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Air Blast Studies With Animals II

by
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FOREWORD

This investigation was authorized under Project 4C99-02-022, Wound Ballistics, (U), and was supported by the Armed Forces Special Weapons Project (AFSWP), now the Defense Atomic Support Agency. The experimental work was started in March 1958 and was continued until April 1959. The experimental data are recorded in notebook MN-687.

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DIGEST

The damage to be expected in man from exposure to long-duration blasts is important because of the threat of fission or fusion bombs, and is not well known. As a result of previous work, the large shock tube at the Ballistic Research Laboratories, Aberdeen Proving Ground, was judged suitable, after modification, for obtaining additional information.

The velocities of goats (under Nembutal) and a dummy blown from the shock tube were measured under various conditions. At a given tube stage and overpressure, the major variable determining the velocity was the initial orientation of the goat or dummy. The distance thrown was related in a fairly regular way to the velocity.

Goats exposed to shots in the shock tube at overpressures of 8 lb/sq in. (plateau), 10.4 lb/sq in. (peak), suffered broken bones or death in about one-third of the cases when they were so oriented that they were displaced at velocities of 40 to 78 ft/sec. Ear damage and perhaps some lung damage occurred as a result of the pure blast as such at these pressures, but other broken bones and death were produced primarily by displacement so far as could be judged. In the shock tube, the threshold for serious injury, apart from the ear damage, was, therefore, much lower for displacement than for pure blast. When displacement was minimized or prevented by appropriate side chambers, as was feasible for small animals, the threshold pressure for death increased severalfold, and death of mice was produced by pure blast.

Shelters are thus of great importance in the field, and position of a man if in the open is also important. The more quantitative use of tube data in the field is handicapped by lack of proof that consistent measurements of dynamic pressure were made under different conditions. This lack is of particular importance, because the dynamic-pressure impulse, an important factor in displacement, may have quite different relations to overpressures in the tube and in the field. One set of pressure measurements suggests that the impulse may even be larger for a given overpressure in the tube than in the field.

The interrelation between maximum velocity during displacement and probability of injury over different terrains have been discussed.

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AIR BLAST STUDIES WITH ANIMALS II

I. INTRODUCTION.

Previous work done with the Aberdeen Proving Ground (APG) shock tube¹ had as a major purpose the testing of the tube as a suitable instrument for studying potential injury to man by atomic blasts. It was found that animals exposed to blast in the tube under certain circumstances did suffer severe, even fatal, injuries. All the indications suggested that, apart from ear damage, the injuries to goats in the 4-foot section of the tube occurred primarily as a result of displacement, and the same was true for some mice and rabbits even in side chambers. Additional injuries at comparable pressures in the field caused by pure blast could not, however, be ruled out, because tube conditions were different from field conditions. Substantial overpressures were of very short duration at the end of the 4-foot section, where photography was possible, and they were still relatively short, even inside that section. The APG laboratory, therefore, modified the shock tube to increase the duration of overpressures and to permit photography inside the open end of the tube.

In the subsequent work, because displacement had been such an important part of the injury picture, an anthropomorphic dummy was exposed in the tube as also were goats (under Nembutal) and mice. Even though estimates of injury to the dummy were not attempted, physical measurements were made. The earlier work on goats was extended, goat displacement under the modified tube conditions was studied, and qualitative observations were made during the periods of the overpressure and dynamic pressure.

The much longer duration blast wave in the modified tube, while producing ear damage presumably by pure blast, again seemed to produce the most serious injuries to goats in the 4-foot section primarily by displacement. Thus, threshold pressures for producing serious injury by displacement were, under shock-tube conditions, lower than those for comparable injury by pure blast. In the high overpressures, off the 2-foot section of the tube, conditions were found that uniformly produced a substantial proportion of deaths of mice without permanent displacement. These deaths were apparently caused by pure blast.

II. METHODS AND MATERIALS.

The animals used were anesthetized, castrated, male, Angora goats from Texas, presumably at least 5 years old, and CF1 male mice

from Carworth Farms. The goats were clipped shortly before the experiment, and, in most cases, their horns were cut to a length of about 3 or 4 inches. The mice in most cases weighed from 24 gm to 32 gm but the extremes were 18 gm and 34 gm.

The 50th-percentile anthropomorphic dummy, 5 feet 9 inches tall and weighing 165 pounds, was of the general type frequently used by the armed services. It was furnished by the Alderson Company as model P1-50. It was clothed in a cotton jacket and trousers, both olive green - 107. Where it is so indicated, the dummy wore various items of equipment in the usual manner or the equipment was placed by itself on the bottom of the tube. The equipment consisted of: a steel helmet with detachable strap and a liner; an M1 rifle, M9 protective mask, pistol belt with canteen, cup, and canteen cover; a combat field pack containing mess kit and filler, suspenders, combination entrenching tool, and carrier; and a horseshoe roll containing a shelter half, blanket, poles, etc.

The location of the shock tube with respect to the grassy pasture over which the animals were blown remained essentially unchanged. A concrete apron was extended beyond the end of the tube, but in the goat experiments, which were carried out following this change, the animals were protected against striking the bare concrete by canvas-covered straw.

A number of important modifications were made in the shock tube for the recent work. The 2-foot-diameter cylinder forming the high-pressure chamber was lengthened from 36 feet to 55 feet. The 4-foot-square section on the open end of the tube was increased from the 30-foot length, at which almost all of the initial work with goats had been done, to 58 feet. The 58 feet include two 4-foot-long test sections which carry 18-inch-square ports in the middle of each panel. The ports are normally fitted with steel plates, but these can be replaced with glass or Lucite plates. The lengthening of the high-pressure chamber increased the duration of the overpressures at a given point. The longer 4-foot-square section permits placing animals a foot or two farther from the adapter section leading to the 2-foot-diameter tube, yet also much farther from the open end of the 4-foot-square section than previously. Effects from the open tube end, therefore, take longer to reach the animal.

The ports permit photographic observations inside the tube while the animals are exposed to the shock wave and to overpressures of relatively long duration as compared to sites outside the open end of the tube. One port in each 4-foot-long section was used for a camera. Light from a bank of 28 photoflood lamps, drawing about 7.5 amps per bulb, shone through another port usually at right angles to the camera port. Figure 1 shows the

two cameras on top of the tube with the boxes containing the lights covering the side ports. Further improvement of the lighting was attained with a Signal Corps searchlight, drawing about 50 amps, that was placed in the field 115 feet from the end of the tube and shone directly into it. The searchlight was protected from flying objects, such as diaphragm fragments, by a screen placed in front of it. The searchlight had its own generator, and a second portable generator supplied the heavy current required for a few seconds by banks of light bulbs. Since the cameras ran for only 1 or 2 seconds after reaching a speed of 1000 to 1500 frames per second, it was necessary to synchronize very carefully the lights and cameras with the firing of the tube. Wollensak Fastax and Eastman high-speed cameras were used, each equipped with an internal timing light operated by a 100-cycle generator. A flash bulb was placed in the field of view of each camera. The bulbs were triggered by the arrival of the shock front 6 feet upstream from port A. (The first and second ports reached by the shock front are called A and B, respectively.)

In an intermediate stage of tube modification, during which a number of experiments were performed, the compression chamber was at its original length of 36 feet and the 4-foot-square section was 44 feet long with only one set of ports. Timing in these experiments was by a special argon lamp, on 60-cycle house current, placed in the camera field of view. For convenience, the several tube dimensions are summarized in table 1.

The animals or dummy were placed near the upstream edge of port A, except for a few instances in which they were near the center of the port.

The velocities were calculated by measuring on movie film the times required for the animal to pass between various points. These points were: from port A to port B; across port B; from ports A, and B to the open end of the tube; and between points 5 feet apart, immediately outside the open end of the tube. The velocities obtained from port A to the end of the tube and port B to the end of the tube are undoubtedly the values that are the freest from random errors of measurement, including those dependent on the exact distance of the goat from the camera, because the travel distances of 36 feet and 32 feet, respectively, are the longest. Deceleration certainly occurred to some extent in both cases, however, so that the values probably tend to be less than maximum. The values from port A to port B are relatively free of deceleration, but acceleration may have occurred in some cases, depending on the initial position of the animal. The velocity across port B would, in principle, be the best, but it was very difficult to estimate velocity of an irregular, twisting object such as a goat over such a short distance. The velocity outside the open end of the tube was, in general, observably less than that between port A, or port B, and the end.

Unfortunately, because of experimental difficulties of which fog was by far the most serious, the several values for velocity were not obtainable in many of the individual experiments. Also, measurements were made on various portions of the animals and this pattern varied from experiment to experiment. Therefore, no uniform method has been applied to all experiments in obtaining the velocity values given. These values represent the best estimate that could be made of the velocity of the main mass of the goat (center of gravity) from the measurements that were available from each experiment. In general, the measurements of velocity made between two points outside the open end of the tube were not considered in the average.

One very serious difficulty in many experiments was the appearance of a dense fog a short time after the shock front had passed. It was apparently a condensate of water, in spite of condensers placed ahead of the compression chamber, and it was caused by the low temperature of a late phase of the wave. The fog often appeared in a diphasic manner with a relatively clear period between the two first peaks of density. Although variable, in a number of experiments it appeared at the port somewhat more than 0.1 second after the shock front had passed. The fog arrived in time to blot out the dummy and even goats, in some instances, while they were still within range of the first port. More photographic observations were lost at the second port. Fog had often been observed before, but it had interfered less, in part because of the times and places of photography.

Figures 2, 3, and 4 show pressure curves furnished by Mr Ross of the shock-tube group at APG.² The pressures had been measured with gauges at the location of the goats in the 4-foot section of the tube.² The curves represent nominal 10, 20, and 30 lb/sq in. shots in the 2-foot section of the tube. In the 4-foot section, the peak side-on overpressures were 4.7, 8.0, and 11.1 lb/sq in., respectively. On the other hand, the side-on pressures during the early portion of the "plateau" were 3.2, 6.2, and 8.0 lb/sq in. When additional earlier measurements, two at 20 and three at 30 lb/sq in., were averaged with the measurements from figures 2, 3, and 4, the peak side-on overpressures, for nominal 10, 20, and 30 lb/sq in. shots in the 2-foot section, were 4.7, 7.5, and 10.4 lb/sq in. in the 4-foot section (table 2). The averages of the early plateau side-on pressures were 3.2, 6.1, and 8.0 lb/sq in. The average early plateau side-on overpressures will be used to designate the blast pressure in a given experiment, unless otherwise specified, although this does not mean that the peak pressure may not be significant. One would expect the physical parameters most closely related to pure blast effects and to displacement to be different.

TABLE 1
TUBE DIMENSIONS

Phase of Work	Length			Distance	
	High-pressure chamber	2-foot-diameter tube	4-foot section	Port A to open end	Port B to open end
Initial ¹	36	189	ft 30	—	—
Intermediate	36	189	44	22	—
Final	55	189	58	36	32

TABLE 2

PRESSURE RELATIONS BETWEEN THE 2-FOOT AND 4-FOOT
SECTIONS OF THE TUBE

2-foot section	4-foot section	
Nominal pressure	Peak side-on overpressure	Early plateau side-on pressure
lb/sq in.	lb/sq in.	
10	3.6*	2.7*
	4.7	3.2
20	7.8	5.9
	5.3*	4.5*
	6.7	6.3
	8.0	6.2
Average	7.5	6.1
30	10.8	7.8
	10.2	8.4
	9.5	7.8
	11.1	8.0
Average	10.4	8.0

* Omitted from average.

FIGURE 1

ONE ARRANGEMENT OF CAMERAS AND LIGHT BOXES
AT PORTS IN TEST SECTION OF TUBE

FIGURE 2

PRESSURE-TIME CURVES IN 4-FOOT SECTION FOR A NOMINAL
10-LB/SQ IN. SHOT IN 2-FOOT SECTION

(P_{side} indicates curve for side-on overpressure;
P_{stag} indicates curve for stagnation or total overpressure.)

FIGURE 3

PRESSURE-TIME CURVES IN 4-FOOT SECTION FOR A NOMINAL
20-LB/SQ IN. SHOT IN 2-FOOT SECTION

(P_{side} indicates curve for side-on overpressure;
 P_{stag} indicates curve for stagnation or total overpressure.)

FIGURE 4

PRESSURE-TIME CURVES IN 4-FOOT SECTION FOR A NOMINAL
30-LB/SQ IN. SHOT IN 2-FOOT SECTION

(P_{side} indicates curve for side-on overpressure;
 P_{stag} indicates curve for stagnation or total overpressure.)

The average dynamic pressure and the impulse were obtained from the differences between curves of the total (stagnation) and side-on pressures.

For the work with side chambers, the same two cylinders were used as in the earlier experiments.¹ One cylinder was 32 inches long; the other was 12 inches long. The diameters were 8 inches in both cases. One end of each cylinder was closed by a plate; the other end was threaded. The threaded end was fitted into a threaded opening in the side of the 20-inch-square test section of the main shock tube so that the long axis of the cylinder was horizontal and at right angles to the axis of the shock tube. The mouse cage was, in form, a segment of a cylinder slightly under 8 inches in diameter and about 1 1/4 inches in length. It was constructed of 1/4-inch wire mesh and contained six separate compartments; one mouse was placed in each compartment. The cage was held at the desired location within the chamber by a steel rod passing through the center of the cage and the chamber end plate.

III. RESULTS.

A. Injuries in Goats.

Results with respect to lethality are given in table 3. Of 33 goats (32 under Nembutal) exposed to the full effects of 8.0 lb/sq in. (early plateau) overpressures at the animal, seven died within a few hours. Six of these animals were exposed when the ground was frozen, and two were killed. Of the seven killed, three were initially suspended broadside to the oncoming blast while four were on the floor of the tube, three with back-in, one with feet-in. In addition to the animals killed, three animals had bone fractures. All were initially broadside, two in the intermediate-tube phase. Two additional animals, not included above, were killed by missiles peculiar to the shock tube. In one case, the missile was a piece of the metal diaphragm used to contain the high pressure; the blood-stained metal was found nearby. In the other, the missile was a block of wood anchored in the tube by preceding investigators in connection with their tests. Both animals suffered large penetrating wounds. One died within a minute or two, and the other was sacrificed at once. All of the other 26 animals survived until they were sacrificed for autopsy; 10 after a few hours on the day of the experiment and 16 after 48 hours.

TABLE 3
LETHALITY IN GOATS

Blast pressure, early plateau	Initial orientation	Fraction of animals killed or partially paralyzed	
		2nd and 3rd tube stage	1st tube stage
lb/sq in. 8.0	Broadside	3/12*	4/14
	Broadside	0/5**	—
	Head- or rump-in	0/3***	0/7
	Feet-out	3/7	2/3
	Feet-in	1/6	0/3
	Total	7/33	6/27
6.1	Broadside	0/7	—
	Head-in	0/1	—
	Feet-out	0/2	—
	Feet-in	0/3	—
	Total	0/13	—

* One animal had the frontal bone fractured; another was fatally injured by a wooden block and is not included.

** Intermediate stage of tube. Two of these animals had multiple rib fractures. A port blew out in one experiment, and that animal is omitted.

*** One additional animal was fatally injured by a fragment of the metal diaphragm and is omitted.

The most common injury found at autopsy* in these goats was bruising of different parts of the body. The bruises ranged in severity from discoloration to hemorrhages of various sizes, usually limited to subcutaneous tissues, but in some instances extended into the underlying tissues. Injuries of the ear drums were recorded in about 50% of the animals autopsied after 8.0 lb/sq in. blasts. One or both ear drums were involved, with openings ranging from pinpoint holes to complete loss of the ear drum. In three goats the malleus was injured. Several animals had other bone fractures; two had fractured skulls. Injuries were also found in the lungs and, less frequently, in the brain, liver, heart, kidneys, spleen, and peritoneal cavity as indicated by some degree of hemorrhage or laceration in these areas. The immediate causes of death were anatomically demonstrable at autopsy in, at most, three animals; these injuries were of the sort to be expected from deceleration. All seven animals died in less than 1.5 hours post blast.

In a general way, the results on the most serious injuries support the earlier findings¹ (before the tube was modified). Of the three goats that were initially head-in, the position for minimal displacement, none suffered incapacitating injury or death. Combining the results with those from the first tube stage, we have for death or partial paralysis 7/31 broadside, 5/10 feet-out, 1/9 feet-in, and 0/10 head-in or rump-in, or a total of 13 out of 50 at velocities of 40 to 78 ft/sec. Ear injuries were reported more frequently than in the earlier series of animal tests made before modification of the tube. The possible role of the tube walls in producing experimental damage cannot be assessed readily, but it must be kept in mind because many of the animals had obviously hit the walls with considerable force.

Of 13 animals exposed to overpressures of 6.1 lb/sq in. (20 lb/sq in. in the 2-foot-diameter section), none were killed even though a few of the animals were blown beyond the end of the tube; i. e., more than 36 feet. The same absence of lethality was observed at smaller pressures down to about 2 lb/sq in. One animal was exposed to pressures of 6.1 lb/sq in. twice within half an hour. After recovering from the Nembutal the animal stood and moved about in a relatively normal manner. A second animal was exposed three times at 5 lb/sq in., three times at 3.4 lb/sq in., and once at 2.2 lb/sq in. during a few hours without being incapacitated when it recovered from the Nembutal.

B. Goat-Lung Weights.

Previous work¹ mentioned that the goats killed by blast in a number

* Autopsies were performed by members of the Wound Assessment Branch.

of cases had heavier-than-average lungs at autopsy, but that the possibility of post mortem changes had not been eliminated since the animals were in all cases refrigerated overnight. Additional experiments having the same type of result have been accumulated more recently as shown in table 4. The animals that were sacrificed immediately before autopsy had combined lung weights averaging 0.99% of body weight. On the other hand, four animals that died as a result of the experiment but which were also refrigerated overnight before autopsy showed combined lung weights averaging 2.06% of body weight. One animal sacrificed by electrocution, but kept overnight, also showed heavy lungs.

Arrangements were, therefore, made to blast 12 animals and to perform autopsies the same day on 6, including any that were killed. The other six were electrocuted and placed in the refrigerator overnight before autopsy. As shown in table 5, the lung weights of animals handled on the day of death were 0.59% and 0.43% of body weight for the right and left lungs, respectively. On the other hand, the lung weights of animals kept overnight after death were 1.10% and 0.72% of body weight for right and left lungs. The differences, therefore, depend, at least for the most part, on the time elapsing between death and autopsy, rather than on the death of the animal as a result of the experiment.

In six animals, three from each of the immediate- and delayed-autopsy groups, a large number of other organs were weighed. The liver, spleen, and thyroid showed suggestive, but not statistically significant, differences.

Again, in this series of experiments at overpressures of 8.0 lb/sq in. (plateau), 10.4 lb/sq in. (peak) (figure 4) we have failed to find evidence that the overpressure through pure blast effects contributed greatly to the serious injury of any goat, although, of course, "failure to find" does not constitute proof. Some of the small amounts of edema and hemorrhage in goat lungs and probably much of the ear damage observed at autopsy may have resulted from pure blast.

C. Lethality in Mice.

A great decrease in deaths among mice, exposed to nominal 30-lb/sq in. blasts, was previously observed¹ when they were placed in a small rectangular side chamber attached at a right angle to the long axis of the expansion chamber of the shock tube. The purpose of the side chamber was to protect against displacement, but it also decreased the abruptness of the pressure change. By decreasing the volume of the chamber, the rise time for

TABLE 4
LUNG WEIGHTS OF GOATS HELD FOR SHORT AND LONG TIMES
BETWEEN DEATH AND AUTOPSY

Animal		Lung weight		Lung weight X 100 Animal weight		Time between death and autopsy	Remarks
Number	Weight	Right	Left	Right	Left		
	kg	gm				hour	
13019	31.8	170	160	0.53	0.50	0.1	Electrocuted
13020	30.0	220	135	0.73	0.45	0.3	Electrocuted
13021	36.6	165	115	0.45	0.31	0.2	Electrocuted
13026	35.2	200	150	0.57	0.43	0.3	Electrocuted
13018	29.7	320	290	1.08	0.98	20	Died from blast
13022	33.8	435	255	1.29	0.75	17	Died from blast
13027	35.0	525	410	1.50	1.17	20 to 24	Died from blast
13028	30.0	285	150	0.95	0.50	20 to 24	Died from blast
13029	33.0	355	380	1.08	1.15	20 to 24	Electrocuted

TABLE 5

LUNG WEIGHTS OF GOATS HELD FOR SHORT AND LONG TIMES
BETWEEN DEATH AND AUTOPSY

Animal		Lung weight		Lung weight X100		Time between death and autopsy
Number	Weight	Right	Left	Animal weight Right	Left	
	kg	gm				hour
Group 1						
13030	36	180	140	0.50	0.39	<0.3
13031	38	205	155	0.54	0.41	<0.3
13032	38	275	170	0.72	0.45	<0.3
13039	29	170	135	0.59	0.47	1.4*
13040	31	240	155	0.77	0.50	1.6*
13041	35	150	115	0.43	0.33	<0.3
	Average			0.59	0.43	
Group 2						
On right side during refrigeration						
13033	38	510	240	1.34	0.63	19
13034	37	430	275	1.16	0.74	19
13035	36	455	260	1.26	0.72	19
On left side during refrigeration						
13036	32	390	245	1.22	0.77	20
13037	39	285	265	0.73	0.68	20
13038	33	300	260	0.91	0.79	20
	Average			1.10	0.72	

Note: Animals of group 1 were exposed in the blast tube, killed, and autopsied on the same day. Animals of group 2 were exposed in the blast tube, were killed on that day, and autopsied on the following day after overnight refrigeration.

* Died from blast effects.

the pressure was decreased to about 5 msec. Cylindrical side chambers were also used, but, although some protection was given, many animals were killed when blown out of the chamber. These experiments were completed in 1956, and it has since been reported^{3, 4, 5} that the lethal effects of sudden increases in pressure were very dependent on the time, when the time required for the change was of the order of 1 msec. In Richmond's experiments, at the Lovelace Foundations,⁵ the animals were placed near the end of the closed shock tube so that they were exposed to both a primary and a larger reflected pressure wave. The time for the maximum pressure change was varied by varying the distances of the animals from the blind flange, since the distance determined the separation in time of the primary and reflected waves.

It seemed possible that death among mice in our cylindrical side chamber on the open-end, APG shock tube might also depend on the animal's position with respect to the end plate of the chamber, in view of pressure measurements in chambers,⁶ even though the high pressure during reflection was of relatively short duration. A number of unanesthetized mice were, therefore, placed in a cage that had one side against the end plate in one set of experiments, and the same side of the cage 4 inches away from the end plate in another set of experiments. The centers of the mice and of the cage were about 0.5 inch and 4.5 inches away from the end plate in the two types of experiments. Table 6 shows the results with nominal 30-lb/sq in. blasts as measured in the main shock tube. Notice that in the long side chamber, 14 of 24 animals were killed when they were against the end plate, but none of 18 were killed when they were placed 4 inches from the end plate. In the latter position, the cage was bent somewhat by the blast.

The behavior of the animals following the blast was fairly typical. Death occurred within less than 10 minutes, and often, within less than 5 minutes, in all but three of the animals that were killed. Most of the animals that were to survive indefinitely were initially quiet with fast respiratory rates. The fatally injured animals had slower, and ultimately intermittent, respiration, and many also showed intermittent violent muscular movements. After death many showed blood on the nose.

Pressure measurements were made by the shock-tube group in both side chambers with a gauge at the blind-flange end of the chamber. In the 32-in. chamber, a side-on gauge was also placed 12 inches from the blind flange in some shots. Pressure tracings are shown from these two sites in figures 5 and 6 for nominal 30-lb/sq in. shots. The mouse cage was 4 inches (figure 5) and 0 inch (figure 6) from the closed end of the chamber.

TABLE 6
LETHALITY IN MICE

Length of side chamber in.	Fraction of mice killed	
	0 inch from end	4 inches from end
32	14/24	0/18
12	7/24	—

Mean plateau pressures* at the end gauge ranged from 44 to 46 lb/sq in. in six experiments. In four experiments the gauge 12 inches from the end had lower plateau pressures of 39 to 41 lb/sq in. The steeply rising major reflected pressure reached this gauge at about 1.8 msec after the response to the primary pressure wave and the time was constant to 0.1 msec. This represents the travel time to the end of the chamber and back, a distance of 2 feet. With the cage placed 4 inches from the flange, the time between primary and reflected waves at the animal is estimated to be about 0.7 msec. In the same four experiments, the maximum of the reflected wave followed the primary wave at the side-on gauge in from 2.0 to 2.7 msec. Presumably 0.7 to 1.0 msec separated the primary wave from the maximum of the reflected wave at the mice placed 4 inches from the blind flange.

The location of the cage containing the six mice modified the form of the pressure-time curve in a number of ways. For instance, the time to the maximum reflected pressure, shown by the gauge in the blind flange, is longer with the cage at 4 inches than at 0 inch. Also, the sharpness of the reflected pressure rise as measured 12 inches out is greater in the latter case.

D. Mice Autopsy Results.

The mice that had been killed did not show permanent displacement or any evidence of gross injury from deceleration connected with temporary displacement, so the lung weights were of particular interest. Table 7 shows the lung weights of these mice. The animals killed had much heavier lungs

* Peak pressures ranged from 52 to 58 lb/sq in. at the blind flange and from 46 to 49 lb/sq in. 12 inches away.

FIGURE 5

PRESSURES IN 32-INCH SIDE CHAMBER WITH MOUSE CAGE
4 INCHES FROM THE CLOSED END

FIGURE 6

PRESSURES IN 32-INCH SIDE CHAMBER WITH MOUSE CAGE
AGAINST THE CLOSED END

than the survivors in the same experiments. It was necessary, as in the case of the goats, to distinguish weight changes produced by the blast from post-mortem changes, since the time to autopsy was, in some cases, overnight. As can be seen from table 7, groups of unexposed animals, in which lung weights were determined at various times after death from an intraperitoneal overdose of Nembutal, showed only minor changes in lung weight. It is therefore concluded that, unlike the changes found in goats, most of the changes in lung weights in the animals killed in the shock tube were caused by the blast rather than by post-mortem changes. Although microscopic data are far from complete, so far the killed animals show lung hemorrhage. It is reasonable to suppose that these mice died from pure blast effects rather than from displacement.

TABLE 7
LUNG WEIGHTS OF MICE

Animal condition	Combined lung weight, percent of body weight	Number of animals
Killed by the experiment	2.1	23
Survived the experiment	1.1	26
Nonfatal experiment	0.8	18
Unexposed animals killed by overdose of Nembutal. Time between death and beginning of autopsy:		
<10 minutes	0.6	6
2.5 hours	0.6	6
5 hours	0.7	6
22 hours	0.7	6
Control animals from Clemmedson ⁷	0.6	50

E. Displacement and Velocities, Goats, Dummy and Equipment.

Various orientations of the animals with respect to the oncoming blast showed typical responses to it. In figure 7 the early motions of a goat when the shock wave (8.0 lb/sq in.) passed it are illustrated by a series of frames taken from a movie film of an animal initially 1 foot from the end of the tube in its first phase. Notice that different parts of the animal accelerated at very different rates. For instance, the massive trunk lagged behind the legs. It can be seen readily that the straps, which supported the animal, blew off the hooks immediately and, hence, produced no swinging motion. The initial airflow had essentially stopped before the goat disappeared from the view of the camera.

Inside the tube, animals placed on the bottom, with the long axis across the tube, showed very different movements depending on whether their feet were directed toward the wave or away from it. Figure 8 (camera looking down) shows the displacement of the skin and the abdominal wall when the blast wave struck an animal lying on its side with its feet toward the wave. From such an orientation the goat was still close to the tube floor when it passed the second port 4 feet downstream from the first port.

On the other hand, figure 9 shows the result when the animal's back was initially toward the blast. The goat immediately turned through 90° so its back was toward the camera. By the time it had reached the second port, only 4 feet away, it was so close to the top of the tube that only its feet were visible through the side port. During a forward motion of only 4 to 5 feet, it showed an upward motion of at least 3 feet. A goat placed head-in is shown in figure 10.

The distances that the goats were displaced by the blast depended, of course, on the pressure and the initial orientation of the animal. The results for the final stage of the tube are shown in figure 11, using early-plateau side-on pressures. The points for the two larger pressures represent the average for a number of animals. Since it seemed of some interest to observe events at very low pressures, two anesthetized goats, 37 kg and 33 kg in weight, were exposed repeatedly with their long axes across the tube, and one was exposed in the head-in position. With feet-in or feet-out at 3.3 to

3.5 lb/sq in., there were permanent movements of the main body mass of a few inches to over 1 foot and slight pivoting. Only at approximately 2 lb/sq in. was there no appreciable permanent displacement of the animal as a whole. With head-in, the position of minimum presented area, at 6.1-lb/sq in. over-pressure, the animal pivoted through 90° and moved a few feet. At 3.5 lb/sq in., the trunk moved a few inches without pivoting. A shot at 4.9 lb/sq in. gave an intermediate result. There was, thus, not a sharp division between no movement and substantial movement, but a gradual increase of permanent displacement with increased pressure.

The velocities to which the animals were accelerated by the blast were measured as described above. The results from various initial orientations in the intermediate and final stages of the tube are given in tables 8 and 9. The great importance of the initial orientation is again evident. When the area presented to the blast wave was the smallest, head-in position, the velocity was also the smallest. The greatest velocity was given to the goat when it was initially broadside to the direction of the blast wave.

The animals were blown from the tube at higher average velocities from each of the four initial orientations, and on the average they traveled somewhat greater distances than in the first tube phase. This result was expected since the longer high-pressure chamber delivers blast waves of longer duration. It is of interest, although it may not be significant, that the least increase in velocity caused by the increased duration of the wave occurred in the case of the animals placed broadside where the presented area decreased with time. The greatest increase in velocity occurred in the head-in position where the presented area had the chance of the greatest increase. The 30 animals exposed to the highest-pressure shots in the intermediate and final tube stages with their long axes across the tube (not all listed in tables 8 and 9) were thrown distances of from 59 to 151 feet and attained velocities, in the 17 available instances, between 51 and 78 ft/sec.

Comparison of the 8.0-pound with the 6.1-pound shots shows that the velocities reached by the animals in the broadside and feet-out orientations were decreased in the lower-pressure blast to approximately one-half, but in the feet-in position the decrease was to about one-third.

Of the animals killed, velocities were obtained on four, and the average was about 59 ft/sec. The average for all animals at the maximum pressures, except those in the head-in position, was about 62 ft/sec.

FIGURE 7

MOVEMENTS AS BLAST WAVE PASSES GOAT

(The interval between each successive picture is about 10 msec)

FIGURE 8

GOAT EXPOSED TO 8.0-LB/SQ IN. SHOCK WAVE WITH FEET
INITIALLY TOWARD THE ONCOMING BLAST

(Interval between pictures about 10 msec; first picture of
sequence in lower left-hand corner; read up)

FIGURE 9

GOAT EXPOSED TO 8.0-LB/SQ IN. SHOCK WAVE WITH FEET
INITIALLY AWAY FROM ONCOMING BLAST

(Interval between pictures about 10 msec; first picture of
sequence in lower left-hand corner; read up.)

FIGURE 10

GOAT EXPOSED TO 8.0-LB/SQ IN. SHOCK WAVE WITH HEAD
INITIALLY TOWARD ONCOMING BLAST

(Interval between pictures about 10 msec; first picture of
sequence starts in lower left-hand corner, read up)

FIGURE 11

SHOCK-WAVE OVERPRESSURE AND AVERAGE DISPLACEMENT OF GOATS
FROM DIFFERENT INITIAL ORIENTATIONS

TABLE 8
DATA ON GOATS EXPOSED IN SHOCK TUBE

(Intermediate stage of the tube)

Goat no.	Weight	Presented area	Pressure			Goat orientation	Velocity of goat	Distance goat was thrown
			Nominal in 2-foot section	Early plateau in 4-foot section	Peak in 4-foot section			
	kg	sq ft		lb/sq in.			ft/sec	ft
8828	38.0	—	10	3.2	4.7	Broadside	—	0
8829	42.0	—	20	6.1	7.5	Broadside	—	24
8830	44.0	3.89	30	8.0	10.4	Broadside	55.8	84
8831	42.0	3.58	30	8.0	10.4	Broadside	50.7	87
8832	45.0	3.82	30	8.0	10.4	Broadside	55.8	75
8826	42.0	—	30	8.0	10.4	Broadside	—	59
8827	36.5	—	30	8.0	10.4	Broadside	—	67
Average*	41.9	3.76	30	8.0	10.4	Broadside	54.1	74

* Shots at 8.0 lb/sq in.

TABLE 9
DATA ON GOATS EXPOSED IN SHOCK TUBE

(Final stage of the tube)

Goat no.	Weight	Presented area	Pressure			Goat orientation	Velocity of goat	Distance goat was thrown
			Measured in 2-foot section	Early plateau in 4-foot section	Peak in 4-foot section			
	kg	sq ft		lb/sq in.			ft/sec	ft
13009	37	—	30.3	8.1	10.5	Broadside	—	151
13010	41	3.58	29.6	8.0	10.3	Broadside	77.7	124
13011	41	3.39	29.6	8.0	10.3	Broadside	67.6	125
13013	46	4.01	30.4	8.1	10.5	Broadside	65.6	113
13014	48	4.04	30.4	8.1	10.5	Broadside	65.2	114
13015	32	3.98	30.6	8.1	10.6	Broadside	66.4	102
13017	40	3.73	30.9	8.2	10.7	Broadside	65.8	107
13028	30	3.32	30*	—	—	Broadside	64.7	99
13029	33	3.87	30*	—	—	Broadside	65	98
13030	36	—	30*	—	—	Broadside	—	114
13034	37	—	30*	—	—	Broadside	—	96
Average	38.3	3.74	30.3	8.1	10.5	Broadside	67.3	113
13018	32	1.21	30.7	8.2	10.6	Head-in	25.7	47
13019	32	1.21	30.0	8.1	10.4	Head-in	31.5	54
13031	38	—	30*	—	—	Head-in	—	40
13035	36	—	30*	—	—	Unanesthe- ized; feet crossed and tied	—	40
Average	34.5	1.21	30.4	8.2	10.5	Head-in	28.6	45
13020	28	1.51	30.7	8.2	10.6	Feet-in	63.3	113
13021	38	1.80	29.7	8.0	10.3	Feet-in	55.5	93
13027	35	1.79**	30*	—	—	Feet-in	59.9	91
13032	38	—	30*	—	—	Feet-in	—	94
Average	34.8	1.70	30.2	8.1	10.5	Feet-in	59.6	98
13016	37	1.91	30.6	8.1	10.5	Feet-out	58.7	96
13022	35	1.93	29.7	8.0	10.3	Feet-out	54.4	91
13023	40	1.98	29.0	7.9	10.1	Feet-out	—	78
13026	38	1.91	30*	—	—	Feet-out	56.5	71
13033	38	—	30*	—	—	Feet-out	—	92
Average	37.6	1.93	29.8	8.0	10.3	Feet-out	56.5	86
13001	36	3.63	21.2	6.4	7.9	Broadside	29.7	39
13002	36	3.70	21.3	6.4	7.9	Broadside	30.2	31
13003	41	3.34	20.6	6.3	7.7	Broadside	28.3	30
13004	38	4.32	20.9	6.3	7.8	Broadside	28.9	25
13005	33	3.50	22.2	6.6	8.2	Broadside	38.7	58
13024	32	3.57	20*	—	—	Broadside	26.8	35
Average	36	3.68	21.2	6.4	7.9	Broadside	30.4	36
13006	39	1.97	20.5	6.3	7.7	Feet-out	27.6	33
13008	33	1.77	20.8	6.3	7.8	Feet-out	26.4	24
Average	36	1.87	20.7	6.3	7.8	Feet-out	27.0	29
13007	36	1.85	20.6	6.3	7.7	Feet-in	20.5	21
13008A	33	1.63	20.2	6.2	7.6	Feet-in	17.4	14
13025	31	1.55**	20*	—	—	Feet-in	17.4	22
Average	33.3	1.68	20.4	6.3	7.7	Feet-in	18.4	19

* Nominal pressure, not included in the average.

** Estimated from average of animals on wt-area graph.

Individual values of velocity are plotted in figure 12 against the total distance that the animal was thrown. The animals were in several different orientations, varied as to weight, and the experiments were done at two different tube pressures, 8.0 and 6.1 lb/sq in. Also, animals from the first series of experiments¹ are included. There is perhaps no real justification for putting all of the data gathered under quite different conditions and without regard to weight on the same graph, but no very striking systematic differences seem to appear. A curve, concave upward, has been drawn through the points, since it must necessarily go through the origin. Apart from that, the points themselves may be represented by a straight line corresponding to the equation: $\text{velocity} = 8.7 + 0.565 \times \text{distance}$. The random variations are, of course, considerable, but in an unknown case in the tube; some semiquantitative idea of maximum velocity could be obtained from the distance that animals had been thrown. It is much more important that the data also show that for our terrain there was a quite regular relationship between the distance displaced and the velocity. Displacement, which is always easily obtainable, may, therefore, be used for some analytical purposes in place of velocity. It must be noted that in our experiments most of the displacement occurred after the maximum velocity had been reached.

The data on velocities must be related to some general physical characteristic of the shock wave that produced them if they are to have applied usefulness. The goat velocity in a given experiment was the result primarily of a high-velocity wind acting for a short time. The wind velocity is related to the dynamic pressure as follows: $\text{dynamic pressure} = 0.5 \times \text{the air density} \times \text{the air velocity squared}$. The dynamic pressure is the difference between the total pressure and the side-on pressure. Measurements of the latter two pressures were furnished by the shock-tube group and are shown in figures 2, 3, and 4. The dynamic-pressure impulse was estimated by graphic integration under the plot of dynamic pressure versus time obtained from these and other records. In all of these cases the gauge measuring total pressure was in the tube center. If the forces caused by the wind acting on the goats were proportional to the dynamic pressure at all times, and if the goats all had the same mass, the goat velocities would be related in a regular way to the impulses. Obviously, such conditions were not met by our data, yet a plot of the estimated impulses for the initial and final stages of the tube at particular pressures against the average of the velocities given to goats in particular initial orientations (figure 13) shows features not easily

explained by known deviations from the conditions mentioned. For instance, the velocities corresponding to the lowest impulse, 8.0-lb/sq in. shot in the first tube phase, were much larger than the 6.1-lb/sq in. experiments in the third tube phase, although the impulse of the former was slightly smaller. The irregularities are not small, and large changes in velocities or impulses would be required to bring the first tube-phase data and final tube-phase data into line.

The force, which acted on a goat at a given dynamic pressure, depended on a number of factors, including the presented area of the goats, which in turn, depended on the initial orientation. Also, the presented area, even from a given initial orientation, changed with time. Yet, animals in three different initial orientations showed the same type of difference between the first and final tube phase. It seems unlikely, therefore, that the explanation lies in a variable relation between the force acting on the animal and the dynamic pressure.

The groups of goats varied in weight between averages of 35 and 45 kg. The groups placed broadside averaged within 2 kg of each other, while the goats used in the final stage in the feet-in and feet-out orientations averaged 5 and 6 kg lighter. These differences are, in part, compensated for by the relation of presented area to weight, and certainly the differences cannot be an important factor in the major features shown in figure 13.

When the animal is at rest, the wind velocity with respect to the animal is the same as the absolute wind velocity. When the animal begins to move, the significant velocity is the difference between the wind velocity and the goat velocity; this difference also would be a factor in the relation of force on the goat to dynamic pressure. An exact estimate of the difference between air velocity and animal velocity throughout the blast wave cannot be made at the present time because the air velocity in the "cold-gas"* phase of the wave is unknown according to the shock-tube group. The goat velocity, however, was certainly a small fraction of the air velocity during most of the duration of the positive dynamic pressure, and it is difficult to see how relative, in contrast to absolute, air velocity could be an important factor in the anomaly shown in figure 13. Also, if the cold-gas portion of the dynamic pressure was different in the first and third phase of the tube, the gauge measurements should take care of it provided the difference between the side-on and total-pressure gauges represented the dynamic pressure at all temperatures.

* The air that was initially in the compression chamber.

FIGURE 12

DISTANCE OF ANIMAL AND DUMMY DISPLACEMENT
PLOTTED AGAINST VELOCITY

FIGURE 13

VELOCITY VERSUS IMPULSE

(Pressure was expressed in lb/sq ft when the impulse was calculated.)

Systematic errors in the velocity measurements also were possible. As a check on this, the acceleration of gravity on a sphere, which was exposed to a blast during the intermediate tube stage, was calculated. Only one set of data was suitable for the calculation since in some cases the spheres showed upward movements initially, and only in this one were data available after the passage of the shock wave was complete. The value calculated for acceleration due to gravity was 30.5 ft/sec/sec compared to the standard value of 32.17 ft/sec/sec. This is a reasonable check of the timing and length measurements through the photographic system, since the observations on the sphere covered only a few inches of actual fall.

Another test of the velocity data is shown in figure 14. It is based on the same data as in figure 12, but, instead of plotting individual experiments, averages of experiments having a common initial orientation, pressure, and stage of the tube were plotted. This was also the basis for the grouping of animals in figure 13. No support is given to the idea that gross errors in the velocity data are responsible for the curious impulse-velocity relation of figure 13, since, with the exception of the head-in measurements, none of the points are more than a relatively few feet per second off a smooth curve. Head-in experiments are not included in figure 13.

The movement of an anthropomorphic dummy, 50th percentile type, when the blast wave passes over it, is illustrated by the sequence of frames in figures 15, 16, and 17. The contrast with the movement of goats was striking. In the dummy there was none of the flexibility of the goat, and the dummy merely slid stiffly down the tube floor with slight rotational and tipping tendencies. The clothing was whipped about vigorously, and in some cases, at the highest pressures, it was torn. In many cases the clothing clung very closely to the dummy and would in this way modify somewhat the presented area. Such changes were probably minor compared to the contour changes of the goat, but this need not be true of man. Potentially, any type of clothing subject to ballooning can be imagined as increasing the presented area strikingly for brief periods.

The distances by which the dummy was displaced and the velocities which it reached during the higher pressure shots are shown in table 10. The velocity-distance data are plotted in figure 12.

FIGURE 14

VELOCITY VERSUS DISTANCE GOATS WERE THROWN

(Individual points represent average values for a given orientation, tube pressure, and stage of tube.)

FIGURE 15

PRONE DUMMY EXPOSED TO 8-LB/SQ IN. SHOCK WAVE

(Dummy's head toward oncoming blast; first picture of sequence in lower left corner. Read up.)

FIGURE 16

SEATED DUMMY EXPOSED TO 8-LB/SQ IN. SHOCK WAVE

(Dummy's right side toward blast; first picture of sequence in upper left corner.)

FIGURE 17

PRONE DUMMY CARRYING EQUIPMENT, EXPOSED TO
8-LB/SQ IN. SHOCK WAVE

(Dummy, head toward blast; first picture of sequence
in lower left corner. Read up.)

TABLE 10
DATA ON DUMMY EXPOSED IN SHOCK TUBE

Expt no.	Weight	Presented area	Pressure			Dummy orientation	Velocity of dummy	Distance dummy was thrown
			Measured in 2-foot section	Early plateau in 4-foot section	Peak in 4-foot section			
	kg	sq ft		lb/sq in.			ft/sec	ft
2847	165	1.26	29.7	8.0	10.3	Prone, head-in, arms at side	9.7	8
2893	165	2.12	29.5	8.0	10.2	Prone, head-in, arms up near head	15.1	8
2894	165	2.80	29.5	8.0	10.2	Prone at angle, head-in, arms up near head	—	11
2895	165	2.12	29.5	8.0	10.2	Prone, feet-in, arms up near head	19.5	18
2896	165	2.80	29.5	8.0	10.2	Prone at angle, feet-in, arms up near head	24.4	20
2897	165*	2.85	29.8	8.0	10.3	Prone with pack, head-in, arms up near head	—	23
2898	165*	2.85	30.1	8.1	10.4	Prone with pack, feet-in, arms up near pack	22.6	22
2849	165	4.09	29.7	8.0	10.3	Sitting, back-in	26.1	29
2922	165		29.3	7.9	10.2	Sitting, back-in	30.2	33
2850	165	4.55	29.7	8.0	10.3	Sitting, right side in	57.2	71
3101	165	4.55	29.5	8.0	10.2	Sitting, right side in	—	71
3102	165	4.55	31.4	8.3	10.8	Sitting, right side in	—	66
3103	165	4.55	30.4	8.1	10.4	Sitting, right side in	42.3	67
3105	165	4.55	29.5	8.0	10.2	Sitting, right side in	45.5	70
2851	165	4.09	29.7	8.0	10.2	Sitting, face-in	—	96
2923	165	4.09	29.0	7.9	10.1	Sitting, face-in	48.0	73
3104	165	4.09	28.6	7.8	10.0	Sitting, face-in	34.9	58
2899	165*	5.56	30.1	8.1	10.4	Sitting with pack, right side in	52.5	82
2920	165	4.42	28.4	7.8	9.9	On right side, face-in	66.7	84
3106	165	4.42	30.4	8.1	10.4	On left side, face-in	45.5	72
2919	165	4.42	28.4	7.8	9.9	On right side, face-out	33.6	42
2921	165*	—	29.5	8.0	10.2	On right side, face-out, with pack	49.6	59

* In addition to the weight of the dummy, the equipment initially carried by it weighed about 27 pounds in experiment 2897, from 20 to 25 pounds in experiments 2898 and 2899, and about 37 pounds in experiment 2921. A rifle was included in the last three experiments. Various portions of the equipment were separated from the dummy during the blast in each experiment.

For the prone positions, at 4.8-lb/sq in. pressure (table 11), the displacement varied from only 0.2 foot to 1.3 feet, while at 6.1 lb/sq in. it ranged from 1 foot to 4 feet. The dummy in the prone position was also placed at a 25 to 30 degree angle with the direction of blast. The 4.8 - and 6.1-lb/sq in. shock waves, in addition to moving the dummy downstream, rotated it in such a way that the long axis of the dummy tended to become parallel to the tube axis with the feet moving more than the head.

TABLE 11
DATA ON A DUMMY EXPOSED IN THE SHOCK TUBE

(Low-pressure shots)

Expt no.	Weight	Pressure			Dummy orientation	Distance dummy was thrown
		Measured in 2-foot section	Early plateau in 4-foot section	Peak in 4-foot section		
	lb		lb/sq in.			ft
2793	165	10.4	3.4	4.8	Prone, head- in, arms at side	0
2794	165	15.2	4.8	6.2	Prone, head- in, arms at side	0.2
2795	165	15.6	5.0	6.3	Prone at angle, head-in, arms at side	0.8
2796	165	20.1	6.1	7.6	Prone, Head- in, arms at side	0.8
2797	165	20.3	6.2	7.6	Prone at angle, head-in	2.0
2797A	165	20.2	6.2	7.6	Prone, head- in, arms up near head	3.5
2798	165	15.5	5.0	6.3	Prone, head- in, arms up near head	1.2
2799	165	15.7	5.0	6.4	Prone, feet- in, arms up near head	1.3

TABLE 11 (contd)

DATA ON A DUMMY EXPOSED IN THE SHOCK TUBE

(Low-pressure shots)

Expt no.	Weight	Pressure			Dummy orientation	Distance dummy was thrown
		Measured in 2-foot section	Early plateau in 4-foot section	Peak in 4-foot section		
	lb		lb/sq in.			ft
2800	165	20.3	6.2	7.6	Prone, feet-in, arms up near head	2.6
2848	165	19.9	6.1	7.5	Seated, back-in, legs extended	4.0

The displacement, at various pressures, of equipment placed at port A on the floor inside the tube is shown in figure 18.

F. Accident Records.

It has been suggested¹ that, since severe damage to man would result from displacement at high velocities by blast, it is desirable to relate the probable damage in a given case, by two steps, to some physical characteristics of the blast wave, such as pressure or impulse. First, the velocity of displacement of a dummy can be related to blast characteristics as has been described above. Second, it may be possible to obtain from other sources, such as accident data, the probability of serious injury to man during deceleration from various velocities. A related study of one aspect of the problem, i. e., the conditions necessary to produce skull fractures, has been conducted at the Cornell Aeronautical Laboratory.⁸ For the general case, a survey is needed of situations where velocities, rates of deceleration, and injuries are known. Since this type of information might be useful in various directions, and because, in view of the numbers of accidents, it could, in principle, furnish very reliable data, a good deal of time has been devoted to looking for it. Although at first glance many think that an abundance of material exists, as for instance in automobile-accident reports, information of the proper sort, so far, does not appear to be readily available.

FIGURE 18
DISPLACEMENT OF EQUIPMENT

The auto-crash-injury research group under Mr John L. Moore at the Cornell University Medical School was contacted in 1957 through the courtesy of the late Dr Eugene F. DuBois. Exceptionally complete reports are made to them of automobile accidents in particular areas. The reports include estimates of car speeds as well as many other conditions of each accident. The information is placed on punch cards and analyzed in various ways. It is not known definitely what information, if any, could be obtained from these reports suitable for blast-injury analysis. Special sortings of the cards would be required to find out and, so far, no arrangement for doing this has been possible with the government sponsors of their program.

Falls are another type of accident in which important physical factors may be defined. The height of fall gives some measure of the velocity at the moment of impact on the floor, road, or sidewalk, and estimates of the height are often given in reports, although it is realized that these estimates may be very rough. The surface of impact is often known and this, in many cases, makes certain that the deceleration rate was very high. The injuries are defined in reports of the accidents. But, in addition to the numbers of injuries, one needs to know the total number of accidents within which the injuries described occurred. It is the last item which offers the greatest difficulty. Public health records and individual case records in the medical examiner's office in Baltimore, in the central police files, in the state health department, in the Bureau of Labor Standards, Washington, D.C., in the office of the state of Maryland Industrial Accident Commission, in the safety office of a military installation, in the first-aid office of a large industrial concern, and in an accident insurance office, have been examined in large numbers.

Public health reports are based on the numbers of persons that had injuries of a certain type or on injuries that resulted from a particular situation. The data of the state health department on fractures from home falls do not show the fraction of falls that resulted in fractures, but they show that the great majority of fractures from falls at the same level, i. e., to the floor, occurred in older persons. The central files of the police include nonfatal and nonserious accidents, but they are not classified in any way that is useful to us, so a large number of case records must be screened for every usable one. Also, and much more serious, it was stated that the records were but a small proportion of those available in other offices. This means that an unknown amount of selection had been exercised on an unknown basis.

Accident reports available from the medical examiner's office cover only those accidents which resulted in death. For instance, a series of

20 fatal falls described in the files in the medical examiner's office showed 13 that had serious nonhead injuries and 11 that had skull fractures; some had both. In the first group, the heights of fall ranged from an estimated 15 feet to 45 feet, corresponding to terminal velocities of 31 to 54 ft/sec. The average height among the first group, where estimates were available, was about 31 feet, corresponding to 46 ft/sec at impact. The individuals concerned were from 25 to 66 years old, with three over 50.

The estimated heights for the 11 skull fractures ranged from 4 to 45 feet, corresponding to velocities of 16 to 54 ft/sec. In the case of the 4-foot level, the terminal velocity of the head could have been more than the 16 ft/sec corresponding to that height depending on the precise way in which the fall occurred. The average height was 25 feet, corresponding to 40 ft/sec. The deceased were from 25 to 70 years old, with six over 50.

No statement can be made directly from this type of data on the proportions of serious injuries or deaths that would occur from sudden stoppage at various velocities. One valid conclusion can be drawn; namely, that at speeds in the range of 31 to 54 ft/sec, fatal injuries from nonhead damage were about as frequent as from head injuries. This suggests that, within this range of velocities, orientation on striking the surface becomes a much less important factor in injury than at lower velocities, and that serious injury (or death) will occur in a high proportion of cases if the surface is hard enough to cause rapid deceleration. This corresponds to striking rock, walls, etc, in the blast case.

Other possible source of information from accidents are official records of compensation cases. The Bureau of Labor Standards in Washington, D. C., has a large number of individual case histories of injuries to maritime workers to whom compensation was paid. Descriptions of falls were taken from their individual records and grouped according to the estimates of the distances fallen. In table 12, the fraction of the total compensation cases represented by the sum of fractures, permanent total disability, and deaths are shown. Similar data on falls were obtained from individual case records of the Maryland State Industrial Accident Commission, and these also are shown in table 12.

From both sources it is evident that there is little relation between the proportion of fractures or other serious injuries and the height of fall, except for the greatest heights. At estimated heights of 21 to 40 feet (36 to 51 ft/sec striking velocity), 11 of 13 people in the two series showed such injuries. It is obvious from common experience that the fractions of serious injuries from low-level falls in compensation cases do not apply to falls in general.

TABLE 12
FRACTION OF COMPENSATION-CASE FALLS THAT RESULTED IN FRACTURE,
PERMANENT DISABILITY, OR DEATH

Source of information	Injuries versus falls from various heights				
	5 feet or less	6 to 10 feet	11 to 20 feet	21 to 40 feet	45 feet
Maritime workers Bureau of Labor Standards	9/14 (0.64)	11/23 (0.48)	9/16 (0.56)	7/7 (1.0)	
Maryland State Industrial Accident Commission	17/45 (0.38)	12/25 (0.48)	4/13 (0.31)	4/6 (0.67)	1/1
Combined	26/59 (0.44)	23/48 (0.48)	13/29 (0.45)	11/13 (0.85)	

Note: Figures in parentheses denote decimal fractions equivalent to the respective ratios.

The lack of correlation between the number of serious injuries and the height of fall in the three lower groups was probably not a coincidence caused by the small number of cases; i. e., it occurred in two completely independent sets of records and, therefore, it did not seem worthwhile to extend the series. In retrospect, it seems clear that the suitability of the records for our purpose was decreased by the almost inevitable selection in obtaining the original records. This is contrary to the opinion of advisors familiar with compensation cases. That only a fraction of accidents appear in the compensation cases was shown by the internal evidence. Only a small proportion of the cases that we recorded failed to show lost-time claims of at least several days. Yet the summarized reports on shipyard repairmen showed that, only one accident case in four lost time, while for longshoremen it was one in two. An examining physician estimated that, in his experience, three out of four lost no time. Under some circumstances, at least, the proportion may be even higher, as will be evident below. If the proportion of accidents that did not cause a loss of time and did not result in a claim was inversely related to height of fall, a reasonable supposition, a result such as is shown in table 12 could occur. Other possibilities for distortion or selection exist in the reporting of the original data, but these need not be considered until this major and obvious difficulty has been overcome. Some insurance-company records were also examined, but since the data collected suggested similar selection, the survey was discontinued.

It is possible that in the falls of 21 to 40 feet, or even 11 to 20 feet, selection was less important and the fractions have applicability to the general case.

Many installations now have health offices and first-aid stations to which all accidents are supposedly reported. Information on accidental falls was, therefore, collected from the individual case records in a military post safety office, which collects reports of accidents to both military and civilian personnel, and from records in the first-aid station of a large industrial establishment. The fractions of the falls that resulted in fractures, or unconsciousness, are given in table 13. Of the 39 civilians that suffered falls on the military post, only 5 received compensation for lost time; 2 lost a day or less without compensation. Unlike the data from compensation cases (table 12), data from the "5-foot-or-less" group show a small proportion of serious accidents except in the military group and support the interpretation of the compensation results as due to selection. One wonders if perhaps the significantly ($p < .01$) larger proportion in the military group may not again have been caused by poor sampling. Were they less likely than the civilians

to report ground-level falls did not result in injury?

TABLE 13

DATA ON FALLS THAT CAUSED FRACTURES OR UNCONSCIOUSNESS

Source of information	Injuries versus falls from various heights		
	5 feet or less	6 to 10 feet	11 to 20 feet
Military Post Safety Office (civilian)	2/39	—	—
Military Post Safety Office (military)	6/24	—	2/3
Industrial First-Aid Station	3/111*	1/6	1/3
Combined	11/174	1/6	3/6

* Ninety out of the one hundred and eleven were falls at ground or floor level.

In any case, the data, meager though they are, suggest strongly that definitive results could be obtained in this way, provided that enough first-aid-station records in an appropriate industry could be screened. Unfortunately, the apparently most suitable company for the purpose has refused access to their records.

Parachutists⁹ descend at a rate of about 18 ft/sec depending, of course, on the parachute, their own weight, and position, and in free fall they reach a terminal velocity of 160 to 175 ft/sec. The former (18 ft/sec) is about the terminal speed of a 5-foot fall. Parachute jumps show a small percentage of serious injuries.¹⁰ In a series of 4490 jumps by about 800 men there were 121 injuries, of which 32, including 25 fractures, were serious enough to result in hospitalization. Even of these, many might have been caused by wind, which means the descent was no longer a simple fall at the velocity given above. For training in parachute jumping, the candidates were taught to jump from heights of 4 and 6 feet, landing on their feet but rolling forward. It was stated that jumps

from 11 feet were abandoned because of some injuries. The velocities on contact after 6 and 11 feet of fall are about 20 and 27 ft/sec, respectively.

As the data stand at present, in falls of 20 to 40 feet (36 to 51 ft/sec) with rapid deceleration, most (11/13) will result in fractures or other serious injury. This is supported by the data from the Medical Examiner's office that show deaths with nonskull fractures in the same range. In the 11- to 20-foot range, 26 to 36 ft/sec, we have 9/16, 4/13, and 3/6 for the maritime employees, the Maryland state industrial accidents, and the first-aid groups, respectively. The first two should be maximum fractions, because they represent compensation cases, and the last is too small a group to be more than suggestive.

Sporting events furnish some information on injury rates under lower rates of deceleration. Figures were found for the Maryland Hunt Cup,¹¹ a 4-mile race. During the period under consideration, the average winning time for the race was about 9 minutes. Between 1931 and 1954, 53 horses and riders fell at the jumps. Of these, 10 riders remounted. At least seven of the horses were injured seriously enough so that they were killed. A few riders were injured, but information on them is less available, and, of those injured, some were injured by the horse and, hence, are not relevant for this purpose. Lacking specific information on the horizontal velocities at the jumps, let us assume that it was the same as the average for the whole race, about 27 mph or 40 ft/sec. Considering only this forward velocity, 7/53 (13%) of the animals that fell were seriously injured when deceleration occurred by rolling and sliding over a grassy pasture. An unknown, but smaller, percentage of riders was seriously injured.

The extreme importance of slow deceleration is strikingly illustrated by ski jumpers. A few jumps have been made in this country for distances of about 300 feet. The take-off speed for such jumps is approximately 65 mph (98 ft/sec).¹² This is over one-half of the free-fall terminal velocity in air. Downhill ski racing is done at speeds that are lower but still very high, and falls do occur. Thus, we have a range of decelerating conditions from a packed-snow covered slope with the direction of travel nearly tangential to it, where injury rates are low enough when falls occur, even at 90 to 100 ft/sec, to be tolerated in a sporting event, to the other extreme of an essentially vertical drop to the ground with serious injuries beginning at one-fourth of that speed.

IV. DISCUSSION.

Only after our work on the post-mortem changes in goat-lung

weights had been completed did an earlier paper covering work done in an adjacent laboratory¹³ come to our attention.* Rabbits were used and the lung weights were found to depend on the elapsed time between death and weighing. In one series of autopsies, lung weights increased from about 0.4% to 1.1% of body weight in 4 hours. Death by exsanguination completely prevented the increase; a pressure of 30 cm of water through the trachea prevented most of it. Two of the factors responsible for the formation of pulmonary edema in the post-mortem period and, hence, the increase in lung weight were stated by the authors to be (1) the pressure gradient between the pulmonary vasculature and the alveolar spaces and (2) an alteration in capillary permeability. The latter they seemed to ascribe primarily to the presence of Nembutal in the lung capillaries. Whatever the effect of Nembutal, a change of the permeability of capillaries in general would be expected to begin no later than the cessation of the circulation and respiration. This would apply to the lung capillaries unless, because of their unique relation to a gas phase, they continue to have an oxygen supply by diffusion alone. No mention is made of possible flow within the vascular system toward the lungs. Yet in our goats the increase in weight was the equivalent of such a large volume of fluid, an average of nearly 0.3 liter per goat (table 5), that it is difficult to see how it could have been transferred into the lungs without flow. The post-mortem redistribution of blood during a period of hours was qualitatively observed many years ago by Hooker¹⁴ in the ears of cats killed by ether. No differential pressure measurements are available to us; however, if flow did occur under small pressure differences, gravity should have influenced the result. Ratios of left to right lung weights, calculated from the data shown in tables 4 and 5, were 0.74, 0.56, and 0.81 for the animals autopsied at once, and after refrigeration on the right and left sides, respectively. The 0.56 probably differs significantly from the 0.81 ($P < .1$), but definitely, owing to the larger number of animals, from the 0.74 ($p = .01$). Position of the goat, and, hence, perhaps gravity, did influence the result.

Kolder^{3, 4} brought about rapid changes of pressure by puncturing a membrane which separated the inside of a small conical chamber from a larger chamber within which it was contained. He worked with both compression and decompression over a wide range of initial pressures. Considering only compression experiments, with rats initially at 1 atmospere, he killed 8 out of 20 when the pressure was increased to 3 atmospheres in about 1 msec (0.9-1.3). His overpressure was, thus, 29 to 30 lb/sq in.

Richmond⁵ interpreted his results on lethality in several species

* We are grateful to Dr F. W. Light for this reference.

of animals at various distances from the end plate of their closed-end shock tube as caused by changes in the rise time of the pressure to which the animals were exposed. The primary pressure was below the lethal level. The pressure became lethal only after reflection from the end plate, with a resulting severalfold increase in magnitude. When the animals were very close to the end plate, the shock front of the primary wave and the reflection wave fused so that the total pressure developed in a fraction of a millisecond. When the animals were separated from the end plate by a small distance, the primary shock front was separated from the reflected wave by the time of travel to the end plate and back. For a separation of 0.5 foot the time would be less than 1 msec. When guinea pigs were placed at the end plate, 8 out of 20 animals were killed at a reflected pressure of 36 lb/sq in.

In our mice experiments, the significant thing was again the distance to a reflecting end plate. However, the physical situation differed, because the end plate was that of a side chamber on an open-end, shock tube, and the pressure dropped rather quickly to that of the primary wave.

The lethal effects in these experiments where displacement was minimized were probably caused by pure-blast effects. We thus have a series in our own experiments with mice ranging from full exposure to the blast where two out of six were killed at 8.0 lb/sq in. (10.4 peak), and all at 16 lb/sq in., presumably by translation, to the side chamber of 5-msec to 10-msec filling time in which but 1 out of 19 was killed, and that obviously by displacement, at primary tube pressures of 30 lb/sq in. Also, even at reflected pressures of about 40 lb/sq in. (plateau) in the rapid-fill cylindrical side chamber at 4 inches from the closed end, all animals survived if kept from being blown about, or out, by placement in small cages. The necessary conditions for this result were avoidance of displacement, especially out of the chamber but also within it, and the region nearest the end plate, where the rise to full pressure was most rapid and where the peak pressures were larger.

The relation of velocity to impulse is known only within rather wide limits because of the apparent lack of consistency between the work in the first phase of the tube and the final phase. For goats, maximum velocities of from 40 to 65 ft/sec were obtained with animals initially in one of three orientations and in one orientation (broadside) in either of two locations at pressures (plateau) of about 8 lb/sq in. The corresponding impulse, on the assumptions given above, was 20 lb sec/sq ft. In the final phase of the tube, velocities from 54 to 78 ft/sec were obtained with animals initially in the same three orientations at the same pressure but with an apparent impulse of 82 lb sec/sq ft. The increase in velocity was much less than might be

expected from such a large increase in impulse, but so far the difficulty has not been explained.

Having failed to find an adequate reason for the discrepancy between the first phase of the tube and the final phase in the data based on displacement, the pressure measurements themselves come into question since especially the dynamic pressures are said to be very difficult to measure. It is important that the doubt be resolved for an entirely different and more general reason. In the shock tube, as has been shown in two separate series of observations, the threshold for serious injury by displacement has appeared to be lower in terms of overpressure than that for pure-blast effects. The displacement depends largely, however, on the dynamic-pressure impulse, while pure-blast effects probably depend on the peak or plateau overpressure plus a time element. The ratio of peak or plateau overpressure to dynamic-pressure impulse in the shock tube must, therefore, be similar to that in the field if one is to transfer this concept of relative thresholds from the shock tube to the field. At first glance it may seem that because of the much longer duration of the positive phase in the field, the ratio would if anything be smaller than in the shock tube. Unlike the field blasts, however, the dynamic pressure, especially according to the measurements in the final phase of the tube, was at a maximum toward the end of the positive wave and continued beyond it (figures 2, 3, and 4).

The dummy movement was studied only in the final phase of the tube (table 10). The experiments showed dummy velocities in excess of 40 ft/sec with the highest-pressure shots (8.0 lb/sq in.) when the dummy was initially seated with side toward the blast or when lying on its side with face-in. The velocities were but little less from the seated, face-in position. Back-in orientations, whether the dummy was seated or on its side, gave lower velocities. The prone position with head directly toward the blast and arms down showed the smallest dummy displacements. At 3.4-lb/sq in. plateau pressure (peak 4.8), no displacement from the initial position was observed after the blast. At 4.8-lb/sq in. plateau pressure (peak 6.2) it moved 0.2 foot. In one Nevada field shot at 5.3-lb/sq in. peak pressure on a dummy in the same orientation, the dummy was not displaced.¹⁵

Field measurements of velocity and distance displaced on one standing dummy¹⁵ and of distance displaced on 30 dummies in various orientations¹⁶ are also available. In the latter case the displacement of individual dummies was plotted against the product of the presented area of the dummy in its initial orientation, the dynamic pressure, and the duration of the position phase of overpressure (APT). The data were represented by a straight line on a log scale as shown in figure 19 with APT plotted on the horizontal axis, lower scale. Their individual points are not shown in figure

19, but the dotted lines represent the 95% confidence limits; only one point was slightly outside of them.

The single, standing dummy from operation Plumbbob¹⁵ is also plotted as X in figure 19. The area was given as 6.3 sq ft, the dynamic pressure as 0.7 lb/sq in., and the duration, experimentally determined, as 0.45 second. The point differs by a factor of 3 to 4 from the United Kingdom line and also lies outside the limits of the United Kingdom data.

Our shock-tube data on the dummy were replotted in the same figure 19, with the product of dynamic-pressure impulse and area plotted on the horizontal axis, upper scale. It is of interest to compare tentatively the dummy displacements in the field and in the shock tube, remembering that the time courses of the dynamic pressures are very different. For this purpose, instead of multiplying the presented area by the pressure-time product, lower scale figure 19, the dynamic-pressure impulse should be used. According to an earlier United Kingdom report,¹⁷ one-fifth the pressure-time product was considered a reasonable approximation. If the line representing APT values for the United Kingdom field data and the single Nevada point (figure 19) are shifted to the left by a factor of 0.2 and referred to the upper scale, the United Kingdom data does cut through the shock-tube data, but the Nevada point lies well to the left of it. The line representing the United Kingdom data does not appear to be the best representation of them; a line of steeper slope would do better except for two or three low-displacement points, but the points overlap and all would be included within the 95% confidence limits.

It must be emphasized that the above result was obtained by use of the dynamic-pressure impulse measured for the final phase of the tube with which the dummy data were obtained. If dummies had been used during the first phase of the tube, it would be expected, on the basis of the goat data, that a group of points well to the left of those plotted in figure 19 would have been obtained. In that event, the shock-tube data would probably have agreed more closely with the single point from the Nevada test site than with the United Kingdom.

The velocity-displacement relationship of the standing dummy,¹⁵ 21.4 ft/sec and 21.9 feet, falls almost exactly on the curve shown in figure 12. This one instance may be just a coincidence, so it is most unfortunate that more data of this sort are not available. If such a curve as figure 12 has even approximate general validity, it would offer a relatively simple approach to some of the physical factors in the field that are associated with biological problems.

One purpose of the experiments on goats and the collection of the information from various sources, which have been described, was to gain some idea of the velocity range within which or above which death or serious injury is to be expected in man. Combining the two high-pressure series on goats, 13 were killed or obviously incapacitated. All 13 were among 50 animals that had reached the higher velocities (40 ft/sec to 78 ft/sec). In addition to the 13 animals just mentioned, 3 had bone fractures. Hence, 16 of 50 (33%) in this velocity range suffered, at the least, broken bones. Some of these injuries might have been caused by striking the tube wall. In the first series the average velocity for the injured animals was 46 ft/sec. In the intermediate- and final-tube stages it was 59 ft/sec. On the other hand, among animals from all three tube stages that, because of orientation, lower pressures, or a blind flange on the end of the tube, reached velocities of 0 to 31 ft/sec, 0 of 26 suffered such injuries. Insofar as deceleration effects alone are concerned, this agrees with the common experience of running athletes, whose fastest speeds are about 30 ft/sec.

The comparable terrain over which the Maryland Hunt Cup¹¹ was run during 23 years, caused serious injury to 7 of 53 (13%) horses that fell during jumps at forward speeds of probably less than 40 ft/sec. Under the conditions of the Maryland Hunt Cup, from all that it was possible to learn, the riders were certainly not more susceptible to serious injury from displacement alone than the horses. Insofar as conclusions can be drawn from this observation and from the shock-tube work with goats, less than 50% of exposed individuals attaining velocities in the 40- to 78-ft/sec range would suffer bone fractures, paralysis, or death from rolling over grassy ground. To one who has watched the goats thrown out of the tube, this is difficult to believe. The velocities required for serious injuries would decrease from the relatively benign conditions of a grassy pasture as bare ground, rock, walls, or other hard objects occurred in the decelerating area.

V. APPLICATION.¹⁸

The results have emphasized the importance of displacement as a source of injury at relatively low overpressures, primarily during deceleration, and, hence, the importance of shelter.

Serious injury or death was frequent in goats at plateau, side-on overpressures of about 8 lb/sq in. (peak overpressure, about 10 lb/sq in.). This pressure in the tube was associated with dynamic-pressure impulses from 20 to 80 lb sec/sq ft, depending on the tube stage. Ear damage, in single instances, extended to plateau, side-on overpressures of about 6 lb/sq in. (peak overpressure, about 8 lb/sq in.) or lower. The low pressure that produced occasional ear damage in goats is in agreement with

the findings in other species by others.

The limiting factor in the production of serious injuries in the shock tube would have been displacement if ear protection against pure-blast effects had been provided. Decrease of serious injury, from blast, at a given dynamic pressure within this range, thus depends, apart from ear damage, on a decreased displacement. Decreased displacement was brought about in two ways in the shock tube: (1) by protecting against the primary airflow and, (2) by decreasing the presented area. The overpressures of the primary blast waves within which lethality occurred in mice were increased severalfold (from about 10 to 30 lb/sq in., side-on overpressure) when displacement was minimized by restraining the mice within side chambers. Even at the higher pressure, lethality was avoided at a particular position within the side chamber. The results in the chambers are in general agreement with one Plumbbob test¹⁹ in which the peak overpressure outside a large shelter was 39.2 lb/sq in. Although 15 of 80 mice were killed, 14 of those killed were in one cage close to the entrance, which faced the blast. Pressures recorded by gauges inside the shelter were about 30 lb/sq in. The authors stated "the pressure to which they were exposed was undoubtedly much greater than that recorded by the gauges farther inside the shelter." In the shock tube by protecting the mice against displacement, pure-blast effects became the limiting type of damage at the higher pressure.

The importance and applicability of this concept to men are obvious. Serious danger to men from displacement in the shock tube would extend down to overpressures of 5 or 10 lb/sq in. The limiting pressure of long duration for pure-blast effects in man is not known and the available shock tube was not suitable for such studies on goats. It is probably higher than for mice, although the relation between size and pure-blast damage, which was widely accepted a few years ago, may be in doubt. It is reasonable to suppose, however, that overpressures, and the accompanying dynamic pressures, not lethal to men in the field, could be increased severalfold by simple shelters, with a corresponding decrease in the dangerous area due to blast from a given explosion, provided certain criteria were met. The structure must, by its design and orientation, protect its occupant or occupants from the primary air current and from secondary air currents that might remove a man from the shelter or fling him against a wall. We were not able to study in the shock tube any shelter approaching the size required for a man, and our shelters were made of steel, not soil. We thus have no means of estimating the strength of air currents in a field shelter. Also, we have no estimate of conditions necessary to collapse or fill field shelters although information of that sort should be available. For instance, in Operation Plumbbob²⁰ two swine were placed in foxholes 36 inches deep at locations where the dynamic pressures reached 13 and 22 lb/sq in. Both animals were recovered alive in the holes. They died later from acute

radiation effects.

Even though these criteria are met by the shelter, if the shelter design permits a very short rise time of pressure, as was true of our cylinders, some areas within it will be more dangerous than others and this will, in turn, depend in part on the direction of the opening in relation to the blast. Reflected pressures in our side chambers, with the chamber opening tangential to the axis of the primary blast wave, were much lower than would have been true for an opening normal to the axis of the blast wave. How dangerous the reflected pressures would be for man cannot be estimated until more is known about the damage from pure blast to large animals.

The second way in which displacement and consequent injury were reduced in the shock tube was by initial orientation. Minimum displacement of goats and the dummy occurred with minimum presented area toward the oncoming blast wave. Quantitatively, orientation does not compare with shelter in effectiveness, but it is significant. For the goats a given displacement occurred at a 1- to 3-lb/sq in. higher pressure when the animals were head-in as compared to a transverse position. For the dummy, stated differently, at a plateau, side-on overpressure of about 8 lb/sq in. the head-in position showed displacements of 8 to 20 feet while various sitting positions, apart from back-in, showed displacements of 66 to 96 feet. In other words, at this particular pressure, position in the open would mean the difference between relatively slight injuries and a substantial chance of serious injury or death.

VI. CONCLUSIONS.

The velocities of goats (under Nembutal) and a dummy blown from the shock tube were measured under various conditions. At a given tube stage and overpressure, the major variable determining the velocity was the initial orientation of the goat or dummy. The distance thrown was related in a fairly regular way to the velocity.

Goats exposed to shots in the shock tube at overpressures of 8 lb/sq in. (plateau), 10.4 lb/sq in. (peak), suffered broken bones or death in about one-third of the cases when they were so oriented that they were displaced at velocities of 40 to 78 ft/sec. Ear damage and perhaps some lung damage occurred as a result of the pure blast as such at these pressures, but other broken bones and death were produced primarily by displacement so far as could be judged. In the shock tube, the threshold for serious injury, apart from the ear damage was, therefore, much lower for displacement than for pure blast. When displacement was minimized or prevented by appropriate side chambers, as was feasible for small animals, the threshold pressure for death increased severalfold, and death of mice was produced by pure blast.

Shelters are thus of great importance in the field, and position of a man if in the open is also important. The more quantitative use of tube data in the field is handicapped by lack of proof that consistent measurements of dynamic pressure were made under different conditions. This lack is of particular importance, because the dynamic-pressure impulse, an important factor in displacement, may have quite different relations to overpressure in the tube and in the field. One set of pressure measurements suggests that the impulse may even be larger for a given overpressure in the tube than in the field.

The interrelation between maximum velocity during displacement and probability of injury over different terrains has been discussed.

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AIR BLAST STUDIES WITH ANIMALS II - R. S. Anderson,
Fred W. Stemler, and Earl B. Rogers

1. Air Blast Studies
2. Blast Injuries
3. Shock Tube Studies

CRDLR 3049, DASA-1193, April 1961
Project 4C99-02-002, UNCLASSIFIED REPORT

Goats (under Nembutal) and mice were exposed in a shock tube modified to give longer-duration overpressures and equipped with ports for photography. Except for ear damage, displacement still seemed to be the major cause of injury in goats in the 4-foot section of the tube. However, it was found that mice were killed, apparently by pure blast, in a particular position in a particular type of side chamber attached to the higher-pressure, smaller-diameter, section of the tube. The relation between maximum velocity of displacement and the distance animals were thrown was fairly regular. The probability of injury over different terrains is discussed.

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