set forth in Table II.* The grouped data show the arithmetic** and geometric† means of the maximal pressures measured and the related incidence of eardrum failure. To emphasize the diversity of the wave forms to which the animals were subjected, the average rates of pressure rise are shown in the table.

(b) *'Near-typical' wave forms.* In contrast, animals studied in the shock tube were

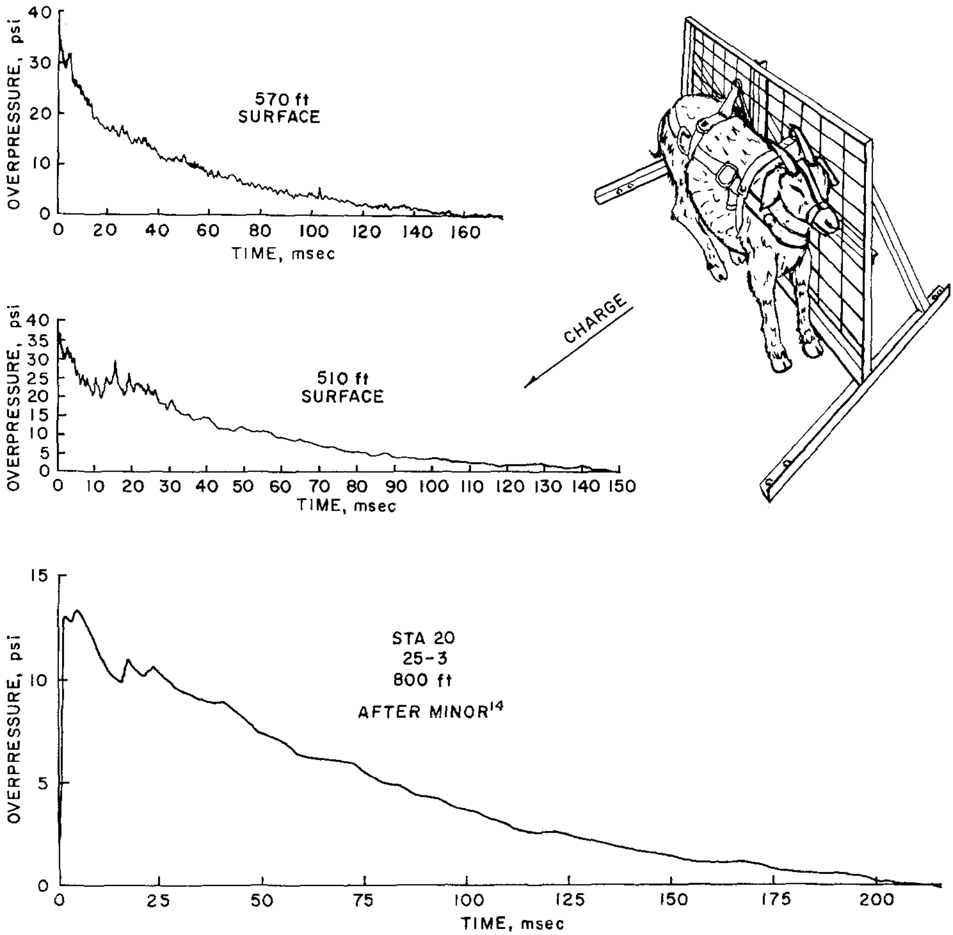


Fig. 22. Type of free-field incident wave forms recorded either at or near the same range as the foxholes (two tracings at top), sketch of a screen and an animal (right portion), and a sample free-field wave form recorded between the 10- and 15-psi stations (bottom). (Data from Minor, 1964 and Gaylord *et al.*, 1965.)

* All animals survived and were recovered within a few hours after exposure except two critically injured as a result of translational events.

** In contrast with the weighted arithmetic mean computed using a pressure for each animal.

† The weighted geometric mean is computed as the *N*th root of the products of the pressures included, one for each animal (*N*=number of animals).

exposed to much more uniform pulses of overpressure (see Figure 23). The findings on 72 dogs are detailed in Table III. The maximal overpressures shown are the measured reflected pressures occurring following the impact of the incident shock (also measured) with the end-plate of the shock tube. In the grouped data, the average overpressures given are the unweighted and weighted arithmetic as well as the weighted geometric means.

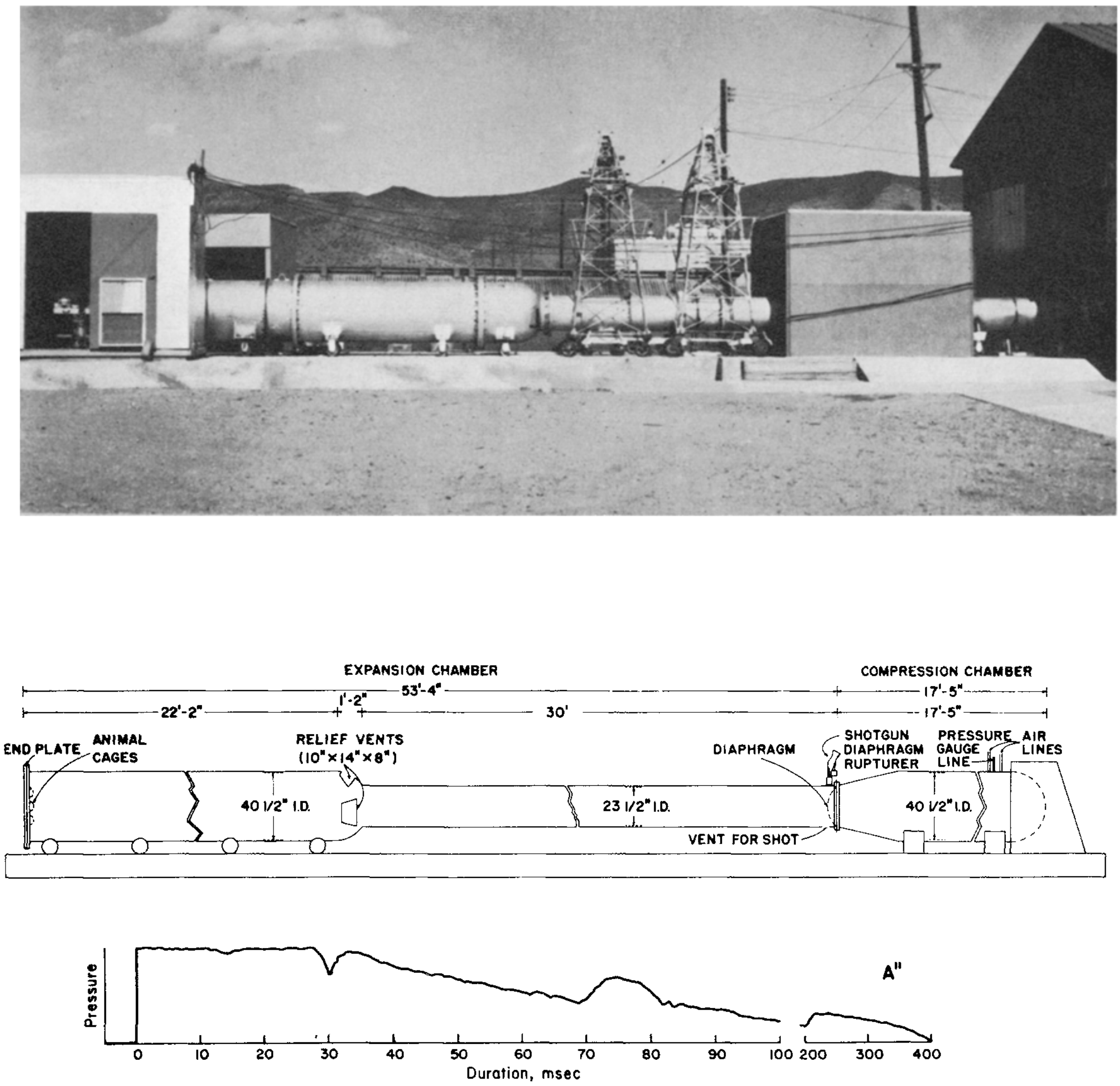


Fig. 23. Shock tube that generated 'sharp'-rising overpressures of about 400-msec duration and a sample of the wave form recorded from a gauge located at the center of the end-plate. (Data from Richmond *et al.*, 1961, 1966b.)

TABLE I

Number of animals and eardrums assessed and ruptured when exposed to 'fast'- and 'slow'-rising overpressures of 'long' duration[a]

Operation or source	Number of animals					R/N[b]
	Guinea pigs	Rabbits	Dogs	Swine	Goats	
Upshot-Knothole 1953			48			8/96
Teapot 1955			64			45/111
	52					49/67
		52				34/56
Plumbbob 1957	84					114/144
		36				47/69
			24			21/46
				8		7/8
Laboratory (last few years)			72			115/144
Snow Ball 1964					58	89/103
Totals	136	88	208	8	58	529/844

[a] Upshot-Knothole, Teapot, Plumbbob – Nevada Test Site – 12.5 psi ambient pressure.
Laboratory, Albuquerque, New Mexico – 12.0 psi ambient pressure.
Snow Ball, Suffield Experimental Station, Ralston, Alberta, Canada – 13.7 psi ambient pressure.
[b] (Number eardrums ruptured)/(Number assessable).

2. *Goats*

(a) *'Typical' wave forms.* Among the goats exposed in the open at Operation Snow Ball in 1964 to the blast wave from a 500-ton TNT detonation, there were 40 whose eardrums were observed postshot. Details, given in Table IV, include the maximum incident overpressures read from the curve constructed from the measured blast line data (Minor, 1964), the findings for the right and left ears summarized separately, and the incidence of eardrum rupture. In the grouped data, the overpressures noted are the unweighted arithmetic means of the pressure figures shown.

(b) *'Atypical' wave forms.* Also on Operation Snow Ball, 18 goats located in deep and deep-with-offset foxholes were observed following recovery after the explosion. The incidence of eardrum failure is given in Table V along with other pertinent data including the magnitude of the overpressures read from the specified portions of the pressure-time curves recorded inside one foxhole of each type at each range; namely, the overall maximal pressure, the initial spike of the rise noted in the earliest evaluation of the pressure, and the maximal pressure occurring during the early phase of the pulse.

The data are reassembled in Table VI in the order of the pressures read from each of the designated portions of the pressure-time tracings.

3. *Other Animals Exposed to 'Atypical' Wave Forms*

Eardrum data from 136 guinea pigs, 88 rabbits, and 8 swine exposed in the rectangular shelters in full-scale tests in 1955 and 1957 are shown in Table VII. The maximal over-

TABLE II

Dog eardrum tolerance when exposed inside shelters at the Nevada Test Site to 'slow'-rising, 'long'-duration overpressures (ambient pressure: 12.5 psi)

Operation	P_{max}, psi		Average rate of pressure rise psi/msec	Number of dogs	R/N[e]	Drums ruptured %
	Range	Average[f]				
TP[a]	1.3	1.3	0.003	2	0/4	0[b]
TP	2.6	2.6	0.009	2	0/4	0[b]
TP	3.7	3.7 (2.3)	0.028	2	0/4	0[b]
PB[a]	4.1	4.1	0.020	2	1/4	25
TP	4.3	4.3	0.02	2	0/4	0
TP	4.6	4.6	0.05	2	1/4	25
TP	6.7	6.7	0.03	10	0/20	0
UK[a]	7.5–8.5	8.0	0.12–0.20	12	1/24	4.2
PB	9–10	9.5	0.80	5	0/10	0
Total	4.1–10	6.2 (7.0)		33	3/66	4.6
UK	8–13	10.5	0.18–0.42	17	0/34	0
TP	11.5–13.5	12.5	0.155	2	0/4	0
UK	12.5–16.0	14.3	0.44–Inst.[c]	8	1/16	6.3
TP	18.5	18.5	0.325	2	2/4	50.0
TP	21.4–22.8	22.1	0.154–0.191	10	8/12	66.6
Total	8.0–22.8	15.6 (13.1)		39	11/70	15.7
UK	19.0–24.0	22.5	0.50–Inst.[c]	7	1/14	7.1
PB	23.8–27.0	25.5	0.481	9	8/16	50.0
PB	30.0–30.5	30.3	0.466	8	12/16	75.0
TP	26.6–36.9	33.8	0.313–0.773	10	10/20	50.0
Total	19.0–36.9	28.0 (27.8)		34	31/66	47.0
UK	38	38	'Fast' (mech. gauge)	4	5/8	62.5
TP	38.6–43.1	40.9	1.09–7.84	2	2/4	50.0
TP	38.6–47.0	42.8	1.05–2.19	2	2/4	50.0
TP	53	53.0[d]	10.6[d]	2	3/4	75.0
Total	38–53	43.7 (42.2)		10	12/20	60.0
TP	63.6–73.2	66.6	0.587–0.812	10	10/12	83
TP	71.6	71.6	0.645	2	3/3	100
TP	85.5	85.5	21.45	2	4/4	100
Total	63.6–85.5	74.6 (71.0)		14	17/19	89.5

[a] TP – Teapot (WT-1179), PB – Plumbbob (WT-1467), UK – Upshot-Knothole (WT-798); [b] Not used in average for following group; [c] Instantaneous; [d] Estimated value; [e] (Number eardrums ruptured)/(Number assessable); [f] Figures represent either single values or the average of those from more than one gauge. Values in parentheses are the weighted geometric means; other 'total' pressure figures are the unweighted arithmetic means.

TABLE III

Dog eardrum tolerance when exposed side-on against the end-plate of a shock tube to 'fast'-rising, 'long'-duration overpressures (ambient pressure: 12.0 psi)[a]

Maximal overpressure, psi			Weighted geometric mean	Number of animals	R/N[b]	Drums ruptured %
Range	Arithmetic means					
	Unweighted	Weighted				
8.5– 8.6	8.5	8.5	8.5	3	1/6	16.7
8.9– 9.5	9.2	9.2	9.2	7	4/14	28.6
9.8–13.1	11.5	11.8	11.8	6	7/12	58.3
13.2–19.3	16.3	14.9	14.8	11	18/22	81.8
19.4–25.0	22.2	21.7	21.6	14	24/28	85.7
25.1–38.6	31.9	31.6	31.4	31	61/62	98.3
Totals				72	115/144	

[a] All animals except one in the highest pressure group survived exposure; those subjected to overpressures above 30 psi showed a post-exposure increase in lung weight above controls.
[b] (Number eardrums ruptured)/(Number assessable).

TABLE IV

Goat eardrum tolerance when exposed side-on in the open to 'fast'-rising overpressures of 'long'-duration from a 500-ton TNT explosion (ambient pressure: 13.5 psi)

Exposure conditions	Max incident pressure psi	Number of animals examined	R/N[c]			Drums ruptured %
			Right	Left	Both	
Open[a]	10	10	6/10	5/10	11/20	55
Open[a]	15	10	8/10	5/9	13/19	68.4
Average	12.5	20	14/20	10/19	24/39	61.5
Open[b]	29	3	2/3	2/3	4/6	66.7
Open[b]	35	3	3/3	2/3	5/6	83.3
Average	32.0	6	5/6	4/6	9/12	75.0
Open[b]	40	3	3/3	1/3	4/6	66.7
Open[b]	43	4	4/4	3/4	7/8	87.5
Average	41.5	7	7/7	4/7	11/14	78.6
Open[b]	50	4	4/4	3/4	7/8	87.5
Open[b]	54	1	1/1	1/1	2/2	100
	58	2	2/2	1/2	3/4	75
Average	54.0	7	7/7	5/7	12/14	85.7
Overall		40	33/40	23/39	56/79	70.9

[a] All exposed animals survived except one at each range injured by crater ejecta.
[b] All exposed animals were critically injured by overpressures and/or crater ejecta except one at the 29-psi station.
[c] (Number eardrums ruptured)/(Number assessable).

TABLE V

Goat eardrum tolerance when exposed inside deep and deep-with-offset foxholes to blast overpressures from a 500-ton TNT explosion (ambient pressure: 13.7 psi)[a]

Range in ft	Type of foxhole	Free-field incident	Overpressure, psi			Number of goats exposed	R/N[b]		Drums ruptured %	
			Early rise		Later max		Deep	Offset	Deep	Offset
			Initial	Max						
510	Deep	40	15.2	33.3	58.5	3	4/4		100	
	Offset		18.3	18.3	67.3	3		4/6		66.7
Totals						6	8/10		80.0	
540	Deep	35	14.1	27.2	56.4	3	4/6		66.7	
	Offset		21.3	21.3	36.7	3		5/6		83.3
Totals						6	9/12		75.0	
580	Deep	29	14.2	21.4	50.1	3	3/6		50.0	
	Offset		18.3	18.3	40.1	3		3/6		50.0
Totals						6	6/12		50.0	
Totals	Deep foxholes					9	11/16		68.8	
	Deep-with-offset foxholes					9		12/18		66.7
Totals all						18	23/34		67.6	

[a] Of the 18 animals all, except 2 injured by crater ejecta, survived.
[b] (Number eardrums ruptured)/(Number assessable).

pressures tabulated are the averages from the several gauges mounted on the walls of the chambers in which the animals were located.

C. DOSE-RESPONSE RELATIONSHIPS

1. *Dogs*

(a) *'Atypical' wave forms.* Using the individual maximal pressures given in Table II for each single animal or group exposed to 'atypical' wave forms recorded during field operations at the Nevada Test Site and the associated incidence of eardrum failure, the dose-response relationship applicable to 136 dogs was explored employing the probit technique (Finney, 1952). The initial results, graphically portrayed in Figure 24, revealed the P_{50} – the pressure associated with rupture of 50% of the eardrums – to be 29.9 psi with the 95% confidence limits ranging from about 21 to 53 psi. More interesting than, but related to, the wide spread in the data, however, was the fact that the Chi square routine, included in the computer program for testing the distribution expected of data sampled adequately to account for the significant variable or variables influencing an experiment, 'judged' the material to be inconsistent; viz., the sample was influenced by one or more spurious variables. In a way this was not surprising in

TABLE VI

Goat eardrum data from foxholes arranged in the order of pressures read for the early initial, early maximum and overall maximum pressure rise (ambient pressure: 13.7 psi)

Exposure conditions[a]	Overpressure, psi			R/N[b]	Drums ruptured %
	Early rise		Later		
	Initial	Max	max		
540 deep	14.1			4/6	66.7
580 deep	14.2			3/6	50.0
510 deep	15.2			4/4	100.0
510 offset	18.3			4/6	66.7
580 offset	18.3			3/6	50.0
540 offset	21.3			5/6	83.0
510 offset		18.3		4/6	66.7
580 offset		18.3		3/6	50.0
540 offset		21.3		5/6	83.3
580 deep		21.4		3/6	50.0
540 deep		27.2		4/6	66.7
510 deep		33.3		4/4	100.0
540 offset			36.7	5/6	83.3
580 offset			40.1	3/6	50.0
580 deep			50.1	3/6	50.0
540 deep			56.4	4/6	66.7
510 deep			58.5	4/4	100.0
510 offset			67.3	4/6	66.7

[a] Numbers give range from ground zero in feet; deep and offset indicate type of foxhole (see Figures 20 and 21).
[b] (Number eardrums ruptured)/(Number assessable).

view of the variations in the wave forms to which the animals were exposed, the different conditions of exposure, and the diverse proximities of animal to gauge.

To learn whether any variables that might be disturbing the dose-response relationship could be 'submerged' by grouping and thus give results that could be helpful for large, random exposures (if not for individual exposures) inside structures, probit analyses were performed. In these analyses, the 'average' figures in Table II were used, first for the unweighted arithmetic mean overpressures, and second, for the weighted geometric mean overpressures. The results for the latter are plotted in Figure 25.

The grouped data were statistically 'acceptable' when tested for internal consistency. Also, the envelope defined by the 95% confidence limit lines was much narrower. This included less variation for the P_{50} estimate. For example, for the three instances explored, the results were as follows (see Table VIII).

Not only did using the weighted geometric mean pressures give a minimal spread for the P_{50} value, but the result for the latter was quite close to that obtained using the pressures for the individual or smallest groups; i.e., 29.8 compared with 29.9 psi.

TABLE VII

Tolerance of guinea pig and rabbit eardrums when exposed inside shelters to 'slow'-rising, 'long'-duration overpressures (ambient pressure: 12.5 psi)

Operation	P_{max} psi	Guinea pigs			Rabbits		
		Number of animals	R/N[f]	Drums ruptured %	Number of animals	R/N[f]	Drums ruptured %
PB[a]	4.1	12	0/24	0	10	2/19	10.5
TP[b]	6.7	24	13/28	46	23	11/24	45.8
PB	9.5	25	38/44	86.4	—	—	—
TP	22.0	22	29/32	91	23	18/25	72.0
PB	25.5	35	52/52	100	20	39/40	97.5
PB[c]	30.3	12	24/24	100	6	6/10	60.0
TP	53.0[d]	2	2/2	100	2	1/2	50.0
TP	66.6	4	5/5	100	4	4/5	80.0
Totals[e]		136	163/211		88	81/125	

[a] PB – Plumbbob (1957) operation, WT-1467; 3 swine exposed – none of 6 eardrums ruptured.
[b] TP – Teapot (1955) operation, WT-1179.
[c] Five swine exposed; 7 of 8 usable eardrums ruptured (87.5 %).
[d] Estimated value.
[e] All animals survived blast exposure except: 2 guinea pigs (25.5 psi); one guinea pig (22 psi); and one swine (P_7 – see Figure 11).
[f] (Number eardrums ruptured)/(Number assessable).

TABLE VIII

Pressure values used	P_{50} pressures psi	95% confidence limit	Range in confidence limit
Individual or smallest groups	29.9	21.4–52.6	31.2
Unweighted arithmetic means	31.5	26.7–39.0	12.3
Weighted geometric means	29.8	25.3–36.7	11.4

However this may be, the spread in the results appeared to be disturbingly large and further work was undertaken to learn, if possible, why this should be so.

(b) *'Near-typical' wave forms.* To help appreciate how much spread might characterize eardrum data obtained when animals were exposed to fairly uniform, 'fast'-rising, 'long'-duration blast waves, probit analyses were carried out on the data obtained employing a shock tube. This included using as input to the analyses individual results and the grouped figures noted in Table III. In the latter case, computations were carried out for the unweighted arithmetic mean pressures and the geometric mean pressures, both weighted and unweighted. The findings were within 0.4 psi for the P_{50}, and the results of the analyses using the weighted geometric mean pressures for the shock tube studies noted above and for the field experiments given previously are compared graphically in Figure 26. It is clear that the P_{50} values are

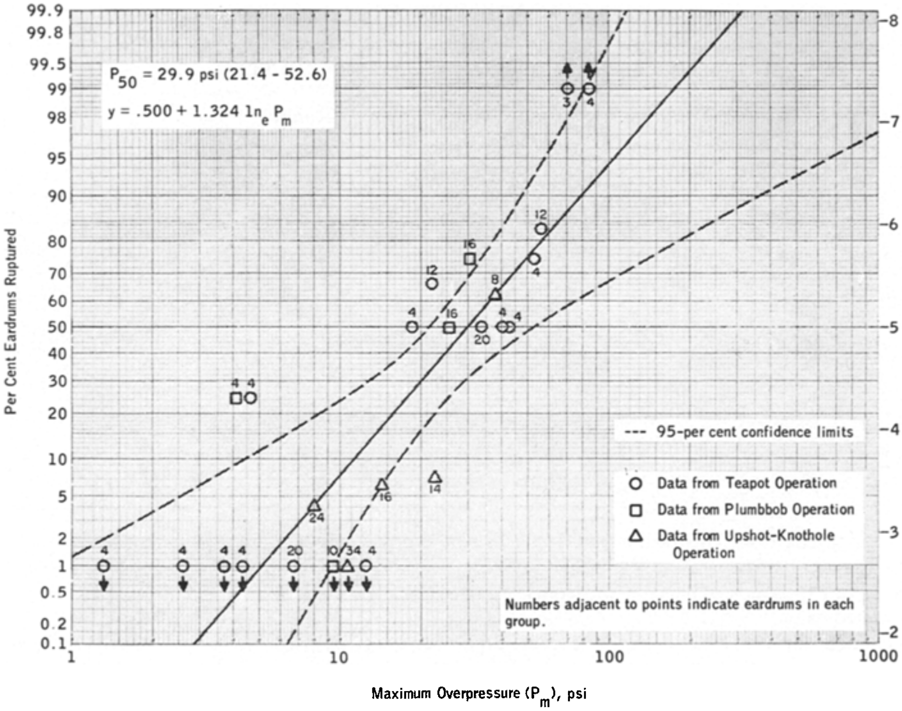


Fig. 24. Response of canine eardrum exposed in field operations to a variety of 'atypical' blast waves; ambient pressure, 12.5 psi. (Individual or smallest group data shown in Table II used.)

significantly different, there being the probability of <0.0001 that the observed variation might be due to chance. Also, the two probit curves converge at the lower overpressures and the distributions below an incidence of eardrum rupture of about 10% appeared not to be impressively different at the 95% confidence levels. This, however, is very much a consequence of the slope constants of the two probit lines. Not so apparent from inspection of Figure 26 is the fact that there is no reliable statistical difference between the slopes of the two curves. In fact, the probability that the difference is due to chance is 0.155. Since the meaning of the converging curves as well as the difference in the P_{50} figures is not entirely clear at the present time, further discussion of the matter will not be pursued here.

2. *Goats*

(a) *'Typical' wave forms.* Probit analysis of the eardrum data in Table IV for goats exposed right-side-on in the open to 'typical' blast waves from a 500-ton TNT explosion were carried out. The results for the smallest groups of data (unweighted) yielded a P_{50} of 7.0 psi with confidence limits that varied between zero and 14.2 psi. Essentially similar results were obtained using the grouped and weighted geometric mean overpressures; viz., the P_{50} was 6.6 (–, 14.1) psi. It was thought the broad

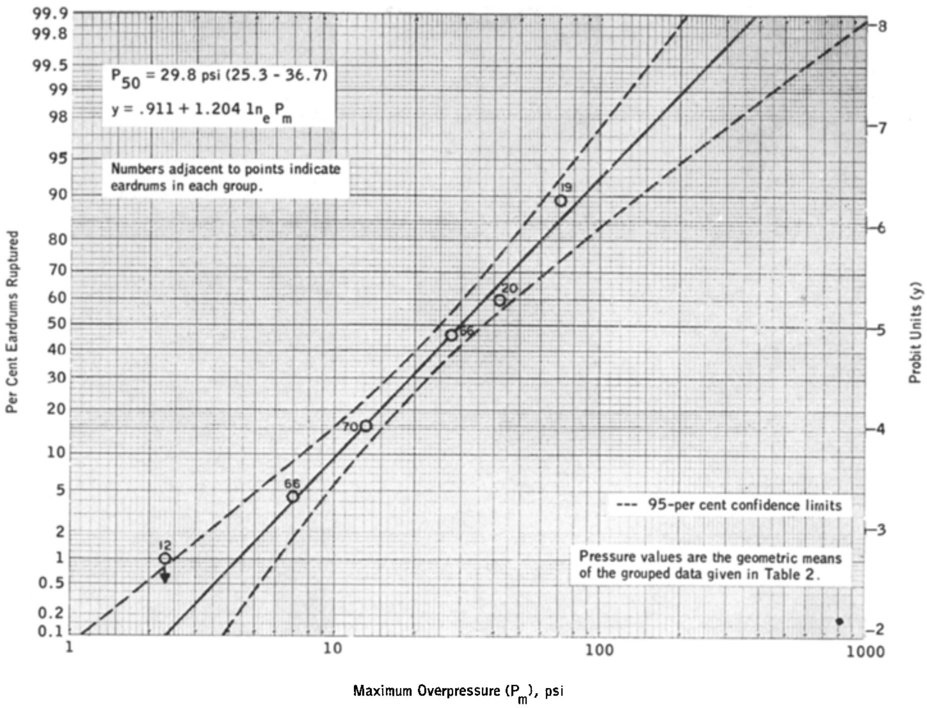


Fig. 25. Grouped data showing the response of canine eardrums exposed in field operations to a variety of 'atypical' blast waves; ambient pressure, 12.5 psi. (Weighted geometric mean overpressures used for all groups.)

spread in the 95% confidence limits reflected, among other things, the lack of experimental data for the overpressures below the P_{50}.

Also, as shown in Table IV, the responses of the up- and downstream ears of the goats were different; e.g., 33 of 40 (82.5%) for the right side facing the blast wave and 23 of 39 (59.0%) for the left side. Because the eardrums themselves might be regarded as 'biological pressure transducers' which were responding appropriately to different pressure loadings, various attempts were made to estimate the *effective* overpressures acting on each ear. Any reasonably successful effort should of course yield estimated effective pressures indicating that the responses of the two ears to overpressure were consistent with one another.

It was possible to achieve this objective by assuming: (a) the effective loading on the upstream ear was equal to the incident plus the dynamic overpressure ($P_i+Q=$ pressure loading on the right ear); and (b) the effective loading on the downstream ear was equal to $P_i\,e^{-0.26\,P_i/P_o}$, a quantity derived from information in a study by Iwanski *et al.* (1957). The data used were those applicable to pressures on the downstream side of cylinders exposed in a shock tube to overpressures of different magnitude.

Using the effective pressures estimated, probit analyses gave a P_{50} figure of 9.4 psi

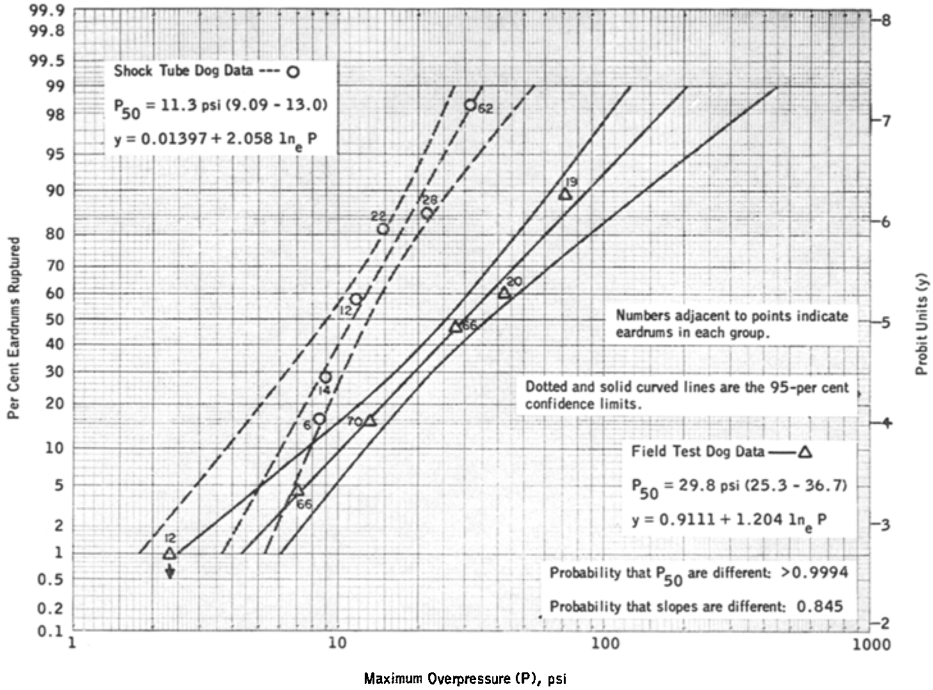


Fig. 26. Comparison of the response of canine eardrums exposed to 'atypical' blast waves in field experiments (ambient pressure, 12.5) and 'near-typical' wave forms produced using a shock tube (ambient pressure, 12.0 psi).

for the right ear and 8.4 psi for the left ear. Since the slope constants were not significantly different, a common slope was used in a subsequent analysis. The P_{50} pressures proved to be 8.1 (0.18–16.0) psi and 10 (0.25–17.4) psi for the right and left ear, respectively.

When the data for both ears were assembled and analyzed together, the probit relationship between the incidence of eardrum rupture and the computed loading for the left and right ears separately was found to be as portrayed in Figure 27. The P_{50} turned out to be 9.6 psi with a range from 3.2 to 14.0 psi for the 95% confidence limits.

(b) *'Atypical' wave forms.* Overall the percentage failure of eardrums of 18 goats exposed to the 'atypical' wave forms in foxholes was 67.6%, as noted in Table V. That this was near the overall incidence of eardrum failure of 72.2% in 9 goats exposed in the open at the same ranges seemed somewhat surprising in view of the fact that the maximum pressures measured in the foxholes, because of reflections, were higher than the corresponding maximum incident overpressures occurring free-field.

Such results might mean – on the one hand – that the foxholes altered the early portion of the pressure pulse in some way to give protection against higher overpressures that developed subsequently, or – on the other hand – that the eardrums of foxhole-exposed animals were ruptured by some component of the pulse occurring

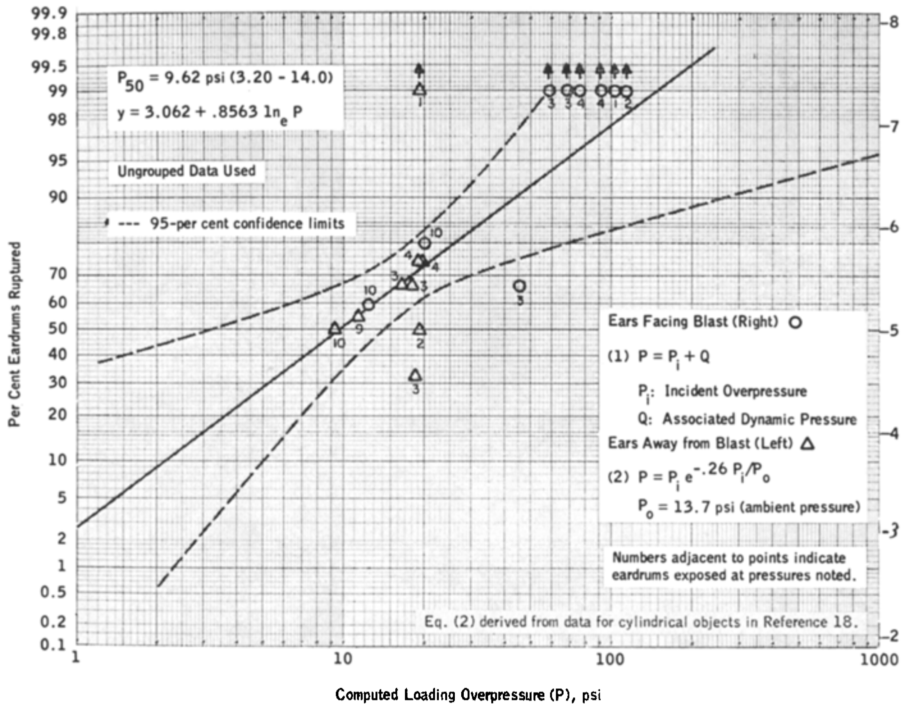


Fig. 27. Response of goat eardrums to right side-on exposures in the open to blast from a 500-ton TNT explosion showing the computed overpressures loading the upstream and downstream ears; ambient pressure, 13.7 psi.

earlier than the maximum* pressure which, due to reflection, was always somewhat delayed. In the former instance one would expect the eardrums to be responding to the maximum reflected pressure whenever it occurred, either early or delayed. In the latter case the eardrum, ruptured by an earlier-occurring but lower overpressure, would hardly 'care' about the after-coming portion of the pulse, however high the pressure might be.

An attempt was made to shed light on the problem by further analysis. First, though the data were meager, probit computations were carried out employing the data in Tables V and VI using three components of the pressure pulse; namely, (1) the overall (or delayed) maximum pressure, (2) the 'early' maximum pressure, and (3) the initial rise of the overpressure. The results for each series respectively are given from left to right in Figure 28 for data grouped as shown in Table VI. Though the confidence limits are very broad, it can be seen that the P_{50} of 8.2 psi using the initial rise of the pressure pulse is the closest to that of 9.6 psi obtained for goats in the open (Figure 27). Also, the associated slope constant of 0.6458 is nearest that of 0.8563 referable to the free-field exposures.

* Note from Figures 20, 21, and 22 that the maximum pressures recorded in the foxholes were always delayed compared with those for the 'fast'-rising, 'typical' pulses occurring free-field.

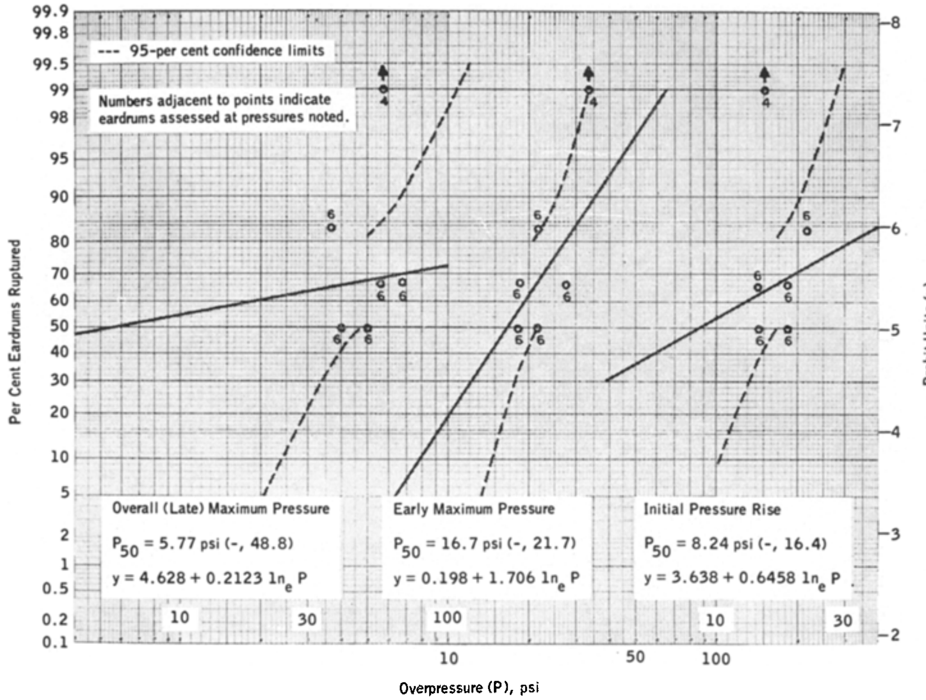


Fig. 28. Goat eardrum response in foxholes as a function of the initial, the early maximum, and the overall (late) maximum rise in the overpressure; ambient pressure, 13.7 psi.

Second, another comparison also suggesting that the eardrums of the goats exposed in the foxholes were responding to the earlier, rather than the later, components of the pressure rise was carried out. This consisted of superimposing on a log-normal plot: (a) the individual datum points given in Table VI for 'foxhole' goats, (b) the averages obtained from pairing the groups in ascending order of pressure, and (c) the probit line and 95% confidence limits referable to goats exposed in the open. The results are portrayed in Figure 29. It is clear that the best fit is shown in the left portion of the figure referable to the initial pressure rise. To the contrary, the worst fit, if it could be called a fit at all, is shown in the right portion of Figure 29 depicting datum points for the overall (or delayed) maximum rise in pressure. For the early pressure rise, four of six of the individual datum points fall within the 95% confidence limits; for the early maximum rise, the numbers were two of six, and for the maximum overall pressure, only one of six.

3. *Guinea Pigs and Rabbits*

Probit analysis of the data in Table VII referable to guinea pigs and rabbits exposed to 'atypical' wave forms occurring inside structures during field operations in 1955 and 1957 revealed results portrayed in Figures 30 and 31. The pressures used were the arithmetic averages of the maximum overpressures recorded by the wall gauges for the

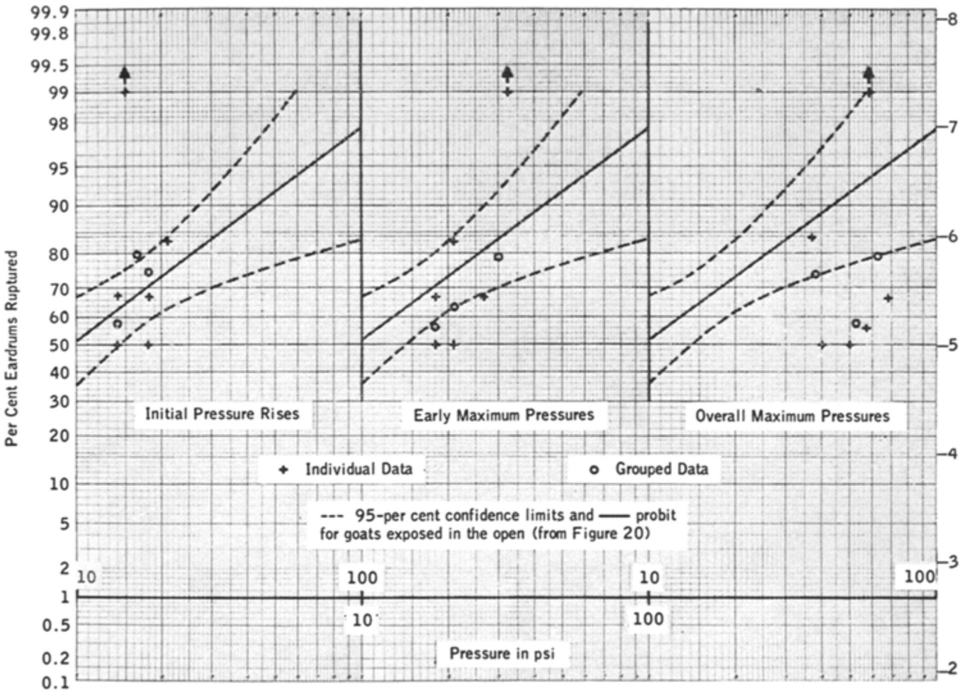


Fig. 29. Goat eardrum response in foxholes compared with probit distribution obtained for free-field exposures; ambient pressure, 13.7 psi.

rooms in whichthe animals were housed. The P_{50} for rupture of guinea pig eardrums was near 7.2 psi and 95% confidence limits ranging from about 4.8 to 20 psi. For rabbits the P_{50} was approximately 9.4 psi with 95% confidence limits from about 1.2 to 18 psi. Scatter in the results was so great in both cases that, as with the ungrouped dog data (see Figure 24), the Chi square test indicated the distributions were inconsistent and influenced by 'unaccounted for' variables. Since the proximity of animal to gauge was even much more diverse than it was for dogs, no further analytical work was attempted to clarify the small-animal results.

4. Discussion

There are several matters of considerable interest raised by the eardrum-response data reported above. Among them are five questions, the proper answers to which are not only interrelated but bear much upon the general understanding of the effects of overpressure on the eardrums of mammals. First is how to account for the almost characteristic variability in the overpressure required to rupture the eardrums among a group of animals. For example, for the shock tube-exposed dogs reported here, the figures ranged from 8.6 psi, the lowest pressure for rupture, to 34.4 psi, the highest pressure without rupture; among the dogs exposed inside shelters, the minimal pressure for

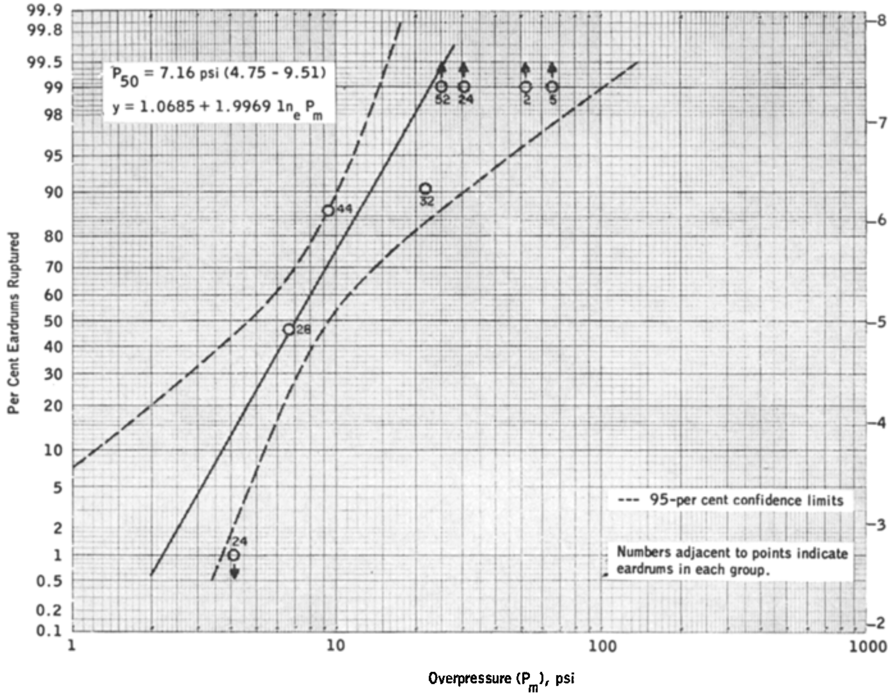


Fig. 30. Response of guinea pig eardrums exposed in field operations to a variety of 'atypical' blast waves; ambient pressure, 12.8 psi. (Data from Table VII.)

rupture was 4.1 psi and the maximal overpressure failing to rupture was 73.2 psi (White *et al.*, 1957). Even for static pressures applied to the drum of 'fresh' human cadavers by connecting a tube into the external auditory meatus, Zalewski (1906) found the minimal and maximal pressures required for rupture to be 5.4 and 43.2 psi, respectively. For 10 dogs, the corresponding figures were 9.1 and 22.8 psi (Zalewski, 1906).

Second is how to account for the apparent tolerance of the eardrum to the higher pressures. It certainly seems unlikely that a paper-thin structure, such as the tympanic membrane, is, in some instances, actually strong enough to resist a pressure as high or higher than that present in most automobile tires.

Third, there is the question about the sensitivity of the eardrum to the shape of the pressure wave; viz., all other factors being the same, is the eardrum really less tolerant to 'fast'-rising than to 'slow'-rising overpressures and, if so, how much is the difference and what time periods separate 'slow'- from 'fast'-rising pressure pulses as far as the tympanic membrane is concerned?

Fourth is the matter of pulse duration, for if there is a real effect attributable to the duration of a 'typical' blast wave, it is important to know what the shape of the curve is describing the pressure-duration relationship for the mammalian eardrum.

Fifth, there is the question of whether the eardrum always fails because it is im-

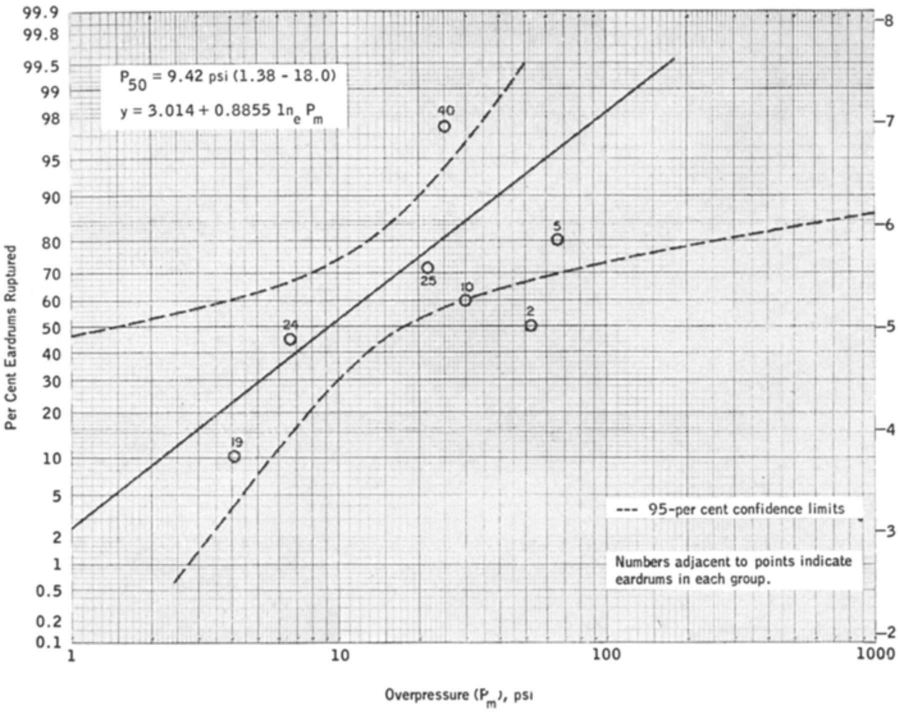


Fig. 31. Response of rabbit eardrums exposed in field operations to a variety of 'atypical' blast waves; ambient pressure, 12.8 psi. (Data from Table VII.)

pelled inwards by a pulse of overpressure or whether – weakened by this experience – it sometimes ruptures as it moves outwards during the negative phase of the blast wave.

Regarding the characteristic variability of the eardrum's response to overpressure, Zalewski (1906) has noted that age in the case of humans is an important factor. His results, portrayed graphically in Figure 32, apply to normal drums. However, scarring, calcification, infection, thickening (fibrosis), and unusual thinning of the tympanum, as well as any material present in the external auditory meatus, were all cited as recognized variables.

It is of considerable interest that the same author measured tolerance after the incus and stapes were removed and found the ossicles gave some support to the eardrum. Too, regarding position of the rupture, it was stated it may occur 'any place', though more often between the anulus tympanicus and the umbo and more frequently in the anterior (73 cases) than in the posterior (44 cases) half of the eardrum. There was an associated quantitative finding relevant to the average pressures for perforations which were higher for the anterior half (25.3 psi) than for the posterior half (20.7).

These last two findings for the very 'slow'-rising, more static type of pressure loading suggest one of three possibilities for explaining how the eardrum apparently tolerates such high pressures without rupture. If the eardrum were elastic enough to move inward until it was supported by various portions of the ossicles and the postero-

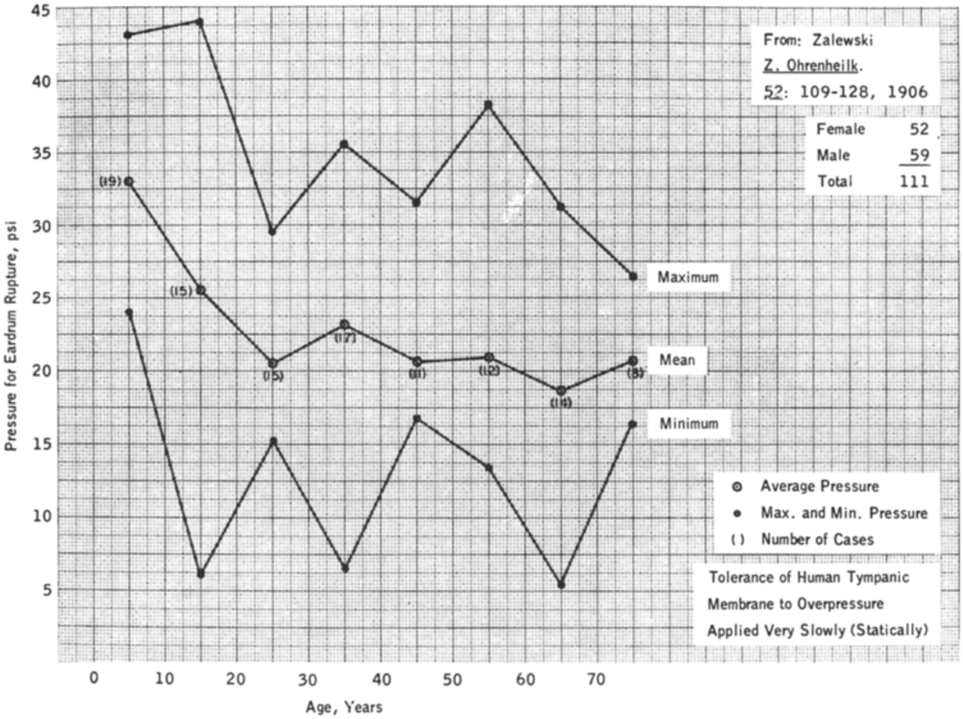


Fig. 32. Tolerance of human tympanic membrane to overpressure applied very slowly (statically).

and antero-lateral wall of the middle ear, this 'bottoming' might occur first posteriorly at a lower pressure and subsequently anteriorly at a higher pressure by virtue of an appropriate oblique position of the eardrum; viz., the anterior portion simply would have farther to move than the posterior half of the drum. If the opposite were the case because of different relative proximities of the eardrum to the middle-ear wall, the anterior portion of the drums might 'bottom' first. Then one would have another rationale for explaining why rupture occurs within the posterior rather than the anterior half of the drum. Thus those eardrums that stretch enough to 'bottom' fairly completely without rupture would subsequently have to be forced into the aditus or the bony portion of the Eustachian canal to account for failure. These can be considered as being in a 'high' tolerance group. A 'low' tolerance group could include those eardrums that were either very inelastic or those that had to move relatively far to 'bottom'. Also, sharp irregularities of the bony contents and walls of the middle ear, if present, might easily puncture the inward moving drum. So it is that drum elasticity as well as the detailed individual size and anatomy – particularly the relative distance between various portions of the eardrum, the ossicles and the lateral wall of the middle ear – emerge as critical variables not only within a given species, but no doubt among different species as well.

A second eventuality relevant to the apparent tolerance of the ear to high overpressure concerns leakage through an area of the drum thinned by progressive stretching as described by Wever *et al.* (1942). These authors noted in a study of the effects on auditory acuity of augmenting the pressure within the middle ear that when the eardrum 'ruptures under gradually increasing pressures, no obvious perforation occurs'. Rather the radial and circular fibers part at slightly different locations, the fiber layers separate and air 'leaks slowly' through the drum.

A third possibility for helping explain high-pressure tolerance involves the more dynamic application of pressure than was the case for Zalewski's studies in which pressure was applied slowly only to the external side of the drum. In response to a blast wave, the eardrum can be visualized as moving inwards fairly suddenly. A consequence of the associated decrease in volume of the middle ear would be a progressive rise in pressure behind the drum, which fact would tend to 'stiffen' the eardrum by providing support from within. The magnitude and time of this pressure rise would be governed by several factors. Among them are the rate and magnitude of the blast-produced pressure rise loading the eardrum, the volume of the middle ear plus that of the mastoid air cells and the upper bony portion of the Eustachian canal, the resistance of air flow from the middle ear through the aditus into the closed mastoid spaces and along the Eustachian canal towards the nasopharynx, and the effect – likely to be significant only for very low and 'slow'-rising overpressures – of contraction of the tympanic muscles known to respond strongly to a rise in middle ear pressure (Wever *et al.*, 1942). Air flow from the ear into the nasopharynx certainly would take an appreciable time and might very well not be much under way before the pressure pulse had passed through the mouth and/or nose and reached the Eustachian orifice in the throat.

In any event it is likely that, except for relatively high overpressures and relatively inelastic drums which would fail quickly in shear, many tympanic membranes, bolstered by the pressure rise in the middle ear, experience delay in moving inwards and, having gained time to stretch, proceed to 'bottom' and gain more substantial support as was visualized as possible for the drums loaded more slowly or statically. Though such events seem quite likely, no pertinent data are at hand. For example, there have been no known attempts under dynamic conditions to obtain pressure-time records simultaneously from the middle ear and the external auditory meatus; nor have there been attempts to visualize (photograph) the concurrent response of the drum under such instrumented conditions.

While the present study suggests that the eardrums of dogs are more tolerant to 'atypical' than to 'typical' blast waves, the findings reported on goats exposed in the open and in foxholes imply one should assess the influence of the shape of the pressure pulse carefully before making a judgment about the importance of the rate of pressure rise; i.e., 'fast' components in the early portion of the rising pulse, if high enough, may be the important parameter, vitiating any relative significance of a maximal pressure developing subsequently no matter what the magnitude of the latter may be. Though one might conclude on the basis of the data reported here that it is highly probable the eardrum will respond differently to 'fast'- than to 'slow'-rising pressure pulses, the information at hand does not allow a firm opinion about which physical parameters of an 'atypical' wave form are critical for eardrum rupture. Further, the authors are not aware of any published data establishing dose-response relationships for the tympanic membrane to pressures rising to a maximum at various rates, to pressures increasing in a stepwise manner, and to pressures incorporating both 'fast' and 'slow' components in the wave form. Thus one must look to the future for the needed definitive studies. No doubt these will come about only when experiments are designed to reveal which descriptors of the pressure-time curve are not only appropriate physical parameters for describing the pressure load on the eardrum, but are also discriminating enough to be of aid in differentiating and explaining various kinds and levels of biologic response, be the latter eardrum or ossicle failure, acute temporary disturbance in hearing, or damage of a more chronic and permanent kind.

Though there are theoretical reasons for expecting the eardrum to tolerate higher overpressures if the duration of the pulse is 'short' rather than 'long' as pointed out by von Gierke (1968), the observations applicable either to 'large' or 'small' animals offered above apply only to 'long'-duration waves. While the analysis of the somewhat stepwise increase in pressures associated with the goats exposed inside foxholes suggests that the time period that is critical for the rising phase of the pressure pulse may be measured in a fraction to several milliseconds rather than a few tens of milliseconds, the results are not directly germane to the discussion of the duration parameter mentioned above. Somewhat helpful are a few data on sheep exposed to 'fast'-rising overpressures of 'long'- and 'short'-duration generated by a shock tube and high explosives, respectively (Richmond *et al.*, 1966c). At 21.4 psi, 38% eardrum rupture was noted; the pulse duration was about 120 msec. There were no ruptures noted at 32.4 psi, the duration of the overpressure being 5.7 msec.

Applicable also is the report of Blake *et al.* (undated) that among humans exposed to bombing in Britain an estimated pressure of about 50 psi was associated with 50% eardrum rupture. For ordnance used in World War II, the pulse durations probably ranged from a few to several milliseconds and hardly ever up to many tens of milliseconds. Likely to be more useful, however, are the human studies under way in Great Britain (Coles and Rice, 1966; Coles *et al.*, 1967) and the work of the U.S. Army scientists (Chaillet *et al.*, 1964) at the Aberdeen Proving Grounds. Both groups are paying increasing attention to pressure variations emanating from the muzzles of small arms, mortars, and other items of modern artillery. Their interest includes the effects of single and multiple exposures on the eardrum and upon the hearing mechanisms as well.

Of the five questions raised in the early part of the discussion, there remains the one concerning possible rupture from outward movement of the eardrum during the negative phase of the blast wave. No doubt this possibility is a real one, particularly if the drum is weakened by trauma experienced during the positive portions of the pressure pulse. This possibility has been noted elsewhere (White *et al.*, 1957) and various pressure figures have been published; e.g., Wever *et al.* (1942) noted outward rupture of the tympanic membrane of cats at a pressure as low as 50 mm Hg (0.96 psi), saying the average lay around 80 mm Hg (1.55 psi). Armstrong (1952) cited 100–200 mm Hg (1.9 to 3.8 psi) as the range for humans whereas Frenzel (1950) placed the figure at 160 mm Hg (3.1 psi). Such figures are generally lower than the overpressures associated with inward rupture of the drum noted above and by other authors (White *et al.*, 1957; Hirsch, 1966). Why this is true poses yet another question, the proper answer to which might very well be the absence of any external support for the eardrum comparable to that given by the ossicles, the bony walls of the ear cavity and the rise in middle-ear pressure postulated as effective under dynamic response of the drum to blast overpressure. If this is not the explanation for the facts cited, the authors are at a loss to propose another plausible one.

By way of further discussion, it seems necessary to note that the pressure responses of the eardrum incorporate more complexities and variables than have already been mentioned. These include orientation with respect to the blast wave; the shape, length and other dimensions of the external auditory meatus; the angular orientation of the eardrum in the external meatus; the increase in pressure known to take place as the wave proceeds inward toward the drum (Golden and Clare, 1965); possible influences of the pinna of various animals acting as a 'valve' to protect the ear; the presence of 'solid' and 'soft' obstructions such as wax in the external canal which may protect or act as a projectile damaging the drum depending upon circumstances; and the very real matter of the accumulative effect of multiple exposures. Beyond the mere failure of the drum or lack of it, there is the matter of damage to the ossicles, production of temporary and permanent hearing loss and perhaps even difficulty due to malfunction of the vestibular portions of the inner ear; viz., ataxia is often a symptom of acute blast injury which may be peripheral or central in origin, possibly a combination of both.

Though it may be difficult to apply animal data to the human case, it is nevertheless unfortunate that more studies with small and large mammals have not been carried out. With the improvements in instrumentation and technology now available and a more enlightened conceptual grasp of the significant parameters at play, the authors feel that a great deal of progress lies ahead for those willing to do the tedious intraspecies work to learn how the external and middle ears of different animals function in transmitting energy to the sensitive portions of the inner ear. It is already clear that progress will require detailed anatomical observations to learn, for example, why it is that the eardrum of the rabbit has been reported by Blake *et al.* (undated) to have a 50% rupture pressure of near 2.2 psi. This figure, obtained during exposures of animals to 'typical', 'short'-duration overpressures emanating from small charges of high explosive, is well below the 9.4 figure found in rabbits exposed inside structures at the Nevada Test Site to a variety of 'long'-duration, 'atypical' blast waves. Even though the 2.2-psi value is within the 95% confidence limits for the field data*, the difference may be real and the rabbit eardrum might well have a very low tolerance to

* See Figure 31 for the probit curve.

blast overpressure compared with some other mammals. If this were true, it would reinforce the belief that the rabbit, unlike the dog and goat, indeed has an eardrum very susceptible to injury by overpressure. A likely explanation could lie in differences in eardrum elasticity and in a critical variation in the size and shape of the middle ear and its contents as suggested in previous portions of the discussion. Should this indeed prove to be the case, it would help establish ground rules to guide the detailed search for a mammalian ear likely to bear important similarities to that of man.

Finally, it is important clinically to learn much more about the relation between blast damage to the ear and to the animal as a whole. While it is true – and many are aware of it – that the ear has a low threshold for damage from overpressure, it does not follow that persons exposed to blast who have intact eardrums should be considered free of internal injury due either directly to overpressure or indirectly to impact involving debris or whole-body translation. Indeed, the tympanic membrane has such a wide range of tolerance that pressures high enough to injure the lung severely and pose a serious threat to life may, on occasion, not even rupture either eardrum. This fact is not well known. The otoscope is no substitute for the stethoscope. The condition of the eardrum in blast casualties is not much of a guide for the clinician and this truth needs considerable emphasis.

5. Summary

(1) Dose-response relationships were determined for the tympanic membranes of dogs, rabbits, and guinea pigs exposed inside various structures to a variety of 'long'-duration, 'atypical' blast waves. Typical figures for the P_{50}, the pressure associated with 50% failure of the eardrums were: 29.8 psi (25.3–36.7) for dogs; 9.2 psi (1.4–18.0) for rabbits; 7.2 psi (4.8–9.5) for guinea pigs.

(2) In the case of dogs exposed to 'long' duration but 'near-typical', shock tube-produced overpressures, the P_{50} for eardrum failure proved to be 11.3 psi (9.1–13.0).

(3) The P_{50} for the eardrums of goats, exposed side-on in the open to 'long'-duration, 'typical' pulses from a 500-ton HE detonation, was 9.6 psi (3.2–14.0) when the loading for each eardrum was estimated separately.

(4) Goats exposed inside foxholes of two designs experienced essentially the same incidence of eardrum rupture as did animals exposed in the open at the same range even though the maximum pressures measured inside the foxholes were considerably above the free-field pressures.

(5) An attempt was made to understand the above finding by relating the incidence of eardrum rupture with various portions of the pressure-time curve recorded inside the foxhole. Three P_{50} values were obtained: for the overall maximum pressure, 5.8 psi; for the early maximum pressure, 16.7 psi; and for the initial pressure rise, 8.2 psi.

(6) These data along with a comparison of the grouped datum points with the probit distribution limits estimated for goats exposed in the open indicated the eardrums in foxhole-exposed animals were probably responding to the early, 'sharp'-rising components of the pressure pulse. However, the association of eardrum response

with the proper parameter of the pressure pulse for 'atypical' wave forms cannot be handled in a straightforward manner at the present time.

(7) All data along with selected information from the literature were discussed in some detail. The characteristic variability of the mammalian eardrum's response to overpressure was pointed out as was the 'high' and 'low' tolerance noted in different species. A conceptual explanation to account for these variations was proposed.

(8) While the goat and dog results indicated the eardrum was probably more sensitive to 'fast'-rising than to 'slow'-rising blast waves, the data were insufficient to prove rigorously either this was the case or to say what might be expected for blast waves with both 'slow' and 'fast' components having different magnitudes and time constants.

(9) Theoretical and empirical data from the literature were cited which suggest, all other things being equal, that the eardrum is more tolerant of 'short'- than of 'long'-duration blast waves.

(10) Because of the wide tolerance limits of the tympanic membrane, failure of the eardrum or lack of it was not considered a reliable clinical sign for judging the severity of a blast injury. This stems from the fact that the drum often remains intact when exposure pressures produce serious lung injury, but may also rupture at pressures well below generally hazardous ones.

Acknowledgements

The authors are grateful to Dr. E. Royce Fletcher for help with the probit and related evaluations; to Mr. Wilmer R. Kerzee and the staff of the Department of Biomathematics and Computer Systems for processing the data; to Mr. Robert A. Smith and others in the Medical Illustration Department for aid with the illustrative material; to Dr. Donald E. Kilgore, Jr., Dr. Emanuel M. Roth, Dr. Frederic G. Hirsch and Dr. Richard L. Masters for comments on the manuscript, to Mr. Fred C. Rupprecht, Miss Mildred E. Blake and Mrs. Ruth P. Lloyd for editorial assistance.

The research was conducted according to the principles enunciated in the *Guide for Laboratory Animal Facilities and Care*, prepared by the National Academy of Sciences-National Research Council.

This work was supported by the Defense Atomic Support Agency of the Department of Defense by Contract DA-49-146-XZ-372 and by the Division of Biology and Medicine of the U.S. Atomic Energy Commission under Contract AT (29-1)-1242, both with the Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico. By permission of the Defense Atomic Support Agency, this report, with minor changes, was taken from document DASA-2064 (White *et al.*, 1967) wherein appear references to the original data collected over the years beginning in 1953 under support of the AEC and DASA.

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