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Division 2, National Defense Research Committee
of the
Office of Scientific Research and Development

AIR BURST FOR BLAST BOMBS

A Compilation of Papers Presented at the
Division 2, NDRC, Symposium on
Air Burst for Blast Bombs
March 20, 1945

NDRC Report No. A-322
OSRD Report No. 4943

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Approved on April 17, 1945
for submission to the Committee

E B Wilson Jr

E. B. Wilson, Jr., Chief
Division 2, NDRC
Effects of Impact and Explosion

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Preface

This report consists of seven papers presented at a symposium on Air Burst for Blast Bombs held under the auspices of Division 2, NDRC, at the National Academy of Sciences, Washington, D.C., on March 20, 1945. The purpose of the symposium was to discuss the effect on blast damage of detonating bombs in air above the ground. The papers given at the morning session were devoted to discussions of broad interest with emphasis on questions of practical military importance. The papers given at the afternoon session discussed the more detailed technical aspects of the problem. Of the seven papers given, five were presented by representatives of Division 2, NDRC, one by a representative of Division 4, NDRC, and one by a representative of the Bureau of Ordnance, Navy Department.

The subject matter presented is pertinent to War Department project OD-03 and to Navy Department projects NO-224, NO-144, NO-208 and NO-283. The work described in the report was performed by Princeton University under Division 2 contract OEMsr-260, by the Woods Hole Oceanographic Institution under Division 2 contract OEMsr-569, by the National Bureau of Standards for Division 4 under a transfer of funds, and by the Bureau of Ordnance, Navy Department.

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A. INTRODUCTION TO SYMPOSIUM ON AIR BURST FOR BLAST BOMBS

Sponsored by Division 2, NDRC

by E. B. Wilson, Jr.
Chief, Division 2, NDRC

The purpose of the air-burst symposium was to present to representatives of the Services the present status of our knowledge of the effect of air burst on the blast from bombs. Attention was confined to blast; fragmentation was not discussed since it is quite a separate problem.

Numerous experiments have shown that a bomb which is detonated at a proper height above the ground produces a stronger pressure wave at distances of most interest than does the same bomb detonated on the ground. A rough physical picture of this phenomenon is given below.

Let us consider first an explosion high in the air, say a bomb used for air-to-air bombing. A shock wave will spread out from the explosion almost spherically. A pressure gauge located a short distance away will record a pressure-time curve similar to that shown in Fig. 1. The pressure rises almost instantly to a maximum and then decays in a few hundredths of a second to zero or slightly below. If the gauge had been located further away the maximum pressure recorded would have been lower but the duration would have been slightly longer. If gauges had been put at various positions in space around the bomb but at the same distances from its center, they would have shown some differences in pressure off the nose, tail, and side; but as a rough approximation the energy spreads out in all directions evenly, as indicated by Fig. 2.

Now consider a bomb detonated at a moderate height above the ground. A pressure-gauge record at a suitable distance would then look like Fig. 3. In addition to the direct pressure pulse, there is an additional pulse which, investigation shows, is due to ground reflection of the direct shock wave. Figure 4 shows the geometry of this reflection, which is essentially the same as that of any sound wave. The ground reflection, in fact, acts just as if it came from a second bomb located at a point below the ground (but not interfered with by the earth). This imaginary bomb is called the

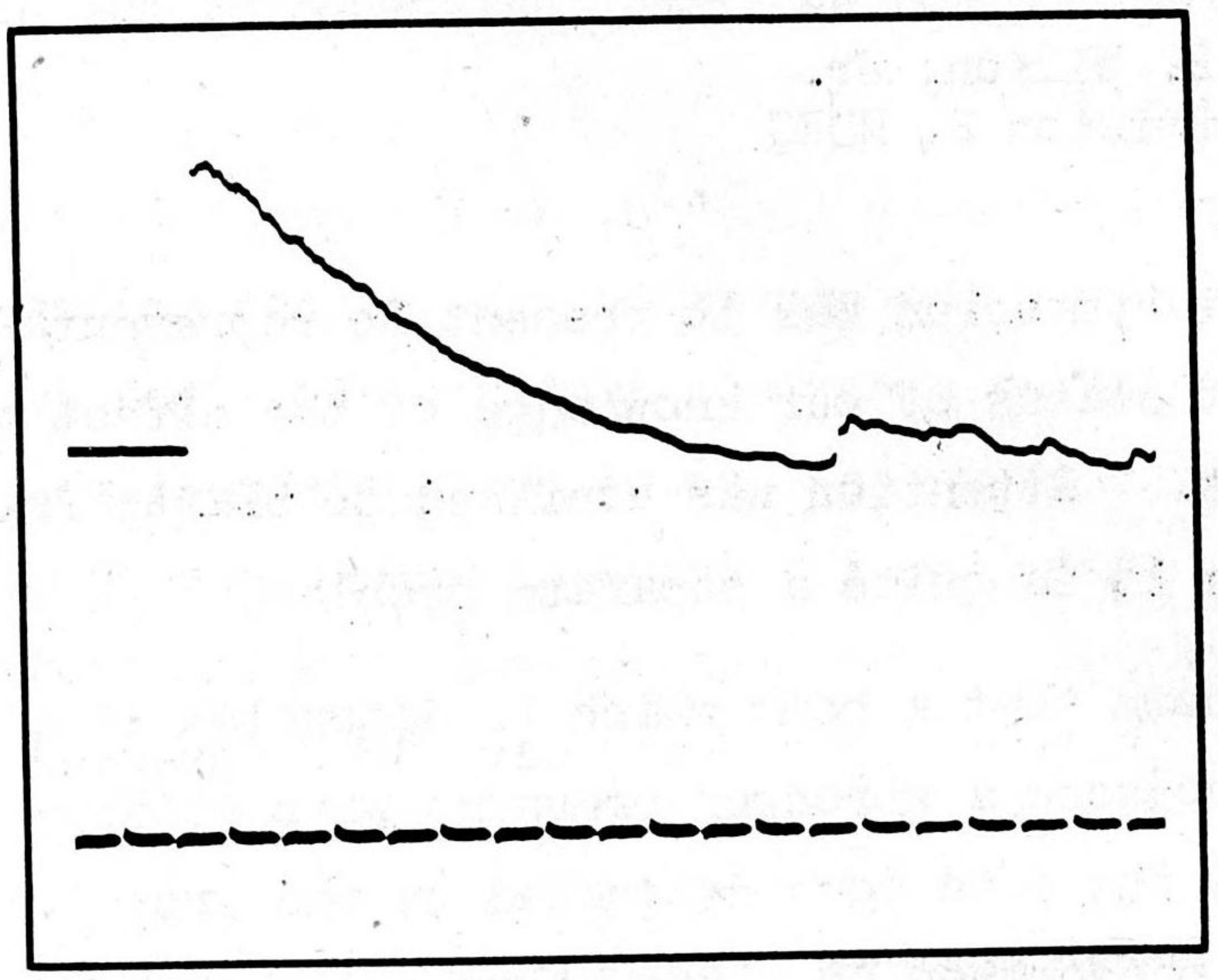

FIG. 1. TYPICAL PRESSURE-TIME CURVE IN ABSENCE OF GROUND REFLECTION

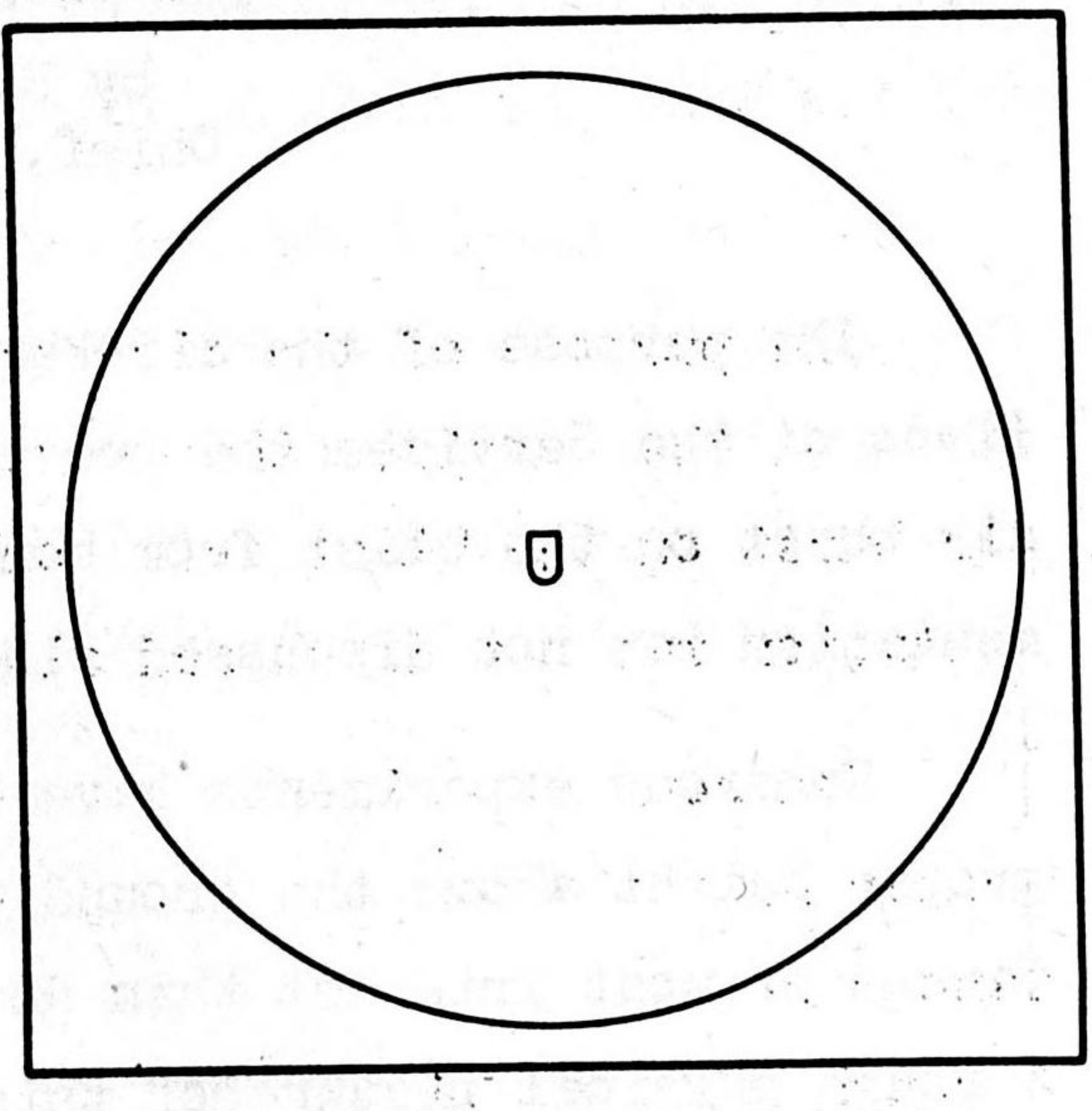

FIG. 2. SPREAD OF SHOCK WAVE FROM FREE-AIR EXPLOSION

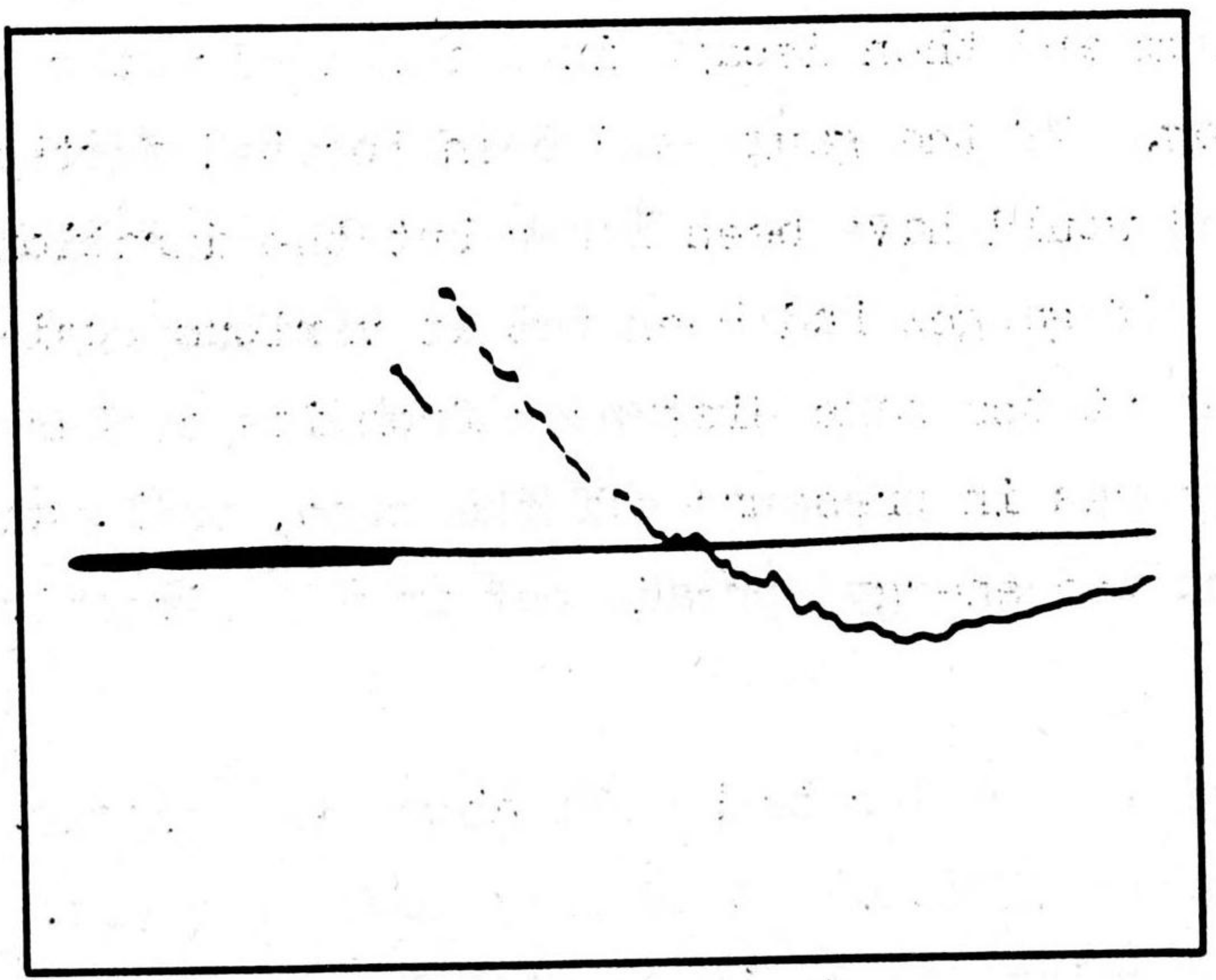

FIG. 3. PRESSURE-TIME CURVE WHEN THERE IS A GROUND REFLECTION

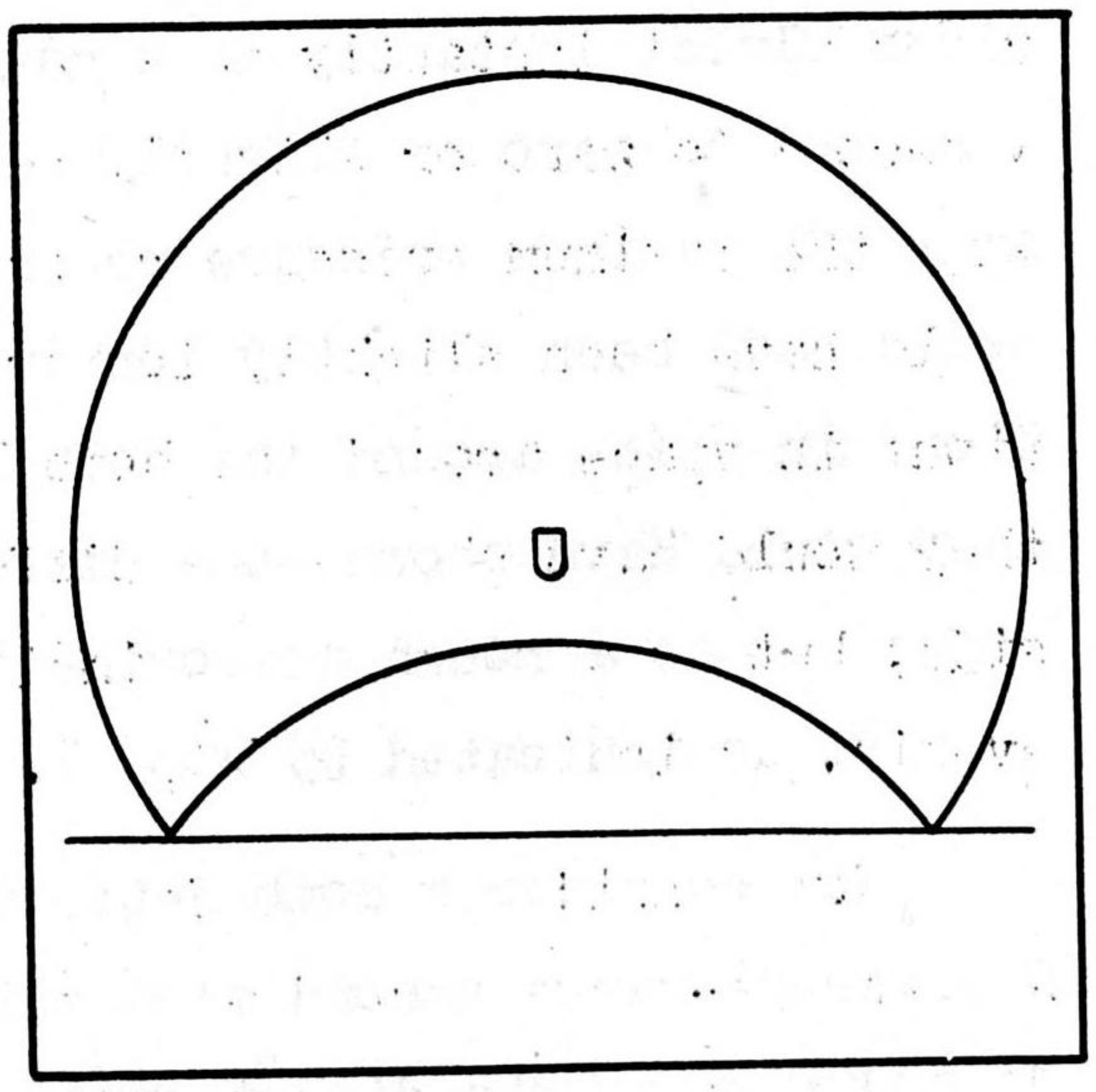

FIG. 4. GEOMETRY OF REGULAR REFLECTION

"image" of the first one, and any considerations of the geometry of the problem can be carried out by replacing the bomb and the ground by the bomb and its image as shown in Fig. 5.

As the bomb is lowered, or the gauge is lowered, or the gauge is placed farther away, the time interval between the arrival of the direct and reflected waves decreases until finally at a certain distance above the ground it can be neglected. At this height above the ground the pressure-time curve looks like Fig. 6; that is, just like the free-air result except that it shows roughly twice as much pressure. Therefore bringing in the ground reflection has almost doubled the pressure that would have been observed for the bomb detonated high above the ground.

If the bomb is lowered still farther, the ground reflection acts as if it came from a point nearer the surface, and finally when the bomb is detonated on the ground, its image will be right under it so that we should expect the whole system to be equivalent to a bomb in free air having twice the weight of the real bomb and expect such a bomb to produce twice the pressure.

But a bomb of twice the weight detonated in free air does not give twice the pressure at a given distance but only about 40% more. Therefore, as the point of detonation of the bomb is lowered from the height at which the direct and reflected waves combined to give almost twice the free-air pressure, something must happen to the laws of reflection so that when the bomb is on the ground the reflection will contribute only about 40% instead of 100%. Figures 28(b) and 28(d) show what actually does happen to the laws of reflection.1/ Figure 28(b) shows the ordinary reflection phenomenon as described above. Figure 28(d) shows what happens when the shock wave approaches the ground at a sufficiently glancing angle. There are still an incident wave and a reflected wave, but there is in addition a third wave, roughly perpendicular to the ground, called a Mach wave because of certain discoveries by E. Mach2/ nearly 70 years ago.

1/ These pictures were taken by L. G. Smith of Princeton University, see p. 51.

2/ Vienna Academy Setzungsberichte, Vol. 78, (1878).

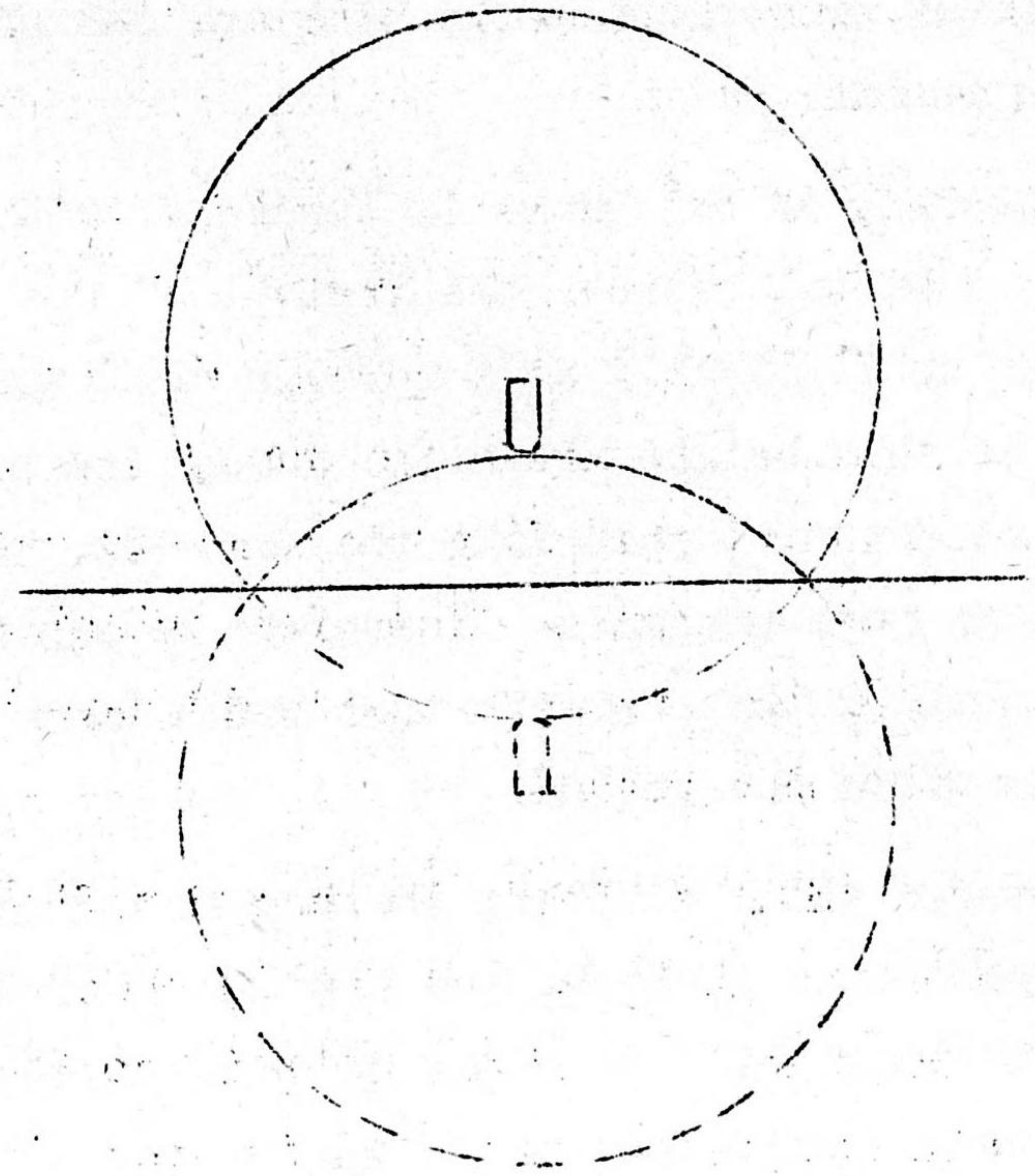

Fig. 5. Bomb and its image.

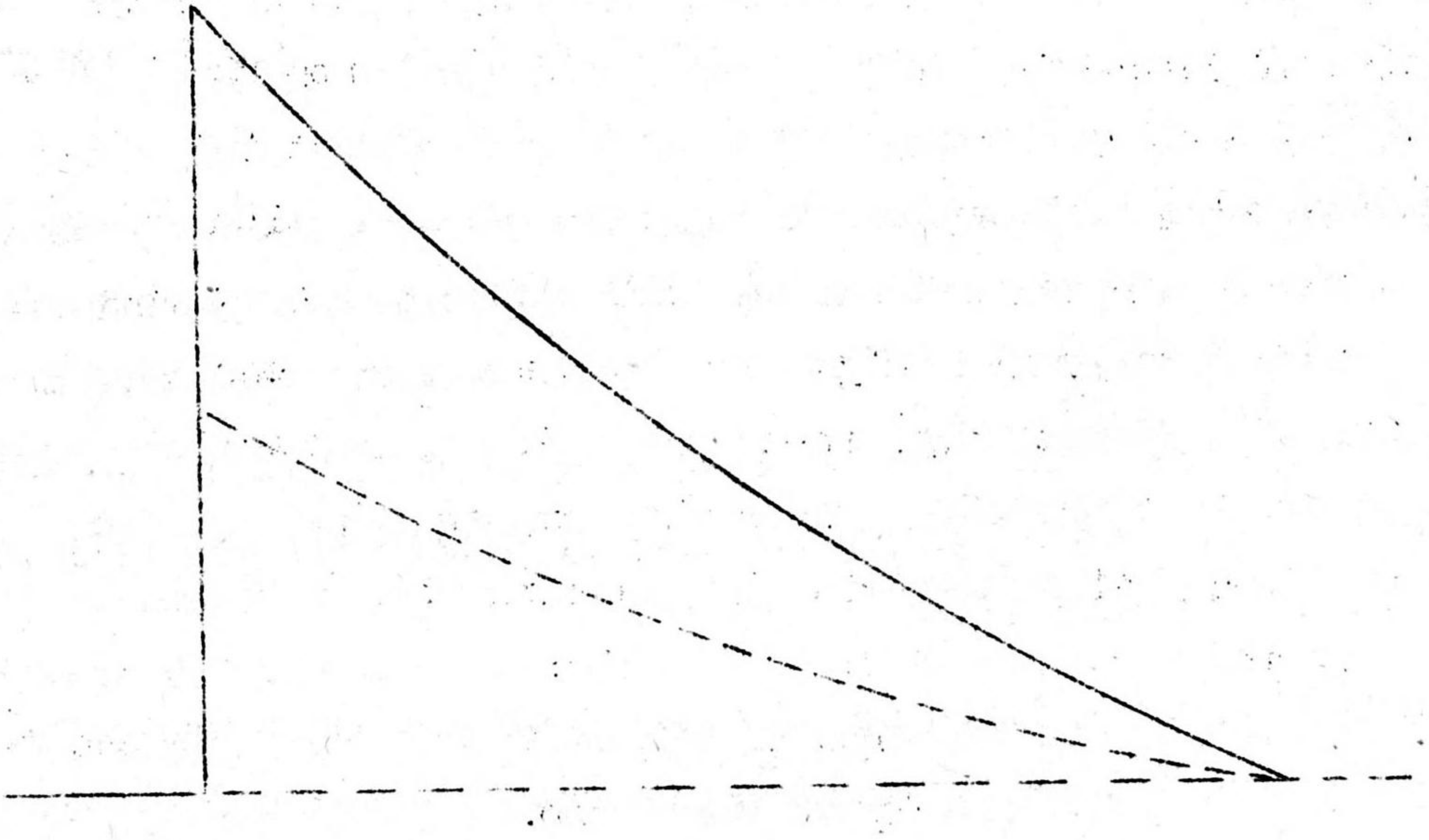

Fig. 6. Pressure-time curve when time interval between direct and reflected waves is zero.

This phenomenon can in fact be predicted from a very straightforward theory developed by von Neumann, Polachek, and Seeger.[3/] They showed that for a wave of a given pressure, regular reflection must change over to some other type of reflection, such as Mach reflection, when the angle of incidence is more glancing than a certain critical angle. Their predictions have been fully verified by experiment.

As a result of this phenomenon, in order to make the best use of the ground reflection, we should not have the charge too low, because then the reflection is of the Mach type and tends to go over to the 40% instead of the 100% gain. Naturally, it should not be too high either, because then the distance from the bomb to the target will be so great as to nullify the gain due to the efficient use of the reflection. For each set of circumstances there will be some best value of the height. This best height, among other things, will depend on the strength of the target and on the size of the bomb.

It is certainly reasonable to ask the source of the extra energy received by a target from an air-burst bomb. In the ground-burst case the energy is spread out more or less uniformly over a hemisphere, so that a considerable fraction is expended upward, where it normally is wasted. With the optimum height of burst, on the other hand, more of the energy is dispatched outward near the ground and less goes upward.

To sum up this explanation, the detonation of a bomb at the optimum height results in the more efficient utilization of the ground reflection whereby more of the energy is sent out in the direction of the target.

It is estimated that the area of damage to a blast-susceptible target from a 4000-lb bomb can be nearly doubled by detonating the bomb about 70 ft above the ground instead of at ground level.

Estimates of the gain to be expected from air burst are based primarily on direct experimental measurements on charges and bombs of a great range of

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3/ J. von Neumann, Explosives Research Report No. 12, Bureau of Ordnance, Oct. 1943, Confidential.

H. Polachek and R. J. Seeger, Explosives Research Report No. 13, Feb. 1944, Confidential.

sizes up to 2000 lb. These experiments have been carried out independently by several laboratories in the United States and in Great Britain, and the results form a very consistent picture which is, in addition, compatible with the partial theory of the phenomenon developed by von Neumann and Seeger.

It is doubtful that it is desirable to use air burst for blast purposes with bombs smaller than 4000 lb against usual targets. With smaller bombs it is probably better to explode them inside the structure being attacked. With the 4000-lb bomb, however, a considerable gain amounting to 80 to 100% in area of damage should be realized against structures of the strength of German load-bearing wall construction. The optimum height of detonation will then be about 70 ft. Against lighter structures, a somewhat greater height should be used and a greater gain in damage area should be achieved.

It may be worth while to mention at this point the quantities in the blast wave that are measured. Going back to Fig. 1, we see that there is a sudden rise to a maximum pressure — the peak pressure. However, this pressure begins to fall off at once and lasts only a few hundredths of a second. Therefore the peak pressure alone is not usually a good measure of the damaging power of an explosion. For example, the stock of a rifle receives a pressure of tens of thousands of pounds when the gun is fired, enough to break anyone's shoulder if it lasted long enough. But since its duration is very short, the pressure is absorbed in a sense by the inertia of the stock, and what is transmitted to the shoulder is the momentum absorbed from the shot. Momentum is measured by the area under the pressure-time curve. It is often called the impulse. Because of the shortness of the duration of shock waves, it is usually the impulse that is important and not the peak pressure. On the other hand, for very large bombs, peak pressure does become important, because the duration begins to be large compared with the time required to break the target.

It should be emphasized that both pressure and impulse are increased by air burst. In the other papers of this symposium the way in which peak pressure and impulse are altered by air burst will be quantitatively explored and the resulting effect on structures will be discussed.

B. EXPERIMENTAL BACKGROUND FOR AIR BURST

by W. D. Kennedy
Underwater Explosives Research Laboratory

That use might be made of the properties of obliquely reflected shocks in order to increase the blast-damage effectiveness of aerial bombs was proposed by von Neumann some time ago.[4] Following his suggestion, extensive tests were begun at two laboratories under the National Defense Research Committee: the Princeton University Station, and the Underwater Explosives Research Laboratory at Woods Hole, Massachusetts.[5]

1. Purposes of the tests

(i) The tests had three purposes: to study experimentally the prediction that the intensity of the blast from a given quantity of high explosive, as measured at a fixed horizontal distance from the charge, would be increased as the height of charge was increased,

(ii) To determine what height of burst would produce the greatest lateral blast intensity, and

(iii) To determine whether or not screening of targets by other structures in built-up areas might affect the advantages of air burst.

2. Characteristics of blast

The blast from a charge of high explosive is a rapidly expanding region of compression, in the front of which the pressure rises instantaneously

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[4] Earlier, it had been proposed by the British that adjacent buildings screen the target from the blast of an impact-burst bomb, and that this screening could be avoided by air burst. Experiments using 2-oz charges at various heights above a scale-model "town" were performed and a gain in peak pressure was observed as the charge was raised. However, at this early stage in the development of air-blast instruments, the optimum heights of burst found experimentally were too large, as demonstrated by the later experiments described here. These early British experiments are described in Note No. ARP/255/RJ, Aug. 1941, "The effect of the height at which a bomb explodes on the blast pressures," and their interpretation in REN 110, Aug. 5, 1941, "General estimate of the results of experiments with the model town."

[5] A bibliography of reports concerning air-burst blast measurements is given at the end of this section.

from that of the atmosphere to some higher value. Behind the wave front, the pressure falls off much more slowly to that of the atmosphere, and then, for a time, to somewhat below atmospheric pressure. The pressure at the wave front, which is ordinarily the highest pressure in the wave, is called the "peak pressure."

Figure 1[6/] is a representation of the pressure recorded by a suitable gauge during the passage of a blast wave. The time during which the pressure is greater than that of the atmosphere is called the "positive duration." It is known that not only is the peak pressure an important property for assessing the damaging power of the blast, but so also is the time during which the pressure of the blast is exerted. The property of the blast wave that is convenient for taking into account both its pressure and the time during which it acts is its "positive impulse." The positive impulse is simply the average pressure in the blast multiplied by its duration. As the blast wave travels away from the charge, its peak pressure and positive impulse decrease, and the positive duration increases.

3. Experimental measurement of peak pressure and positive impulse

The experimental method of obtaining measurements of peak pressure and positive impulse in the blast is illustrated schematically in Fig. 7. The blast wave emitted by a high-explosive charge eventually strikes and passes by a gauge which produces an electric pulse. This pulse is applied to appropriate recording apparatus, in which a permanent photographic record is made.

Figure 1 is one such record. Vertical displacements are proportional to pressure, and horizontal ones, to time. Thus the peak pressure and positive impulse in the blast are obtained.

Figure 8 shows the layout of gauges and charges in the air-burst experiments at the Princeton University Station. In some experiments, gauges were mounted flush with the ground at various fixed horizontal distances from a series of charges whose heights above the ground were varied. In

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[6/] See "Introduction," by E. B. Wilson, Jr. p. 2.

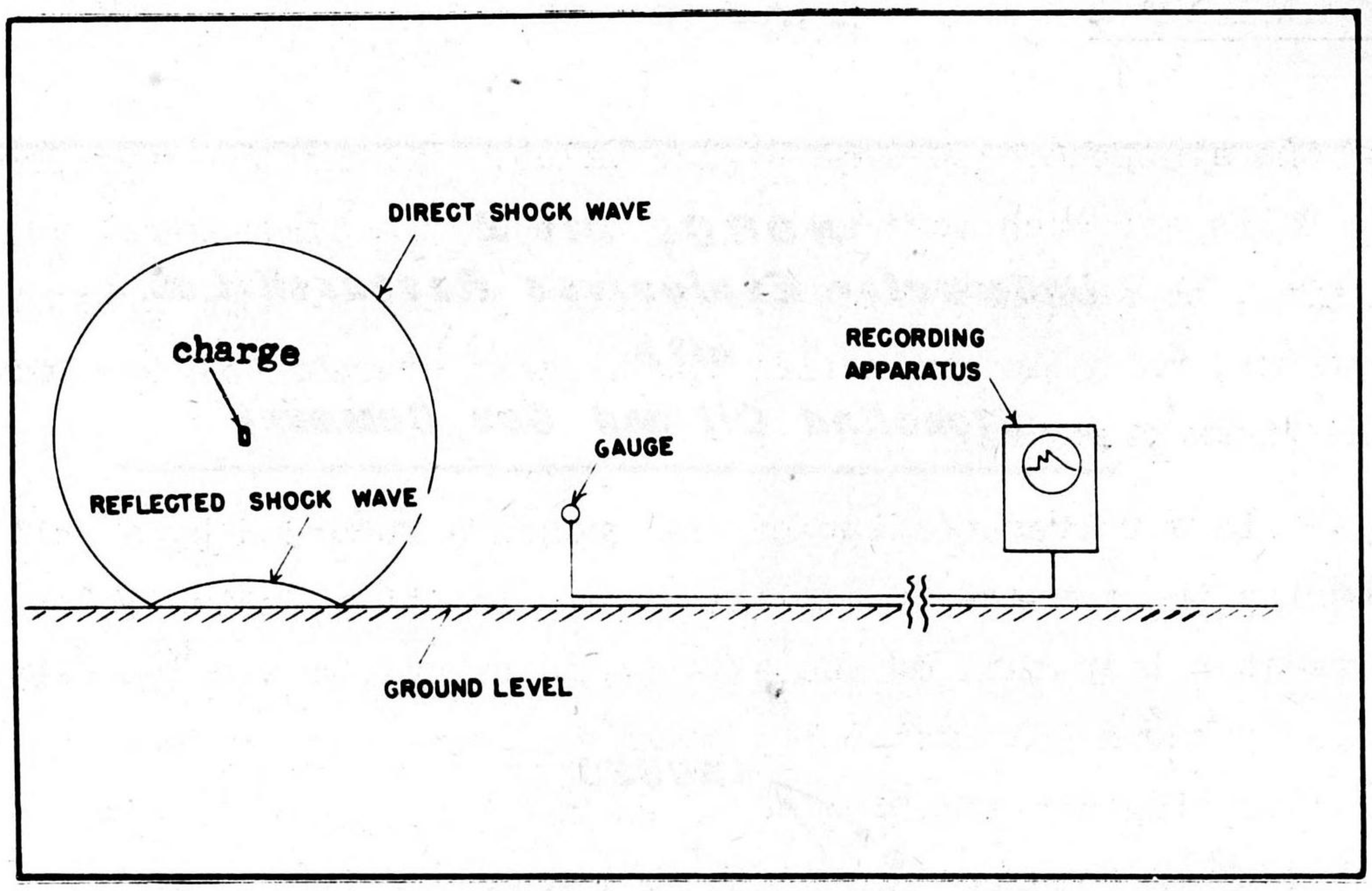


FIG. 7 SCHEMATIC REPRESENTATION OF ARRANGEMENTS FOR BLAST MEASUREMENTS

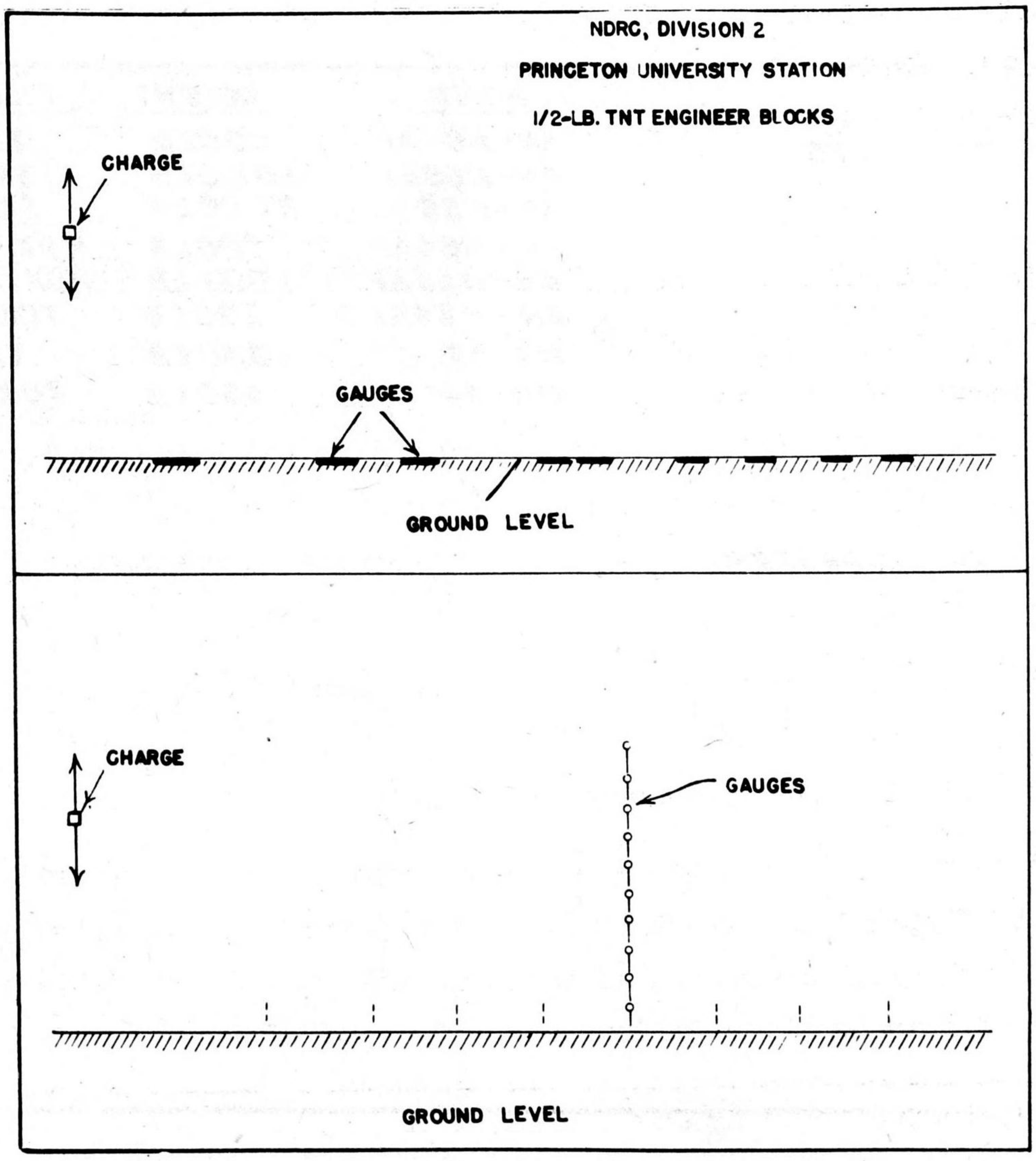
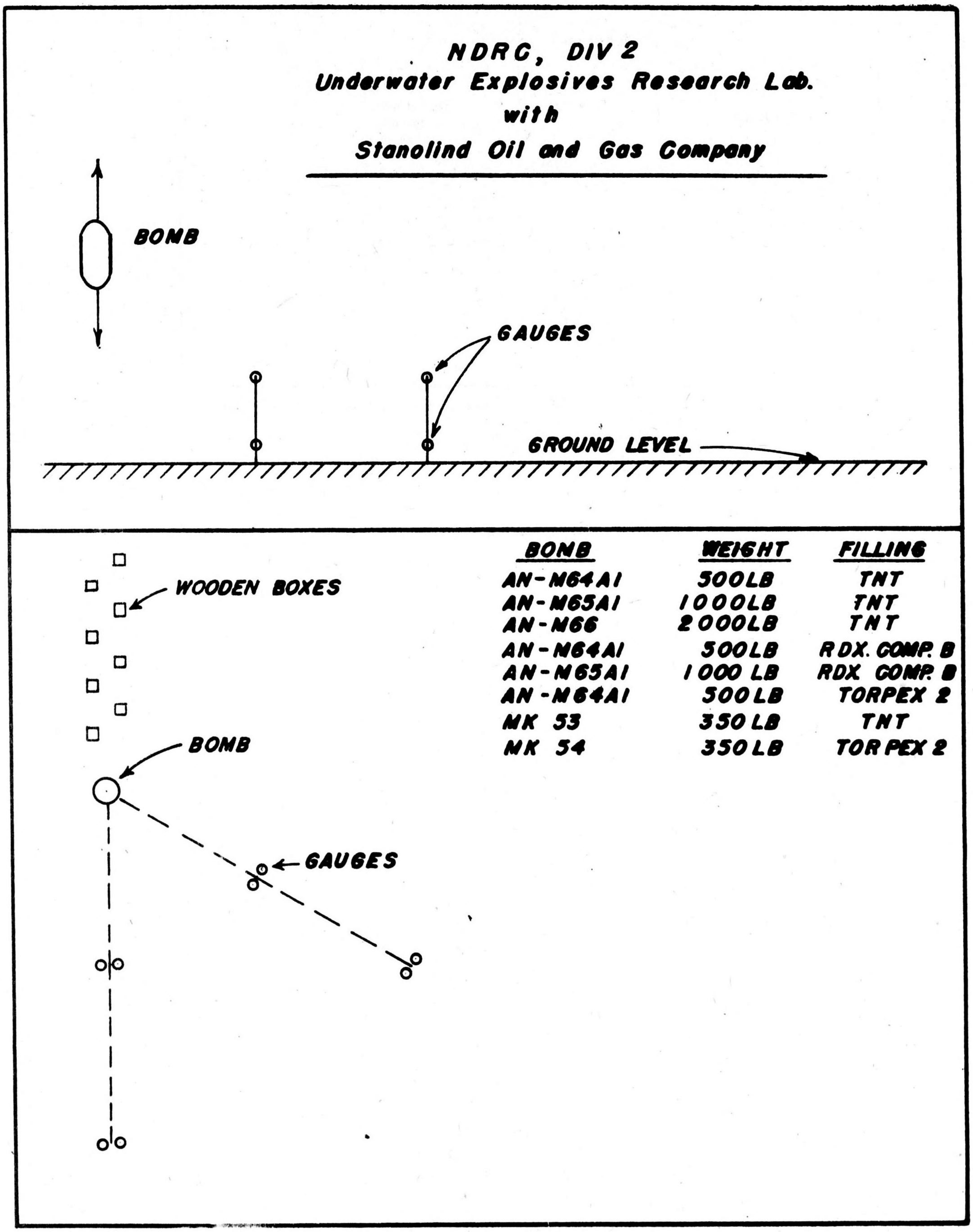


FIG. 8 LAYOUT OF CHARGES AND GAUGES AT THE PRINCETON UNIVERSITY STATION



BOMB	WEIGHT	FILLING
AN-M64A1	500LB	TNT
AN-M65A1	1000LB	TNT
AN-M66	2000LB	TNT
AN-M64A1	500LB	RDX. COMP. B
AN-M65A1	1000 LB	RDX. COMP. B
AN-M64A1	500LB	TORPEX 2
MK 53	350 LB	TNT
MK 54	350 LB	TORPEX 2

FIG. 9. LAYOUT OF BOMBS AND GAUGES AT JEFFERSON PROVING GROUND.

FIG. 10. PIEZOELECTRIC GAUGES SET UP FOR BLAST MEASUREMENTS.

FIG. 11. 1000-LB. G P BOMB AT 28 FT. ABOVE GROUND.

FIG. 12. 1000-LB. G P BOMB AT 54 FT. ABOVE GROUND.

FIG. 11

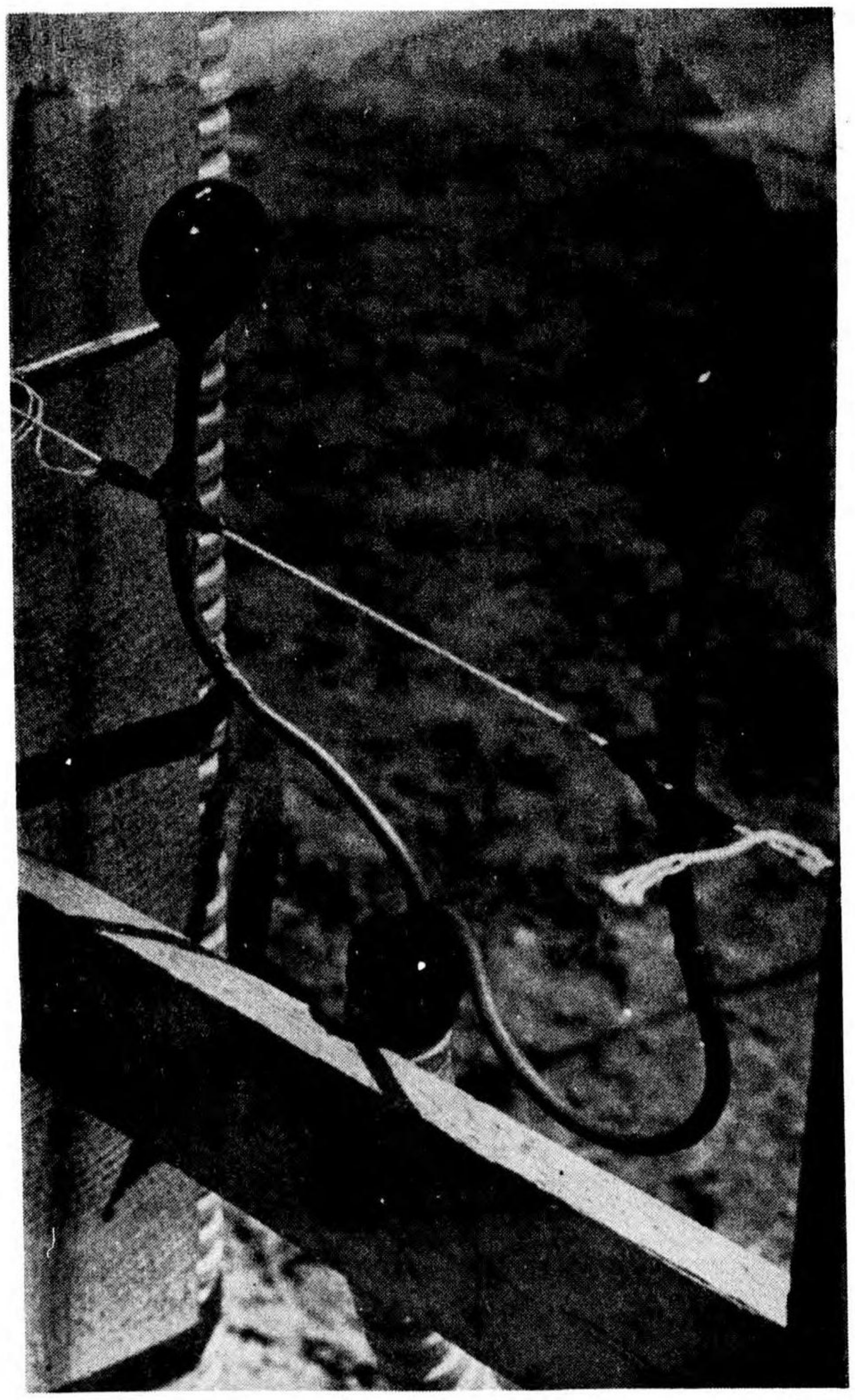


FIG. 10

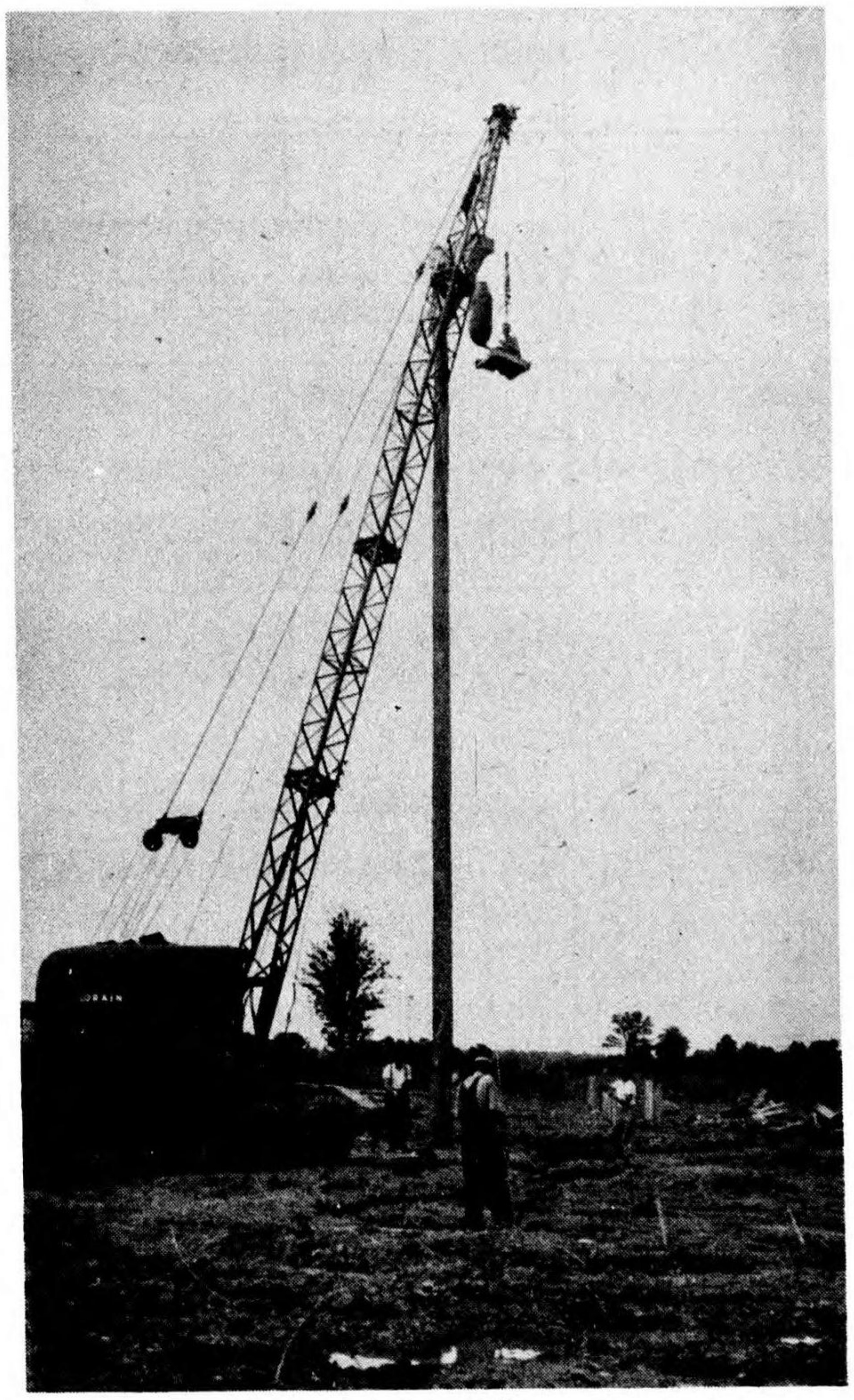


FIG. 12

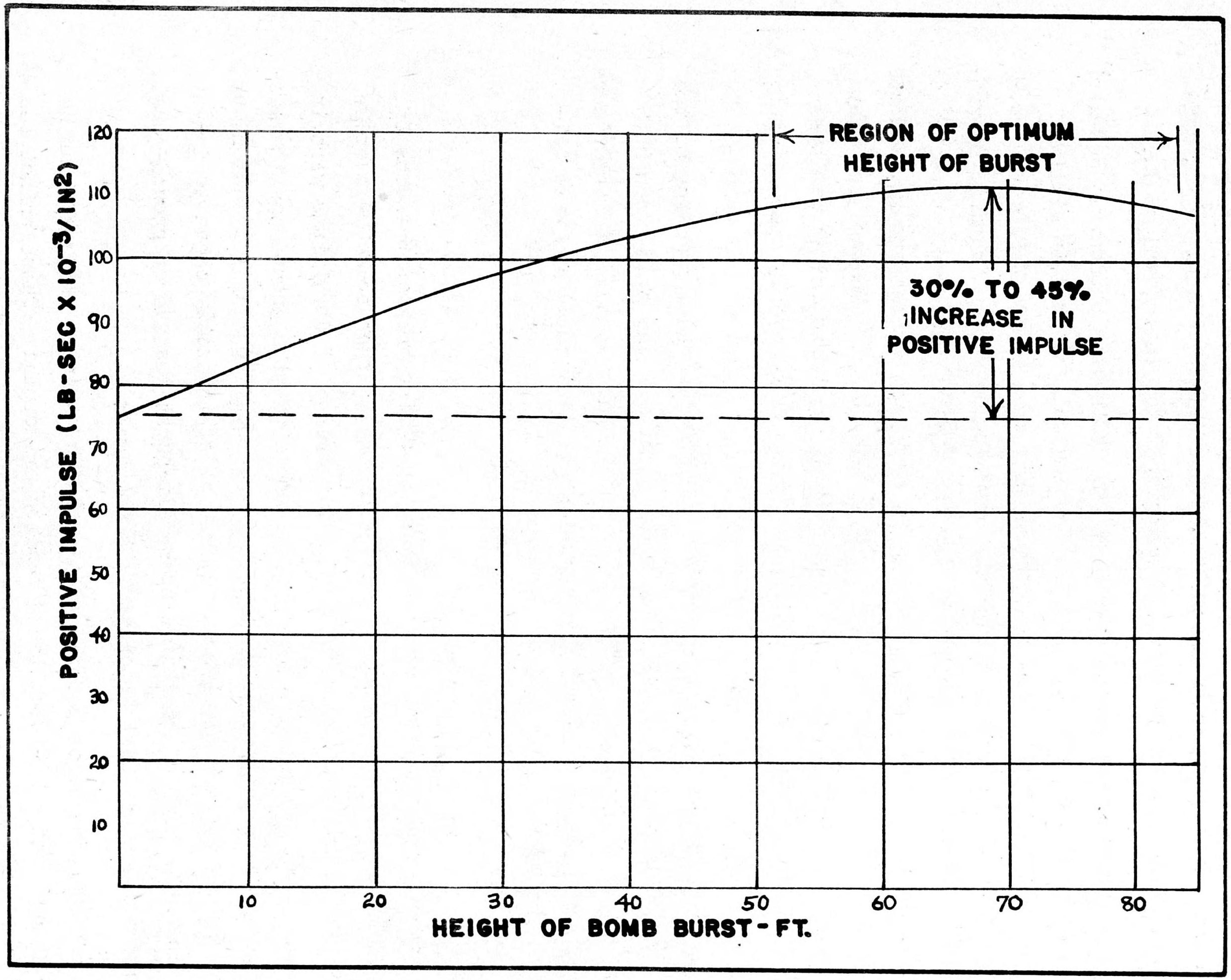


FIG. 13. ESTIMATED POSITIVE IMPULSE AS A FUNCTION OF HEIGHT OF BURST OF A 4000-LB. L.C. BOMB.

other experiments the gauges were mounted at various heights above the ground. Similar tests with entirely independent equipment were carried out by the Underwater Explosives Research Laboratory and the Stanolind Oil and Gas Company, using charges of cast TNT weighing 2 lb, 12 lb, and 40 lb.

Later the blast-measurement groups of the Underwater Explosives Researc Laboratory and the Stanolind Oil and Gas Company collaborated in similar tests using actual bombs. These tests were conducted at the Jefferson Proving Ground, Madison, Indiana, through the cooperation of the Ordnance Department. Figure 9 shows the arrangements for the tests: bombs were supported at various heights above the ground, as well as with nose on the ground, and the blast from their detonation was measured independently by the two groups by means of gauges placed at various distances from the bombs and at various heights above the ground. In addition, a double row of evenly spaced, empty wooden ammunition boxes was set up for each test.

The gauges used are shown in Fig. 10, and the general appearance of the layout is shown in Figs. 11 and 12. In Fig. 11, two of the gauges can be seen, as well as the rows of upended boxes in the background. The bombs were suspended from a wooden gallows, nose down (Figs. 11 and 12) and were initiated from the nose.

4. Results

The experimental results from all tests involving the various sets of apparatus, charges of sizes varying from $\frac{1}{2}$-lb bare charges to 2000-lb bombs with three different high-explosives and a wide range of conditions were in good agreement: as the height of charge or bomb above the ground was increased, the peak pressure and positive impulse were found to increase. When the charge height was too greatly increased, the blast intensity began to decrease. Thus, the prediction that a bomb, air-burst instead of ground-burst, would produce enhanced blast intensity was confirmed.

The results from tests using various sizes of charges and bombs can be compared by applying well-established scaling principles. These principles state that the peak pressures in the blast from charges of different weights are identical at distances from the charges that are proportional to the cube roots of the charge weights. Also, at these distances, the positive impulses are in the proportion of the cube roots of the charge weights. Upon applying these principles, the results from widely different weights of explosive were found to be in good quantitative agreement. By this means, also, reliable predictions of the blast intensities from bombs still larger than those experimentally dealt with can be made. By the simple means just mentioned, the positive impulses in the blast from the 4000-lb LC bomb at a distance of 160 ft were estimated. This estimate is shown graphically in Fig. 13 as a plot of positive blast impulse against the height at which the bomb is detonated.

The general shape of this curve applies to all sizes of charge; only the dimensions themselves (positive impulse, charge height, distance) are specific. As the height of detonation of the bomb is increased, the positive impulse (and the peak pressure) at a fixed horizontal distance from the bomb increase steadily. Eventually a maximum value is reached (at a detonation height of about 70 ft for the 4000-lb bomb), after which the positive impulse decreases as the height of burst is increased. The wide range of height of burst at which very nearly the maximum impulse is obtained is clearly seen here. Experiments are in good agreement in showing an improvement in positive impulse from air burst compared to ground burst of the order of 30% to more than 40%. As will be shown later, this corresponds to a predicted increase of blast damage of the order of 70% to 100% -- that is, the area of damage a given bomb can accomplish should be approximately doubled by use of air burst.

The results from the electric gauges are supported remarkably well by the observations on the empty wooden boxes that were set up for the bomb trials. The distances at which boxes were blown down by the blast from air-burst bombs were considerably greater than those at which boxes were affected by ground-burst bombs.

Thus far, experiments involving only open country, without structures in the path of the blast, have been discussed. The necessity for testing the phenomena under conditions more closely approximating those in a city or other group of buildings under attack was early recognized. Accordingly, in order to perform the experiment on model scale, wooden boxes were set up in an area near which charges were to be detonated, and electric gauges were placed at various positions among the boxes. Again, as the height of charge was increased above ground level, all gauges, however much screened by nearby boxes, showed an increase of pressure or positive impulse which corresponded with similar increases obtained in the absence of the boxes. Since the scaling laws were so well borne out in other experiments, it is safe to conclude that the results of tests in open fields are applicable to built-up areas.

During the latter part of these tests, confirmatory tests of two types were undertaken in Britain. In one series of tests, performed at Millersford, 66-lb charges of Composition B were detonated at various heights above the ground, and peak pressures and positive impulses were recorded by electric gauges located at two heights above the ground and at eight different distances from the charge. These tests confirmed those described here, substantiating the large increases in damage area obtainable by use of air burst.

A second series of tests on a model scale was performed at Richmond Park. Here a model town was built, consisting of simulated city blocks, residential and factory districts, with streets, constructed to scale. Gauges were placed among the "buildings" in a wide variety of ways, and the charges were detonated at various points in the "city" and at various heights above the ground. Again, the advantage in the use of air burst was confirmed.

5. Summary of experimental results

(i) The area of blast damage to be expected when air-burst bombs are used is almost double, on the average, that which would have been obtained by the use of the same bomb fuzed to detonate on impact.

(ii) The height at which the bombs should be fuzed to burst is not critical, practically maximum damage being obtained over a wide range of heights.

(iii) The effects of air burst are not adversely affected by the screening of buildings in heavily built-up areas.

(iv) The improvement in blast damage with air burst over that with ground burst is expected for all explosive fillings. That is, a more powerful explosive produces greater blast intensity than a less powerful one in air burst as well as in ground burst.

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C. EFFECT OF AIR-BURST BOMBS ON TARGETS

by A. H. Taub
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The results described by Kennedy on the influence of height of burst of a bomb on the pressure and impulse recorded by a gauge[7/] may be interpreted in terms of damage to certain targets. It is the purpose of this paper to show how this is done and to compare the damage that one would predict on the basis of the extensive experiments just reviewed with that actually achieved in some incidents in which V-1 bombs were detonated unintentionally in the air. There are two other incidents at Spezia which will also be mentioned.

1. Type of target

The targets that will be considered here in most detail will be buildings with load-bearing walls since most of the data that will be discussed later have to do with this type of construction. In addition, by making various reasonable simplifying assumptions one can obtain a rather satisfying theoretical analysis of the behavior of such a target when it is subjected to the pressure wave from a bomb explosion. The theory has to do with the behavior of the external walls of the target; once they are destroyed the target either collapses or has to be demolished.

A building with such construction constitutes an ideal "blast" target because the vital part of the building exposes considerable area to the pressure wave from the explosion and, moreover, relatively small amounts of work done on the structure (statically or dynamically) will destroy it. The latter statement means that failure occurs when the displacement of a member times the force acting on it is relatively small. Buildings that do not have redundant framing and that are generally weak under static loads behave in much the same way and are good blast targets.

The qualitative statements for load-bearing construction probably apply to the latter type of construction also. The quantitative statements will have to be changed before they can be applied.

[7/] "Experimental background for air burst," p. 7.

This load-bearing construction occurs very frequently in European business and residential construction. The results of German bombing against English cities and those of RAF bombing against German cities give us the means of correlating the gauge measurements and damage sustained by these targets.

We shall be mainly concerned with the German bombing against English cities since it is against this target that the majority of unintentional air bursts of V-1 bombs that we know about have occurred.

2. Effect of bombing on target

The following picture of the behavior of this target under bombing by bombs of different weights and fuzing is borne out by a study of British experience.

Let us imagine that we have a built-up target consisting of a number of buildings each of a certain fixed size, this size being about the same for all buildings in the target. Thus the target could consist of a section of a city devoted to apartment buildings or a suburb of a large city in which there are individual houses. We now consider what various sized bombs would do to such a target. Let us start with a very small one — that is, one which could not destroy the whole of an individual target even under the most favorable circumstances.

The first point to be observed is that for a direct hit the damage produced by this bomb when it is delay fuzed is greater than when it has an instantaneous fuze. This is so because in the latter case the bomb is detonated near the roof of the structure and may leave the lower portion relatively untouched. However, when the bomb is delay fuzed it will penetrate well into the structure and attack more vital parts. This statement also applies to near misses for those small weights because the radius of damage from ground shock (which is about one or one-and-a-half times the crater radius) is larger than the radius of damage by blast. In any case, the damage produced to an individual unit of the target by a direct hit is larger than that produced by a near miss.

As we increase the weight of the charge w in the bomb up to the size required to destroy an individual unit of the target there is no change to be made in these statements. However, the following facts should be noted. The instantaneously fuzed bombs which strike one unit will begin damaging neighboring units, and, as far as total damage is concerned, the advantage for delay fuzing decreases. Moreover, the advantage as far as near misses is concerned also decreases. This is true because the crater radius increases as $w^{1/3}$ and, as will be seen later, the radius of blast damage increases for small values of $\underline{w}$ as $w^{2/3}$.

If we increase the weight of the charge in the bomb sufficiently beyond that required to destroy an individual unit, then the delay-fuzed bomb is no longer better than the instantaneous one, because in the direct-hit case the building that is hit shields the neighboring ones more for the delay-fuzed bomb than for the instantaneous one, and hence part of the effectiveness of the explosive is lost. Moreover, because of the dependence on $\underline{w}$ of the two near-miss radii of damage (that is, ground shock and blast), the radii of blast damage becomes the larger, which makes the instantaneously fuzed bomb the better.

3. Comparative area of damage of optimum-sized delay-fuzed bomb and larger instantaneously fuzed bomb

As we have seen, there is an optimum-sized delay-fuzed bomb, namely, that size that will just destroy an individual element of the target. We next ask how the average area of damage per pound of bomb of this optimum size compares with that of a larger instantaneously fuzed bomb. It will be shown that the efficacy of the large instantaneously fuzed bomb is larger. Before going into the details of the argument it should be noted that we are discussing average effects; that is, we are taking into account near misses as well as direct hits. Even if we have a built-up city area it contains about 50% open spaces, and hence, on the average, half of the bombs will be near misses. Therefore, if we have an instantaneously fuzed bomb with a sufficiently large charge it will not lose much in the near-miss case, whereas the delay-fuzed one will. This is one of the important reasons for the advantage of the large blast bomb over the smaller delay-fuzed one. Another reason is that instantaneously fuzed bombs can have lighter cases and hence can carry more explosive and, moreover, can use this explosive more efficiently. We now examine the behavior of instantaneously fuzed bombs in greater detail. The British have classified the damage sustained by buildings into three categories:

A: buildings completely demolished,

B: buildings damaged beyond repair and requiring to be demolished -- loss of 25% of external brickwork,

C: seriously damaged but repairable and not requiring demolition.

For each of these categories they have correlated the distance between the bomb and the target with the charge weight. The Ministry of Home Security publication REN 214 (revised) gives "House damage by HE weapons acting by blast and earth shock." The blast data for each category are fitted very well by an equation of the form

$$r = \text{constant} \times w^{2/3},$$

where r is the radius (mean or maximum) of a specified degree of damage and w is the weight of explosive in the bomb. The bombs listed here were positively identified by fragments.

Now the distance from a bomb detonated on the ground at which a gauge will record a given impulse varies with the charge weight in accordance with the same law. This is then an empirical correlation between gauge measurements such as were discussed previously and damage to targets.

Table I. Correlation between radius of damage and impulse from data in REN 214 (revised).

Damage Category	Impulse at Mean Radius (lb msec/in.²)	Impulse at Maximum Radius (lb msec/in.²)
A	120	90
B	72	54
C	40	30

For British construction (9-in. brick walls) subjected to blast from instantaneously fuzed bombs the data in REN 214 (revised) may be interpreted to give the correlations shown in Table I.

The maximum radius is greater than the mean, the reason being that because of the built-up-ness of the target there is a certain amount of shielding of the blast. This evidence says that on the average this shielding can be taken into account by decreasing the radius of a given category of damage by 75%.

Christopherson[8] has assumed that a brick wall behaves as a mass with a constant resistive force. When this mass is subjected to a blast wave it will not move unless the pressure is sufficient to overcome the resistive force. If this condition is satisfied, the wall moves until it reaches a critical displacement and then it collapses. By using the results of static tests together with pressure-time curves recorded by gauges at various distances from bombs he was able to show that the radius for B damage was proportional to $w^{2/3}$ for a certain range in w and that the constant of proportionality agreed with the values given in Table I. Thus there is a theoretical justification for the empirical correlation found between radius of damage and impulse.

However, this analysis shows that for large weights of explosive the "impulse-criterion" breaks down. This is so because if we increase the siz of charge indefinitely, we can indefinitely increase the radius at which a given level of impulse occurs, but we will reach a point where the peak pressure in the blast wave is smaller than the constant resistive pressure mentioned in the foregoing. Against German construction the weight of LC bomb at which this state of affairs is reached is around 12 000 lb. For bomb sizes between the 4000-lb LC bomb and the 12 000-lb bomb the pure impulse criterion no longer holds, but the radius of B damage is roughly proportional to $w^{1/2}$.

This is the evidence for the following statements:

(i) Large light-cased instantaneously fuzed bombs have greater areas of damage per pound of explosive than the optimum-sized delay-fuzed ones.

(ii) The gauge measurements of impulse are correlated empirically and theoretically with damage.

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[8] "A modification of the impulse criterion for blast damage," by D. G. Christopherson, British Report R.C. 349, Sept. 1942 (Confidential).

(iii) The impulse criterion fails ultimately; hence there is an optimum-sized instantaneously fuzed light-cased bomb.

4. Air-burst bombs, British incidents

In the light of this discussion let us examine the results of some flying bomb incidents against British 2-story houses. Table II is taken from REN 461.[9/]

Table II. Radii of damage (in feet) from air-burst bombs (from REN 461).

Height of Burst (ft)	Number of Incidents	Radius of A Damage		Radius of B Damage		Radius of C Damage	
		Mean	Standard Error	Mean	Standard Error	Mean	Standard Error
0	19	72	± 4.2	102	± 3.4	169	± 7.3
5	1	62	---	98	---	182	---
10 to 20	6	97	±16.3	130	±11.5	201	±14.5
60	1	90	---	115	---	170	---
75	1	50	---	65	---	200	---

By using the impulse values for the different categories of damage given in Table I we deduce that the explosive in V-1 acts like a bare charge of about 1000 lb of TNT detonated on the ground. To see this we use the relationship that the impulse law for bare TNT is approximately

$$I = 71.2 \frac{W^{2/3}}{r}.$$

This is not unreasonable in the light of the fact that in most of the incidents given in Table II, the explosive, although weighing about 1850 lb, is known to be poorer than TNT and was encased. This agrees with the statement given the Ministry of Home Security that V-1 is equivalent to a TNT-filled bomb with an explosive charge of 1750 lb and a charge/weight ratio of 50%, if we correct for the charge/weight ratio.

[9/] "Air burst bombs - statement of the position on 20th October 1944," by D. G. Christopherson, REN 461.

If we now ask what height of burst of this 1000-lb charge will produce the greatest radius of B damage, that is, will produce an impulse of 72 lb msec/in.^{2} at a point about 12 ft from the ground (half the height of the building) at the greatest radius, we find this height to be 42 ft. Moreover, if the height is between 24 and 60 ft the results will not be much different. The radius found is 138 ft. That is, we may expect the optimum height for B damage to be between 24 and 60 ft; and if the charge is detonated at this height the radius in B damage will be increased by 38%. The actual height of the 10- to 20-ft group is probably higher than that listed, since the heights here are estimated from the tree stumps and the mean could easily be 25 ft. In view of this, one would say that these data bear out the predictions from the measurements reported by Dr. Kennedy.

For this height of burst one would predict that the radius of C damage would become 198 ft and that the radius of A damage would be either unchanged or slightly decreased. In view of the large amount of scatter in the data one can say that both these statements agree with the data.

5. Air burst in Spezia

In 1942-43 there were some intentional cases of air burst produced by the British against continental construction in Spezia. Two 4000-lb LC bomb's were detonated about 200 ft in the air with the result that the radius of minor damage was increased and that of demolition was decreased. This is what would be expected as a result of the experiments reported previously, because the height of burst was too great. From this evidence we would predict that to increase the radius of demolition the height of burst should be 60 ft and that if it were between 40 and 80 ft about the same gain would be obtained -- namely, an increase of about 70% in area of demolition. For much greater heights of burst we would expect what was found -- namely, the area of demolition was decreased and the area of minor damage was increased.

6. Conclusions

The V-1 incidents and those at Spezia are operational verifications of the following predictions based on the gauge measurements:

(i) When the "impulse criterion" holds, the optimum height of burst depends on the target characteristics and the type of damage desired through the assignment of an impulse level to be maximized.

(ii) The optimum heights of burst increase as the level of impulse is lowered, that is, as the level of damage required is lowered or as the strength of the building is decreased.

(iii) When the "impulse criterion" no longer holds, calculations indicate that there is still an advantage to air burst over ground burst of large bombs.

It has been pointed out that there is an optimum weight for very large-sized instantaneously fuzed light-cased bombs, namely, a weight somewhat greater than that for which the "impulse criterion" against a particular target starts failing. Calculations have shown that this optimum weight is more than doubled if the bombs are fuzed for air burst at appropriate heights.

D. VT FUZES FOR AIR-BURST BLAST BOMBS

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1. The problem

The purpose of this part of the meeting which Division 4 has been so kindly asked to contribute is, in essence, to answer the question: "Is it now practicable to airburst a large blast bomb at such a height over a built-up target that the enhanced damage discussed in the previous lectures may be obtained?"

In order to answer this question, it will be necessary to show that it is feasible, with mechanisms already designed and in production, to cause a bomb to burst in a region approximately 40 to 80 ft above the ground, and to do so with adequate reliability by means of a device which does not place undue restrictions on the maneuverability of the aircraft employed in the operation.

In the discussion which follows, this question will be answered by showing how certain new type fuzes perform. While it may be disappointing, the situation is, nevertheless, such that, in this discussion, it will not be possible to present any information regarding the operating principles or methods of achieving them. This arises from the security restrictions that have been placed on information concerning these principles and from the fact that the classification of all information presented in this meeting is to be confidential.

2. The fuze

The fuzes, now in limited production, which can be used for providing the air burst necessary, belong to a new class of fuzes recently given the name VT (variable time). The fuzes are given this name because they automatically select the proper time of function, without adjustment on the part of the operator, to give the desired height of burst.

These fuzes differ from what we might call here adjustable time fuzes. It is quite reasonable to consider the possibility of obtaining the air burst by the use of extremely accurate time fuzes of the conventional type. If the airplane carrying the bomb could measure its altitude above the target with an accuracy of 15 to 20 ft, if the time fuze could be set with the requisite accuracy, and provided the natural dispersion in time of fall of large bombs was sufficiently small, it would be possible to get an air burst of the proper height. Obviously the requirements on time and altitude measurements seriously hamper the use of such a method.

The VT fuzes, on the other hand, function upon approach to the ground, and it is the approaching ground that initiates the explosion, thereby making the movements of the aircraft, the speed at release, and the altitude of the release of minor importance, provided the bombs fall within certain broadly limited regions.

There are two types of VT fuzes that can be used in this application. These are the T51 and T50. For the present discussion, we are concerned mainly with the T51, since it has been tried and found to operate satisfactorily on the American AN M-56 4000-lb bomb. There are reasons to expect that the T50 series should also be advantageous in this application. But as of this date the T50 fuze has not been tested on the large blast bombs and hence will be mentioned only incidentally at certain points in the discussion.

3. Performance of the VT bomb fuzes

(a) Types of function. — When bombs fuzed with VT fuzes are dropped in the normal manner, three types of functioning are observed: proper functions, early functions, and duds. Proper-functioning fuzes cause air bursts at a height of approximately 50 to 75 ft over open flat ground. Early functions occur in a certain small fraction of the cases during the time the bomb is falling and at a location somewhere between the point at which the fuze becomes armed [see Sec. 4(a) on the Arming sequence] and the encounter with the approaching ground. Duds arise from inoperative VT fuzes in a very small percentage of cases. Loss due to duds is practically eliminated by fuzing the bomb at the same time with a normal impact-type tail fuze. Thus a dud VT fuze merely leads to an impact burst similar to that which would be obtained if no VT fuze were used.

(b) Reliability. -- When VT-fuzed bombs are dropped singly from aircraft flying at 10000 ft with air speed approximately 200 mi/hr, if the fuzes are properly installed according to the instructions supplied with them, it can be expected that more than 80% of the functions will be proper. As the producing facilities learn the techniques of fuze manufacturing, the performance score is improving. Acceptance tests at the Aberdeen Proving Ground on current lots of T51 fuzes are 87% proper functions, and at most only 1 or 2% duds. Nevertheless, it seems wise to be conservative in the predictions of the reliability of the fuze, and to use the figure 80% in making calculations of over-all effectiveness.

(c) Height of burst. -- The fuzes have been adjusted at the factory to give an average height of burst in the standard reference bomb, M-57 250-lb GP, of 55 ft over average ground. No field adjustment is available for changing this height of function. There is a fuze now in the design and early experimental stages which will have an adjustment for changing the height of burst, but it is not yet available, hence is not of immediate interest.

Production variations in the operating components of the fuze lead to a spread in the heights of bursts obtained under a given testing condition. If a large number of bombs are tested on the identical target and the distribution of heights of bursts recorded, the result is as shown in Fig. 14. This figure represents the results on a test of some 219 bombs fuzed with T51 from some 22 manufacturer's lots. It will be observed in the study of this figure that 50% of the bursts of properly functioning fuzes fall within the interval ±7 ft from the mean and that approximately 80% of the fuzes fall within the interval ±15 ft.

(d) Effect of terrain conditions. -- In connection with the spread in height of burst, it must be pointed out that aside from the variations among fuzes themselves, the type of target or "built-up-ness" of the terrain will influence the height of burst. This introduces a further dispersion factor upon which no great amount of information is available. For example, bombs dropped over water show approximately twice the height of burst of those dropped over average ground. When bombs are dropped over

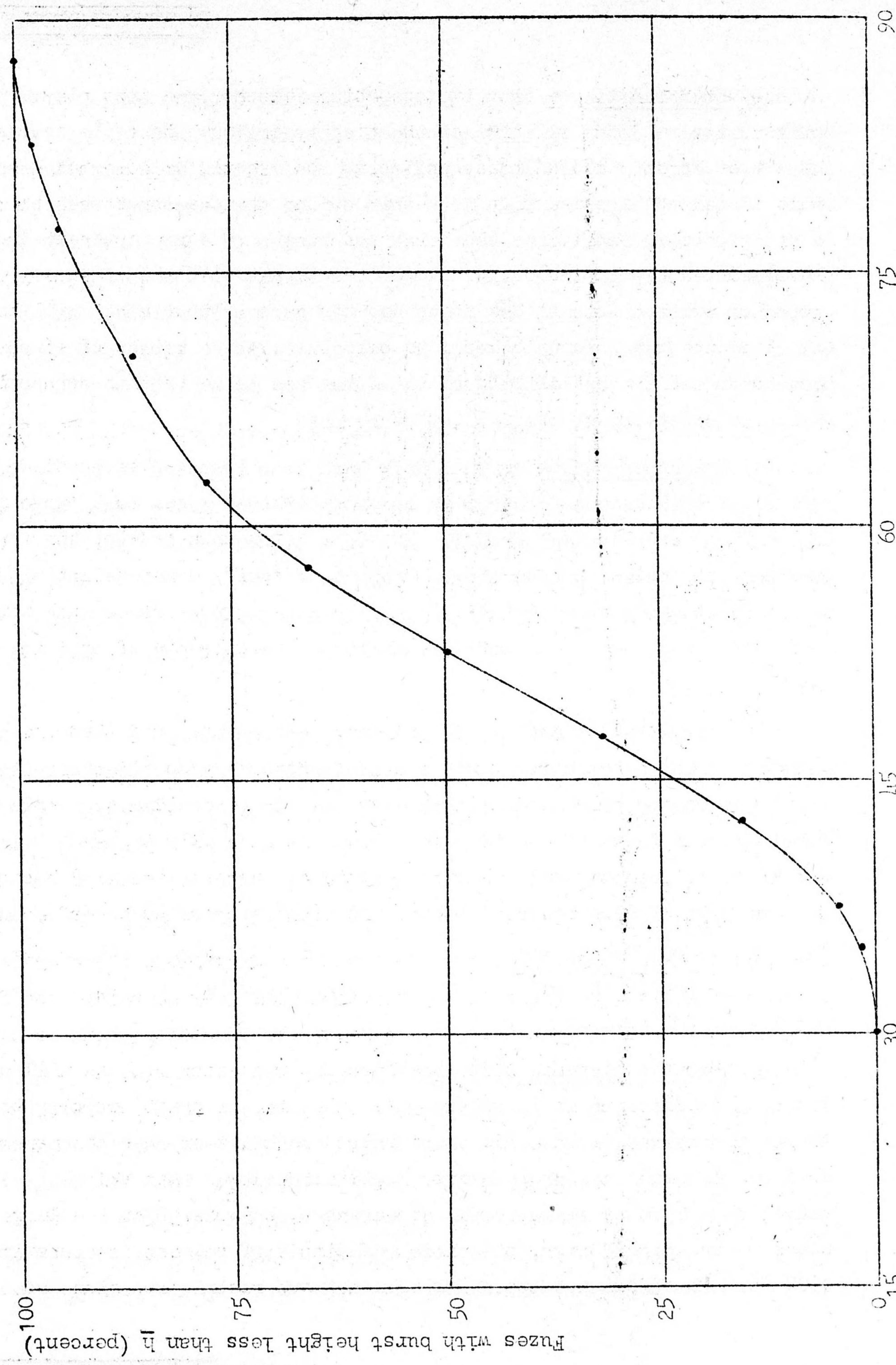

Fig. 14. Cumulative distribution, T51E1 over average ground at 10000 ft and 200 mi/hr. Test includes 219 units, 22 manufacturers' lots.

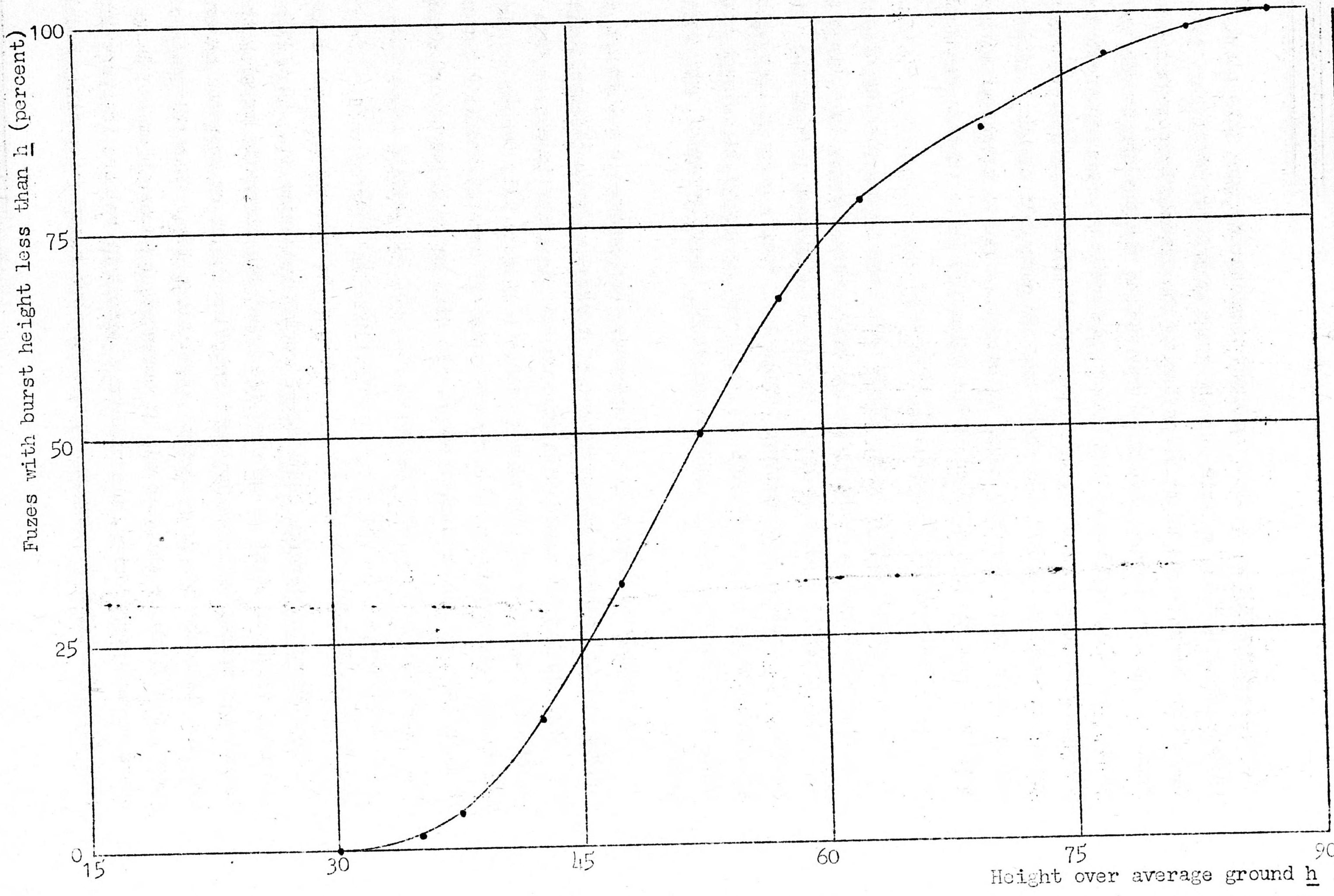

Fig. 14. Cumulative distribution, T51E1 over average ground at 10000 ft and 200 mi/hr. Test includes 219 units, 22 manufacturers' lots.

built-up terrain like a city two competing factors come into play. The type of structure and the material of the targets are such that the average height of burst based on these criteria alone should be somewhat less than that quoted for average ground. However, the various structures themselves form targets and influence the height of burst since the apparent ground level varies from point to point over the target. At the present time, the evidence available indicates that the average height of burst will be raised by an amount approximately equal to half the average height of structures. Some operational test data would be of immense value in this connection.

Attention should be called here to the properties of the T50 fuze mentioned earlier. The T50 fuze is more sensitive to the passing of objects and less sensitive to a direct approach at a steep angle to a large surface. This might mean that a fuze which would function upon passing the tops of the various structures would give a quite effective burst height although if tested on an open flat surface, the burst height might be much too low. Here, too, an operational trial seems to be the only way of arriving at the proper answer.

In previous lectures, it has already been pointed out that the damage is not a critical function of height of burst, and a considerable dispersion in height can be tolerated without much loss in effectiveness. This is fortunate in two ways: (i) because it means that generally the same height of burst can be effective with a wide variety of targets, and (ii) because it does not place undue restrictions on the dispersion of fuze performance.

(e) Release conditions. -- As was mentioned earlier, there are certain broad restrictions on the release conditions that may be used. The fuze design is such that it is not armed and ready for operation until it has fallen a certain distance below the aircraft releasing it. As will be seen later, this distance is large enough so that the aircraft dropping the bomb is not endangered if an early burst should occur at or near the moment of arming. If bombs are dropped from an altitude lower than this safe distance, the VT fuzes will, to all appearances, be duds. For the large blast bombs we are considering, the minimum altitude of release is approximately 3000 ft. This does not appear to be a serious restriction since bombing of the type we are interested in here is not done from such low altitudes and, further, if it were unsafe to allow the bomb to burst closer than 3000 ft to the aircraft, it would likewise be unsafe to drop instantaneous-fuzed bombs from an altitude of less than 3000 ft.

A second restriction is that speed of the plane at release and the altitude must be such that the striking angle of the bomb, measured from the vertical, does not exceed 45°. If this angle is exceeded, the height of burst will be reduced considerably, except for those bombs that pass close to a structure and function upon passing. A little consideration shows that this is essentially no restriction since normal release speeds and release altitudes are such that the striking angle is always much less than 45°.

Thus far when proper arming attachments are used, there is no evidence to indicate an upper limit on the release altitude. To date, tests have been made on only a few fuzes from altitudes of 30000 ft. Those tests have indicated that the stated 80% function score can be achieved for releases up to 30000 ft (see Sec. 4 on Safety).

(f) Mutual interaction. — It will no doubt be evident from the discussion thus far on the properties of the VT fuzes that they are essentially devices which are sensitive to a change in the surroundings and arranged to respond to it. It is common practice to drop bombs in trains arranged by means of a release mechanism so that the impacts on the ground are spaced at regular intervals. This means that there may be several bombs in the immediate vicinity of one another in the air. Thus it is to be expected that an early burst of one bomb in the train would cause a sympathetic response in the others. This is found to be true and experiments have shown it is necessary to maintain a space between the bombs greater than a certain minimum value if an accidental early burst from one is not to cause a sympathetic function in another. The exact mechanism for this interaction is not known, but experiments have shown that it is not due to the interaction of the fuzes themselves. Tests have clearly indicated that the effect is due to the explosion of one bomb in the vicinity of another. For this reason, it is to be expected that small bombs do not require as large a spacing as large bombs. Sufficient numbers of large blast bombs have not been tested to allow information to be obtained on the minimum spacing in this case. Tests have shown that a 50-ft spacing is adequate for 250-lb bombs and that 100-ft spacing is adequate for 500-lb bombs. It is to be expected that an interval of something like 500 ft will be required for the large bombs. However, the size of targets attacked and the type of target for which the use of large blast bombs is considered effective, is such that a large train spacing need not be a serious disadvantage. Tests are certainly indicated to evaluate this minimum interaction distance.

Finally, however, it seems reasonable to assume that the radii of damage obtained from these large bombs is such that to make fully effective use of them would require large spacings anyway.

(g) Dependence on bomb size and shape. -- VT fuzes differ from normal fuzes in that the whole bomb must be considered as a part of the fuze and the size and shape of the bomb determines in a measure the performance of the fuze. For example, a bomb with a flat nose similar to the British 4000-lb LC does not allow the use of the VT fuze without some modifications in design. The flat nose disturbs the air flow and prevents the proper operation of the rotating vane which supplies the energy to operate the fuze. A bomb with a stream-lined nose similar to the American 4000-lb bomb gives quite satisfactory operation.

This dependence of fuze operation on bomb geometry must be considered when a fuze of the VT type is considered for any particular application. It is pointed out here, for the purpose of calling attention to the fact, that when it is desired to use a VT fuze on a bomb for which its performance has not already been investigated, it will be wise to consult with VT fuze engineers before attempting such use.

The size of the bomb also has an effect on the height of burst. Fortunately it has worked out that the fuze when mounted on the American 4000-lb bomb gives a somewhat higher burst than when mounted on the smaller bombs used for anti-personnel fragmentation effects. This increased height of burst on the large bomb compensates for the fact that the average burst height is reduced due to the character of the material of the target encountered in built-up city structures.

4. Safety

(a) Arming sequence. -- Tremendous emphasis has been placed on the safety mechanism incorporated in the VT fuze. The arrangement is such that when the bomb is released, an arming wire is pulled free and allows a wind-driven vane to rotate. For the fuze to function it is necessary that this vane rotate a certain definite number of revolutions in order to complete an interrupted powder train. In addition to this, it is also essential that the arming vane be rotating and continue to rotate at a high speed. Both are necessary for the fuze to function. This means that after the bomb is released from the airplane, it must move a fixed distance from the airplane along its trajectory to reach the point at which the mechanism is armed. This distance is marked on each fuze and called Safe Air Travel. The fuzes are calibrated on a 100-lb bomb because conditions of air flow around the nose are such that the safe air travel on larger bombs is larger. For an airplane traveling 200 mi/hr, the 300 ft of air travel normally incorporated in the fuze is used up when a 100-lb bomb has fallen approximately 1800 ft. The corresponding figure of vertical drop for the 4000-lb bomb is approximately 3000 ft. Higher plane speeds mean smaller vertical drop to the arming point and lower plane speeds mean longer vertical drop. Tables have been prepared giving the safe air travel or vertical drop on the various bombs that have been tested. These tables will be found in technical manuals already published concerning the fuzes.

(b) Arming delay of T2. -- In certain tactical situations it is necessary to increase the air travel to arming in order to provide safety for nearby friendly aircraft. This is accomplished by an adjustable attachment, T2, which can be installed on the fuze in the field to give additional air travel in steps of approximately 1000 ft up to 20000 ft of additional air travel. When installed on the fuze, the arrangement is such that the extraction of the arming wire leaves the rotating vane on the arming attachment free to turn in the air stream. As the bomb falls the arming vane of the VT fuze is locked by the T2 attachment so that it cannot rotate. When the elapsed air travel set on the T2 device has been reached, the arming delay flies off the fuze, releases the rotating vane on the fuze itself, which then must turn through the requisite number of revolutions to its arming point.

The fact that the fuze is inoperative until the arming delay has disengaged itself from the fuze reduces the number of early functions that might obtain otherwise. It has been found during the course of experiments with the VT fuze that early functions are essentially statistical in nature arising from certain features of the internal mechanism which we are not at liberty to discuss here. For this reason the early functions distribute themselves almost at random along the trajectory from the arming point to the target. When the arming delay attachment is used, the length of trajectory in which the fuze is used, is reduced. Therefore the incidence of early functions is reduced almost in proportion. For high-altitude bombing it thus becomes essential to use the T2 device for purposes of fuze performance even in the absence of any consideration about safety to nearby aircraft. In fact, many considerations lead to the recommendation that the arming-delay device be used in all circumstances to reduce the armed part of the trajectory to the last 5000 ft of fall.

5. Summary

To summarize the remarks, it seems adequate to point out that the purpose of the discussion was to answer the question "Can we produce an air burst at the height required to give the enhanced damage pointed out in the other lectures?" I believe the facts indicate that the answer is "Yes."

Afternoon Session

Part II. TECHNICAL ASPECTS OF AIR BURST FOR BLAST BOMBS

A. Photographic Investigation of the Reflection of Plane Shocks in Air

B. The Theory of Air-Burst Action

C. An Empirical Method of Correlating Air-Burst Data

A. THE THEORY OF AIR-BURST ACTION

(A review of the status of the theory of shock interactions)

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1. Statement of the problem

Whenever an explosion occurs, it releases a large amount of energy in a small region in a short interval of time. Consequently the neighboring medium is compressed and, in turn, compresses its own surroundings; thus the disturbance spreads. When this wave passes a particular point, the pressure there increases abruptly and then decreases more or less exponentially with the time [Fig. 15(a)]. The peak pressure itself decreases somewhat more rapidly than inversely with the distance of the point from the source of explosion. The phenomenon, therefore, is described empirically by the pressure-time record at a point and by the pressure-distance relation for various points.

When the initial wave strikes a surface, it is reflected. The resultant effect at any point now depends upon the actions of both the reflected wave and the initial one, or, more precisely, upon their interaction. Hence the primary concern of any theory of air-burst action above the ground is a principle of superposition for such waves. The analogous principle of Huygens in acoustics is inapplicable here inasmuch as the disturbances are so large that the differential equations describing their propagation are nonlinear. The mathematical difficulties presented by this fact are intensified by the necessity of satisfying physical conditions at boundaries which themselves have to be determined simultaneously with the solutions of the equations. Consequently, it is desirable to use some simple model such as a step shock wave in which the pressure rises discontinuously along a plane wave front and then remains constant [Fig. 15(b)]. It is further assumed that this approximation is applicable locally in the neighborhood of the intersection of curved waves. In this very region, however, the phenomenon is elusive and requires great experimental precision, a fact that offers difficulties both for gauge calibration and for optical interpretation. Nevertheless, a combined experimental and theoretical approach has resulted in the acquisition of much knowledge. Even though the complete solution of the problem has not yet been attained, sufficient information is already available to give an adequate theory of air-burst action. This material is best considered in conjunction with the experimental evidence, which will be presented in the following papers. The purpose of the immediate discussion is solely to review the theoretical situation with particular emphasis upon the underlying assumptions, inasmuch as these undoubtedly conceal the yet unsolved aspects of the basic problem of interaction.

2. Nature of elementary phenomena

The elementary phenomena involved are shock waves and so-called "centered, simple waves" [see Sec. 2(b)]. Throughout the discussion the fluid will be taken as ideal, in the sense that thermal conduction and viscosity will be assumed to be negligible.

(a) Shock waves. -- Consider a plane step shock wave moving at supersonic speed into a fluid at rest [Fig. 16(a)]. Then the material behind its front will also be moving in the same direction, but at a subsonic speed with respect to the physical conditions there. It is convenient to observe this phenomenon from the vantage point of the shock front itself. To an observer on the shock front the fluid appears to flow toward the shock front at supersonic speed and then away from it at a subsonic rate after crossing it [Fig. 16(b)]. A knowledge of the initial state of the fluid together with the application of the conservation laws of mass, momentum, and energy requires only the specification of a single parameter for the complete description of this stationary phenomenon. In the case of an ideal gas, indeed, the various physical quantities are uniquely determined by a parameter such as the shock strength (say, the ratio of the pressures on either side of it), as well as by the adiabatic exponent (assumed constant). When the flow is oblique to the shock instead of normal to it, the direction of flow also must be specified. The flow always turns toward the shock front upon crossing it [Fig. 17(a)]; thus supersonic flow into a corner may be said to be made possible by the presence of a shock wave [Fig. 17(b)].

Two particular cases of supersonic flow across an oblique shock wave are worth noting. On the one hand, if the shock strength is kept constant,

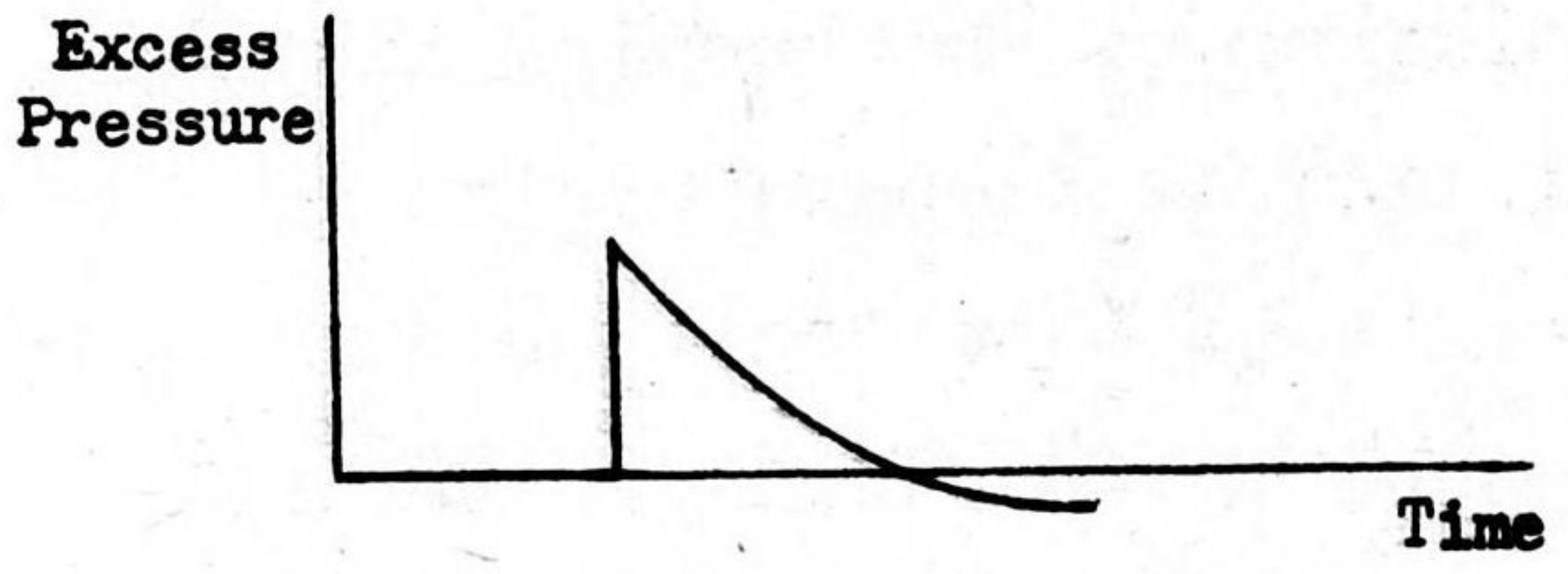


Fig. 15(a). Explosion wave.

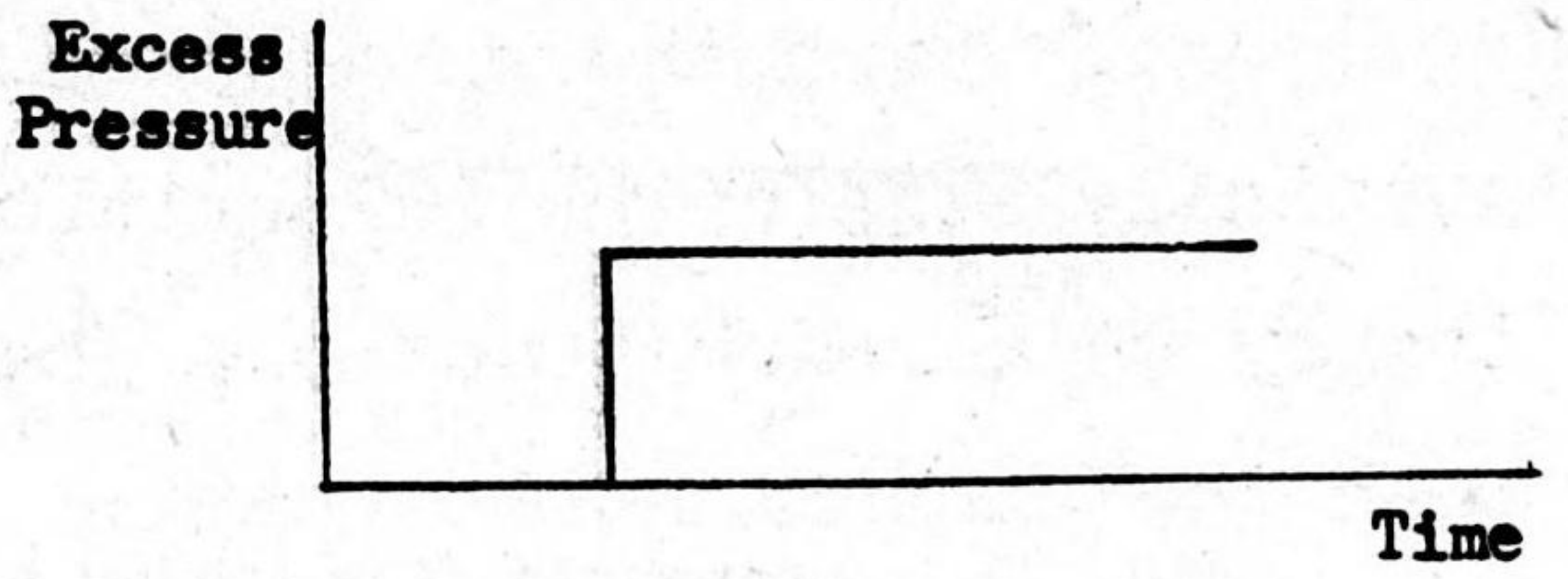


Fig. 15(b). Step shock wave.

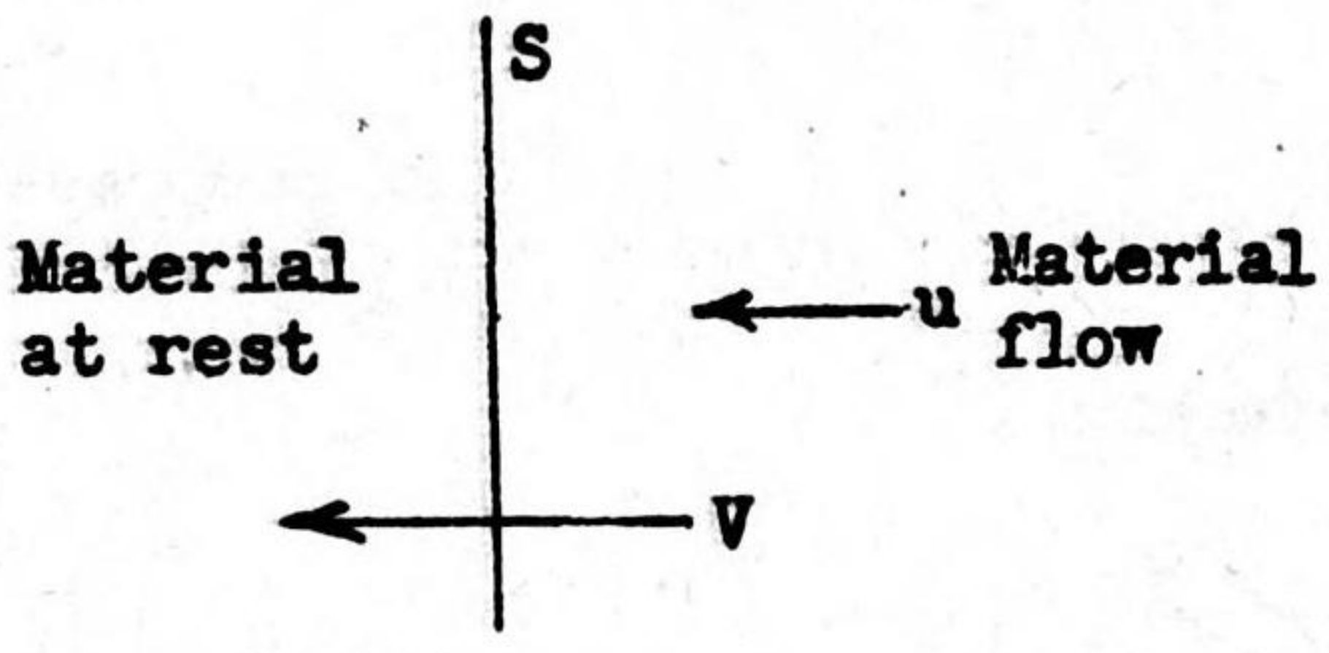


Fig. 16(a). Moving shock wave S.

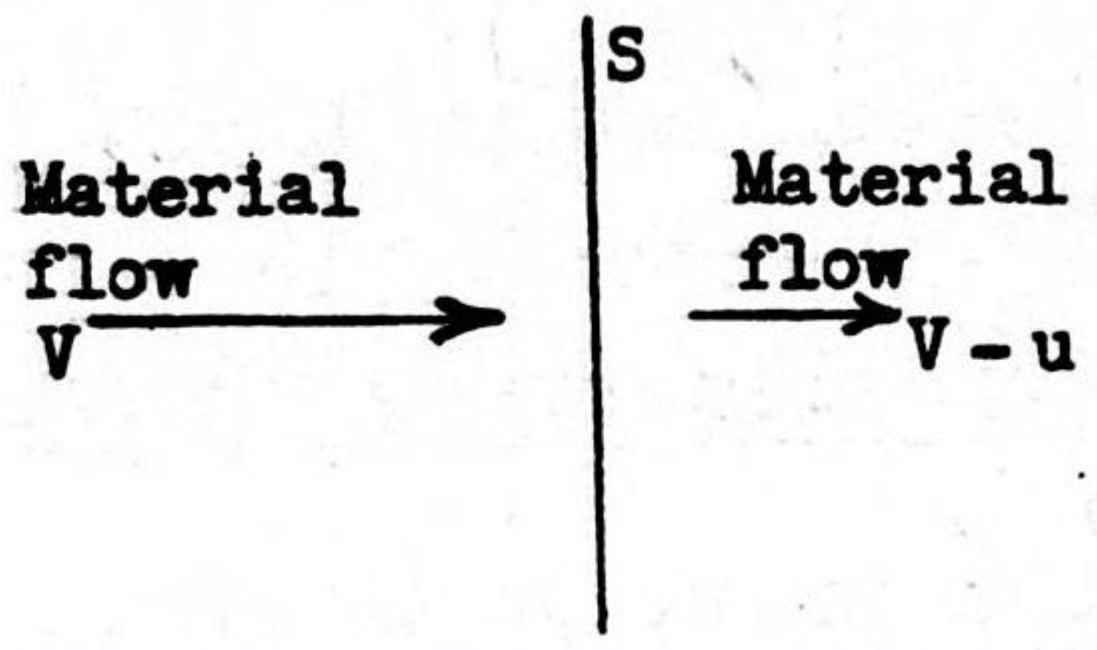


Fig. 16(b). Stationary shock wave S.

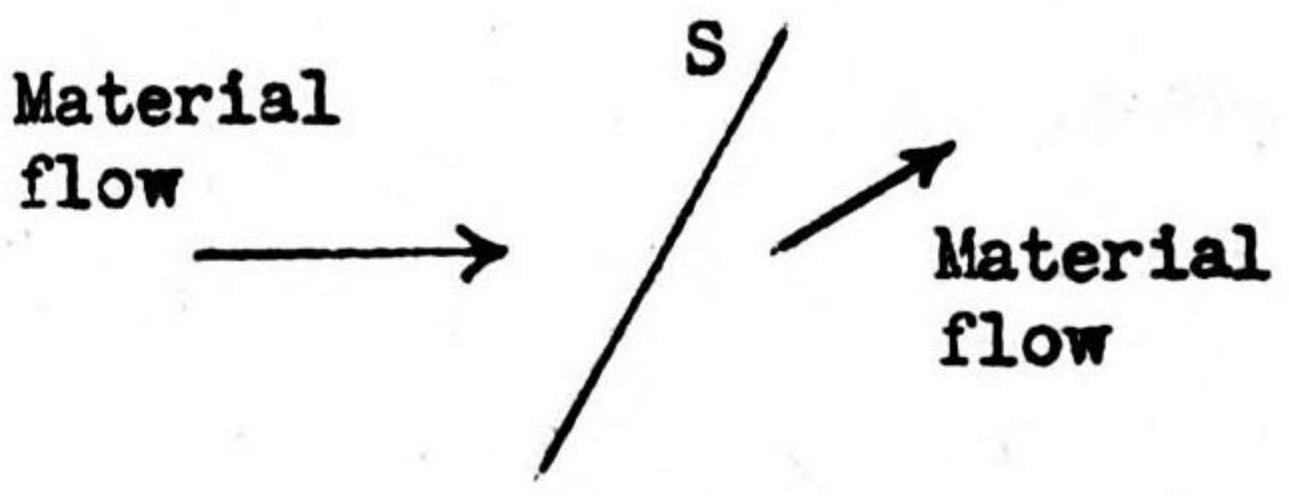


Fig. 17(a). Stationary oblique shock wave S.

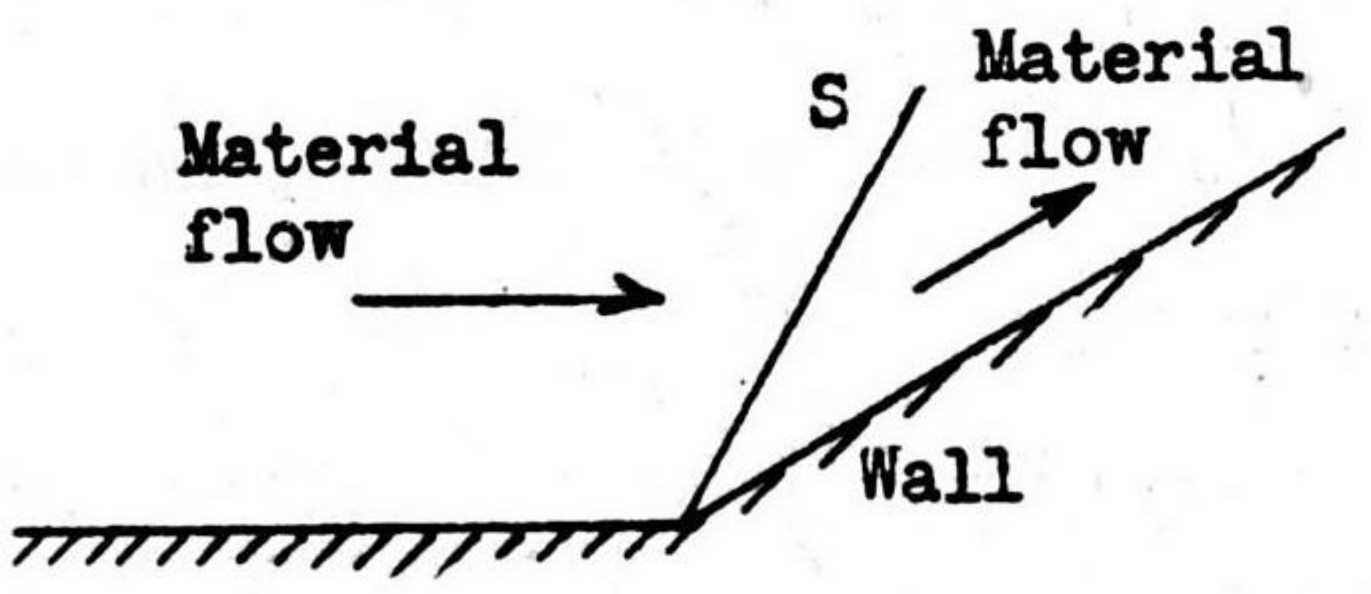
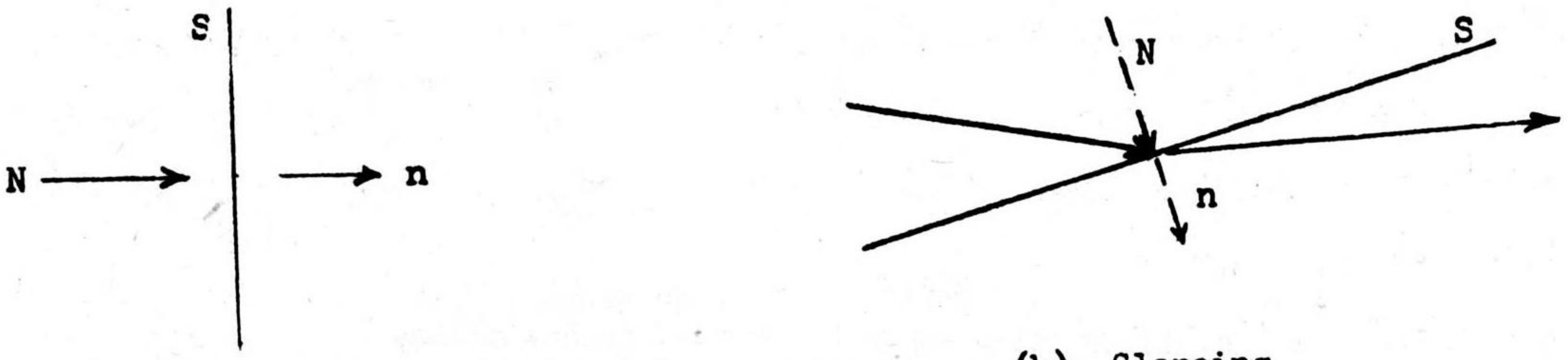


Fig. 17(b). Supersonic flow into a corner.



(a) Normal

(b) Glancing

Fig. 18. Supersonic flows for same shock strength.

(a) Normal

(b) Oblique

Fig. 19. Supersonic flows for same initial speed.

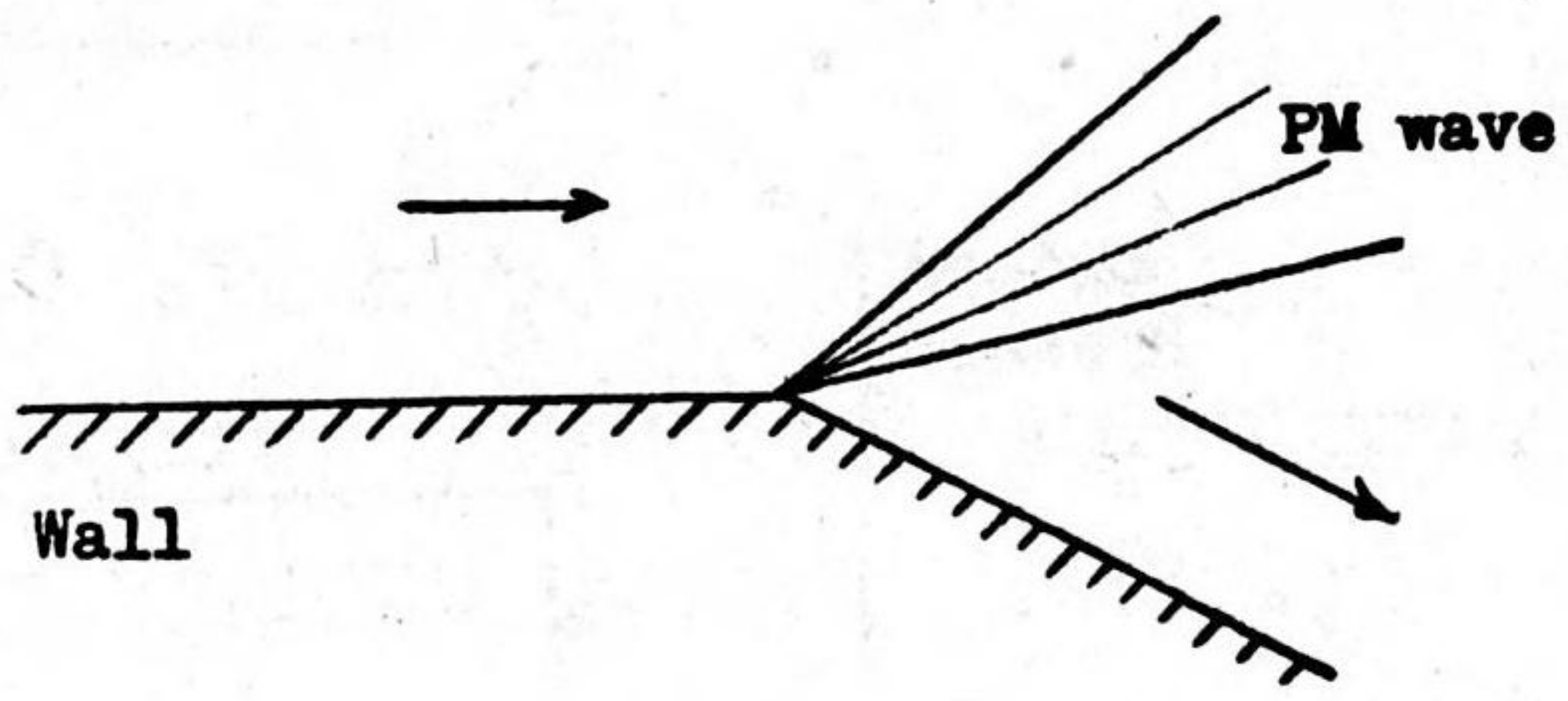


Fig. 20. Supersonic flow around a corner.

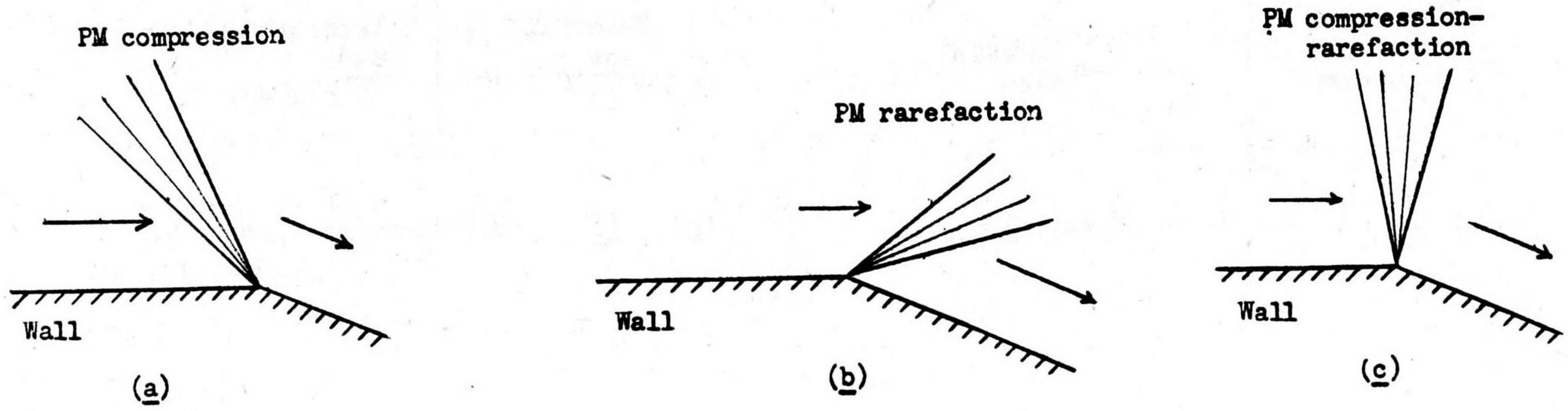


Fig. 21. Stationary Prandtl-Meyer waves.

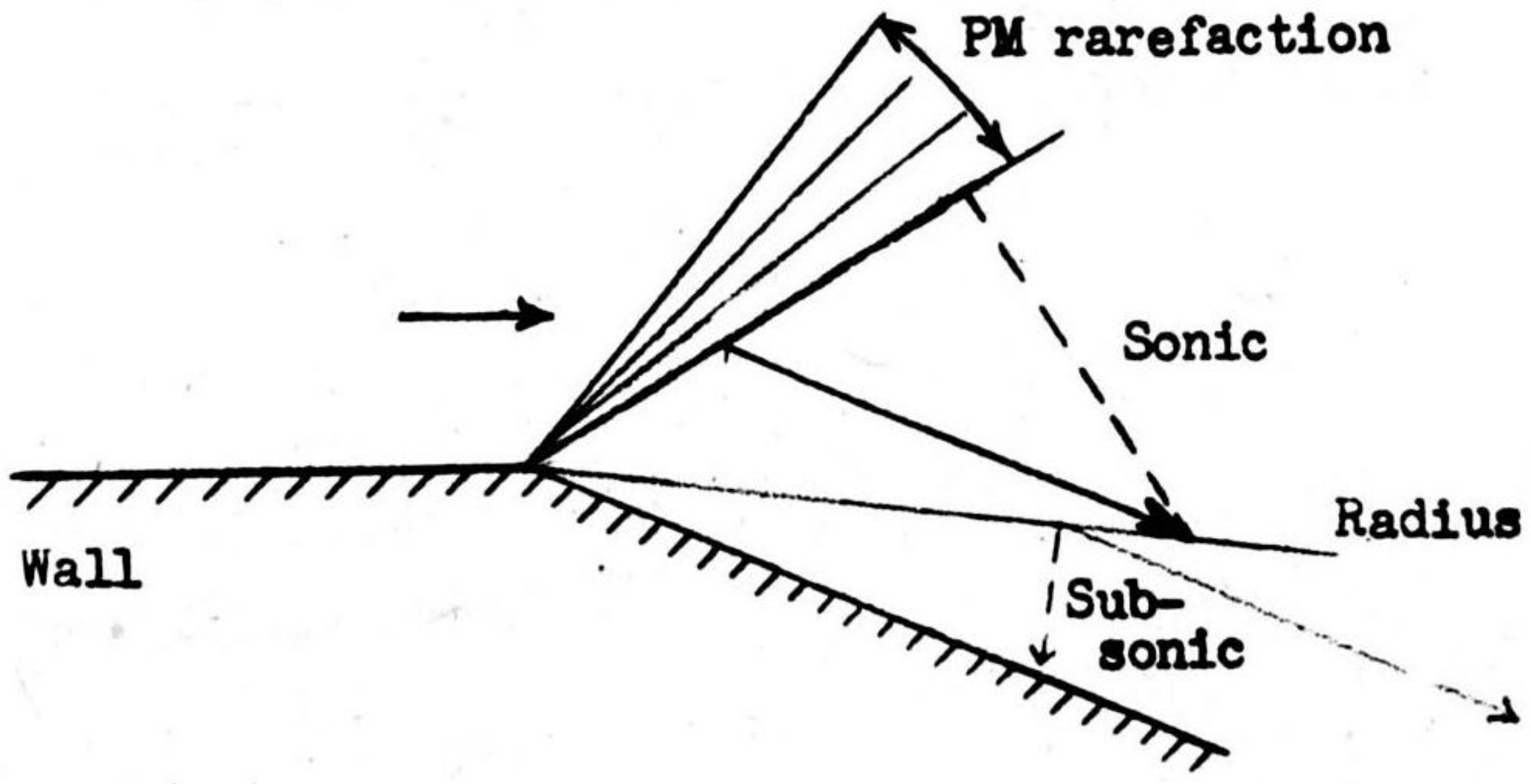


Fig. 22. Prandtl-Meyer rarefaction showing that velocity component normal to any radius beyond the rarefaction zone must be subsonic.

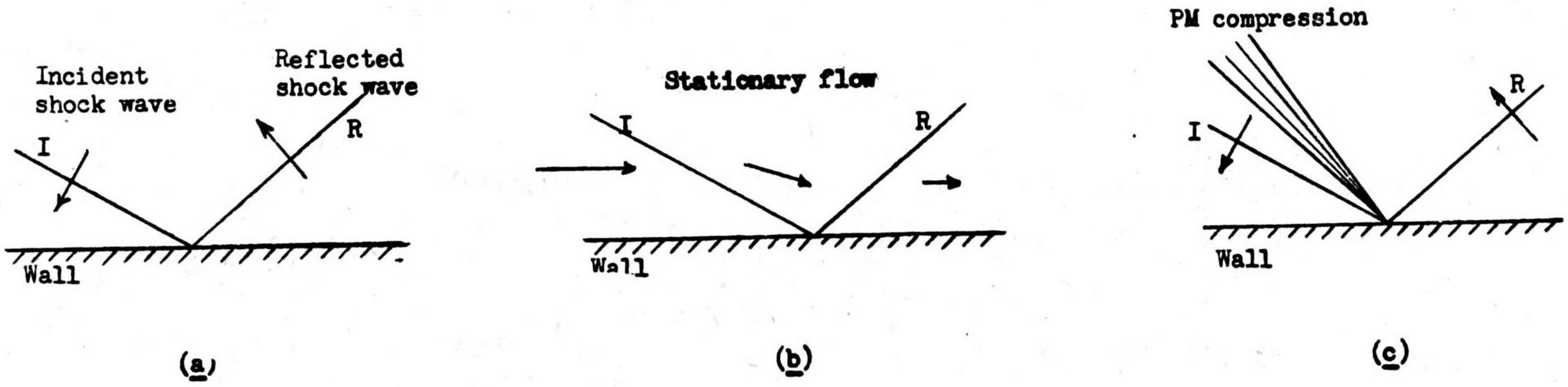


Fig. 23. Regular reflection.

but the direction of flow is changed gradually from normal to glancing, an intermediate position is reached such that for oblique directions the flow downstream is always supersonic (Fig. 18). This position is sometimes called the "extreme sonic limit." On the other hand, if the initial speed of flow is kept the same, but its direction made increasingly more oblique (Fig. 19), a limiting direction is reached such that for more glancing flows no shock wave at all can exist.

(b) Prandtl-Meyer waves. -- Supersonic flow around a corner (as contrasted with that into a corner) is adjusted through a centered, simple wave, usually designated a Prandtl-Meyer (PM) wave (Fig. 20). In addition to the two-dimensional differential equations of continuity and of motion which describe the conservation of mass and of momentum, respectively, it is stipulated that all physical quantities are constant along each radius from some fixed center, such as a "corner," and that the flow is isentropic. The first condition implies that the flow is irrotational and that its component at right angles to each radius is sonic. Combining this latter fact with the second condition, we find that the flow is completely determined by the initial and final values of the flow velocity. In general, the flow is such that the radial component of velocity outward steadily increases. When the radial component is initially inward, the velocity continuously decreases and the pressure increases according to Bernoulli's theorem. Thus the Prandtl-Meyer wave starts as a compression wave [Fig. 21(a)]. If the radial component is initially outward, the wave is one of rarefaction [Fig. 21(b)]. It is also possible for the radial component to be initially inward and finally outward so that a compression-rarefaction wave, too, is possible [Fig. 21(c)]. It is to be noted that stationary flow cannot pass through a PM rarefaction or compression-rarefaction and then cross a shock wave, for the component of velocity normal to any radius beyond a PM wave is necessarily subsonic (Fig. 22).

3. Regular reflection

We shall now consider the possibility of interpreting the interaction of shock waves in terms of these elementary phenomena.

(a) Shock waves. -- Consider a plane, step shock wave incident obliquely upon a rigid wall [Fig. 23(a)]. The flow will be taken as stationary relative to a coordinate system centered at the intersection of the incident and reflected waves as it moves along the wall [Fig. 23(b)]. Now the incident shock wave directs the flow toward the wall -- into a corner, as it were. The reflected shock wave then must be in a position to turn the flow back so as to be parallel to the wall. It is found that for given shock strength and for not too glancing an angle of incidence, there are two possible positions for the reflected wave. Only the one with the lower pressure, however, has been observed to date. As the incidence is made more glancing, the two positions merge. Beyond the "extreme" angle this so-called "regular reflection" is impossible, that is, the reflected shock wave no longer intersects the incident one at the wall. Instead, the line of intersection has been observed to be situated away from the wall and to be joined to the wall by a third shock wave, called the Mach shock or "stem." This type of irregular reflection is termed "Mach reflection" [Fig. 24(a)]. It is believed that the reflected pressure has a maximum value in the region of the incipient Mach effect, inasmuch as the reflected pressure for "extreme" regular reflection of weak shocks exceeds even that for normal incidence. This characteristic is largely responsible for the peculiar effectiveness of air-burst action.

(b) Shock waves and Prandtl-Meyer waves. -- The above configurations for regular reflection are based on the assumption that each of the regions behind a shock wave has uniform physical properties. It is of interest to inquire whether Prandtl-Meyer waves can also exist. A rarefaction or compression-rarefaction cannot be behind the incident shock wave because the flow has yet to pass through the reflected shock. A compression, however, is possible in this region [Fig. 23(c)]. In such a case the reflected wave for regular reflection is always more glancing; moreover, Mach reflection begins at less glancing angles of incidence. On the other hand, it is impossible for any PM wave to exist behind the reflected shock, since the component of flow at right angles to each radius beyond the reflected wave is necessarily subsonic because the latter is always situated so as to deflect the flow away from the normal to the wall.

(c) Comparison with experiment. -- The theory of regular reflection without a PM wave is adequate to interpret -- indeed, it predicted -- the observed data to which it applies. There are only two minor discrepancies. For very strong incident shocks the reflected shock is less glancing than expected. This systematic variation may be due to the assumption of a constant adiabatic exponent. Furthermore, near the "extreme" position for shocks of all strengths the observed reflected shock is not sufficiently glancing. There is no ready explanation for this failure of the theory. (A PM wave would produce a change in the opposite direction.)

4. Mach reflection

(a) Shock waves. -- In the case of Mach reflection the flow is considered relative to the moving line of intersection of the three concurrent shock waves [Fig. 24(b)]. It can be shown theoretically that uniform physical states (pressure, density, and material velocity) cannot exist in all the regions between the shocks. Configurations are possible, however, in which there is a single nonuniformity in one of the regions, namely, a plane of density discontinuity or "slipstream," originating at the intersection. What is more, such a discontinuity is actually observed between the reflected and Mach shocks. In general, for given incident shock strength and for nearly glancing initial flow there are two possible configurations (occasionally three). This new set of solutions has the distinctive feature that the reflected and the incident shock both deflect the flow in the same direction. For less oblique flow, however, only one family of such shock intersections exists, namely, the one which is relative to the solutions of regular reflection; but it, too, is missing for more nearly normal flow. It is to be noted finally that this "simple" theory of three-shock intersections is limited to less normal flow than would be determined by the "extreme sonic condition." In each case the pressure behind the Mach shock decreases as the flow becomes more normal -- a significant fact in the consideration of air-burst action.

(b) Shock waves and Prandtl-Meyer waves. -- It is important to ascertain the effect of Prandtl-Meyer waves in the various regions. Only a compression wave is possible beyond the incident shock wave inasmuch as the PM wave is to be followed by the reflected shock [Fig. 24(c)]. In the region beyond the

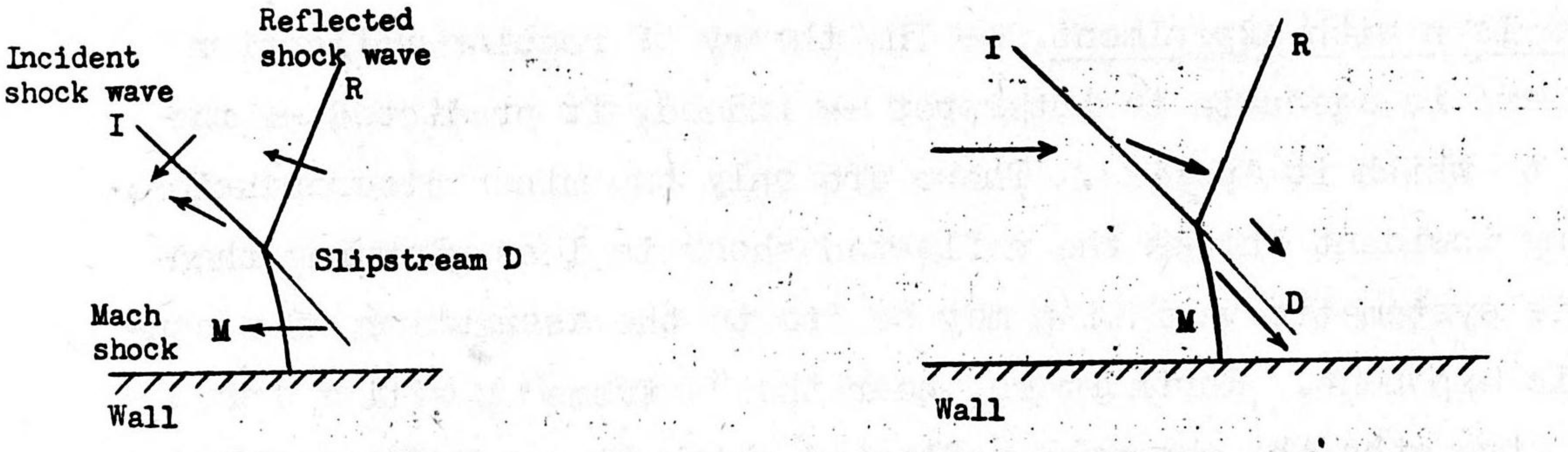


Fig. 24(a). Moving shock waves.

Fig. 24(b). Stationary shock waves.

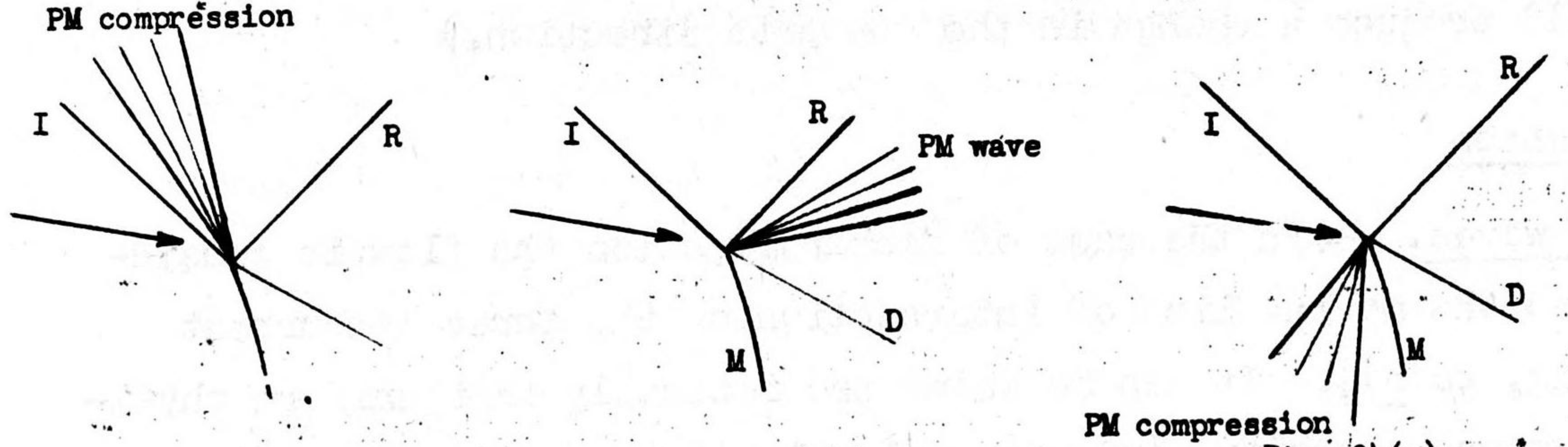


Fig. 24(c)

Fig. 24(d)

Fig. 24(e)

Fig. 24(c,d,e). Possible combinations of Prandtl-Meyer waves with Mach effect.

Fig. 24. Mach reflection.

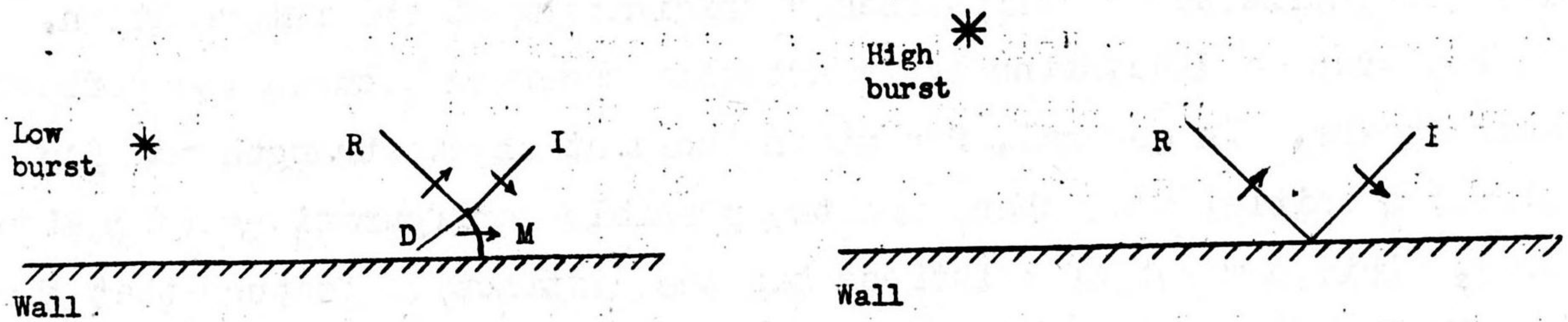


Fig. 25(a). Ground Mach reflection.

Fig. 25(b). Ground regular reflection.

Fig. 25. Air burst at a fixed distance.

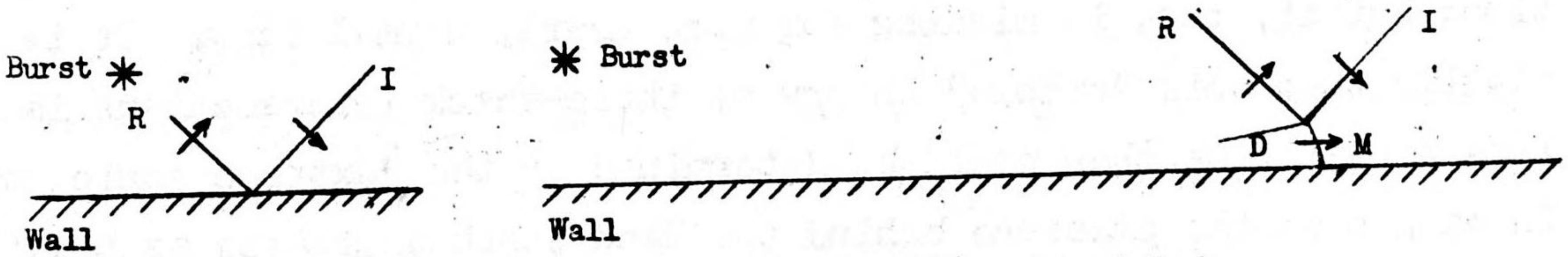


Fig. 26(a). Ground regular reflection near the burst.

Fig. 26(b). Ground Mach reflection far from the burst.

Fig. 26. Air burst from a fixed height.

reflected shock wave all types of PM waves are possible [Fig. 24(d)]. In this case, however, the range of pressure change is limited for those configurations in which the incident and reflected shocks cause opposite deflections of the flow: the flow beyond the second shock is only slightly supersonic, whereas its inclination to a radius is usually too small for the component at right angles to be sonic. Indeed, this same limitation operates even more stringently beyond the Mach shock so that PM waves are not at all possible here. Finally, a compression wave can theoretically exist in front of the Mach shock [Fig. 24(e)] -- but not a rarefaction or compression-rarefaction, on account of the subsequent shock wave. It is significant that all the PM modifications, except the one with the compression between the incident and reflected shocks, allow more normal flows than the configurations involving discontinuities alone.

(c) Comparison with experiment. -- It is difficult to compare the theoretical predictions with the existing experimental observations in view of the fact that the conditions of the latter do not completely satisfy the assumptions of the former. In the first place, stationary flow is limited to observations of wind-tunnel shocks and of projectile headwaves. Such data, however, are rather fragmentary. The evidence to date indicates that one of the "simple" three-shock families is adequate to describe the few wind-tunnel results (for comparatively strong shocks), whereas the other family is applicable to the known intersecting headwaves (weak shocks). In the latter case the agreement between theory and experiment is apparently improved by PM modifications, but it awaits confirmation from a more systematic study. It must be remarked that the actual shock waves in these instances are not simulated by step shocks; they are more nearly like explosion waves. Secondly, the reflection of step shock waves in a so-called shock tube is only quasi-stationary, that is, the development of the configuration remains similar to itself, but not congruent. Moreover, the effect of the wall and its corner still further complicate the situation here. Precise observations in this regard have now been completed over a wide range of shock strengths. For relatively strong shocks the "simple" theory of three-shock intersections is satisfactory except for certain flows that appear to be more normal than those allowed. In this case PM modifications offer hope of a satisfactory explanation. For weak shocks, however, the "simple" theory is wholly inadequate.

At present, some preliminary investigations of PM modifications indicate that this difficulty, too, may be resolved -- particularly by a compression ahead of the Mach shock. Nothing conclusive, however, can be formulated until the general survey of PM waves now under way has been completed and applied to the analysis of the data. It may well be that some effect which is large for weak shocks is still active, but relatively insignificant, for strong shocks; in other words, that the apparent satisfactoriness of the "simple" theory for the latter is, in a certain sense, accidental. Of course, various combinations also of the elementary types of such configurations can be made; the addition of the parameters involved renders the theory somewhat ad hoc. What is definitely needed is the exploration of the various regions in question by sensitive optical techniques such as interferometric and schlieren methods. The use of the available schlieren apparatus to date, it is true, has disclosed various density variations, but none that can as yet be identified with PM waves. One of the difficulties in this respect -- indeed, what vitiates any too positive statements concerning even the positions of certain of the discontinuities -- is that the optics in the neighborhood of the intersection is complex. This difficulty, of course, is aggravated by incident shocks that are not plane, such as explosion waves, ballistic headwaves, and wind-tunnel shocks. It should be added that gauge measurements are even less reliable for this purpose.

In view of the inadequacy of the simple theory, including Prandtl-Meyer modifications, it is highly desirable to apply analytical methods for the determination of nonuniform solutions that rigorously satisfy the boundary conditions. Up to the present it has been possible to obtain only one such solution, namely, that for the reflection of a weak shock wave at infinitesimally glancing incidence. The pressure distribution predicted behind the Mach shock has certain peculiar characteristics that have not yet been detected experimentally. In any event, more experimental guidance is needed before the power of such methods can be utilized efficiently.

5. Air-burst action

Fortunately the main features of air-burst action can be understood without a complete knowledge of the mechanism of Mach reflection. The theoretical considerations given in the foregoing indicate that a maximum peak pressure should be observed when reflection takes place for incidence in the neighborhood of the "extreme" angle. For example, consider the effect at a fixed distance from a charge exploding at various heights (Fig. 25). When the charge is near the ground the incidence is more glancing than when it is very high; the pressure, too, is greater. At some intermediate height, therefore, a correspondingly weaker shock wave must be at its "extreme" angle of incidence. On the other hand, consider a charge at a fixed height (not too great). Just beneath the charge the incident shock wave strikes the ground normally [Fig. 26(a)]. At a great distance away, however, the shock wave is at glancing incidence and is much weaker [Fig. 26(b)]. Again it can be shown that at some smaller distance there is an angle of incidence which is "extreme" for a corresponding pressure of intermediate strength. Thus in both cases there should be a position for maximum peak pressure. These predictions have been verified experimentally. Moreover, it is found empirically that an impulse criterion gives the same optimum heights, respectively. The important factor in this regard is that even though the pressure behind a regularly reflected wave (near the "extreme" position) may be less than that behind a neighboring Mach configuration, its duration is much longer -- hence the greater impulse. As yet it has not been feasible to attack the problem of impulse for oblique reflection.

B. PHOTOGRAPHIC INVESTIGATION OF THE REFLECTION OF PLANE SHOCKS IN AIR

by L. G. Smith
Princeton University

1. Experimental procedure

The reflections of plane shocks in air by a plane rigid wall have been studied by shadow and schlieren photography. Shocks of accurately predetermined strength are produced in the expansion chamber of a rectangular tube by bursting a cellophane diaphragm separating it from a compression chamber. The tube (Fig. 27) is of $\frac{1}{4}$-in. steel with inner dimensions 2 × 7 in. and is mounted horizontally with the 7-in. dimension vertical. The compression chamber is $1\frac{1}{2}$ ft long, while the distance along the expansion chamber from cellophane to the point where reflection photographs are obtained is $7\frac{1}{2}$ ft. At this distance it has been found that the shock fronts are very nearly plane. Reflection takes place on a steel plate normal to the side walls, the angle $\underline{\alpha}$ between the plate and the (vertical) shock front being adjustable to any value from 0 to 90° by turning the plate from outside the tube. Photographs of the shock configuration at some instant during the reflection process are obtained by either the shadow or schlieren methods through either glass windows or lenses or both mounted in the side walls. Illumination for a time not exceeding 1 μsec is provided by a spark initiated through a time-delay circuit by a contactor in the tube wall which closes as the shock front passes it.

The strength of a shock measured by the ratio $\underline{\xi}$ of the pressure P_0 ahead to the pressure $\underline{P}$ behind the shock may be predicted with an accuracy of better than 1% from the ratio P_0/P_1 of pressures on the two sides of the cellophane before it is burst.[10/] Since the pressure differences $P_1 - P_0$ across the diaphragm cannot exceed about 1 atm with the cellophane used, shocks for which $\xi < 0.8$ were produced by lowering the pressure P_0 with a vacuum pump. In this way shocks with any value of $\underline{\xi}$ down to 0.15 were readily produced and photographed. A calibration curve showing P_0/P_1

[10/] The diaphragm is burst by a pointed rod run through a sliding seal in the closed end of the compression chamber.

versus $\underline{\xi}$ was obtained by accurate measurements of shock velocities with a spiral chronograph[11] triggered by the pulses from photoelectric cells. Each pulse was produced as the shock front refracted a narrow beam of light traversing the tube away from a knife-edge which normally prevented the light from reaching the photocell.

In Figs. 28, 29, and 30 are reproduced typical shadow photographs of shock reflections for $\xi = 0.8$, 0.5, and 0.15. In the "parallel shadow" photographs a lens between the light source and the tube made the light parallel as it traversed the tube. These photographs show regular reflection for small angles $\underline{\alpha}$ (between incident shock and wall), the transition to Mach reflection at an angle near the theoretical "extreme angle," α_e, and the appearance of Mach reflection at large angles $\underline{\alpha}$.

From photographs on a single plate of Mach reflections for shocks of the same strength, which are photographed at different distances along the wall, it has been found that the triple point moves along a straight line making a definite and reproducible angle $\underline{\chi}$ with the wall and that the entire configuration remains similar to itself but simply grows as it proceeds. This means that the phenomenon may be described in terms of two variables such as the ratio r/t and the angle $\underline{\theta}$, where $\underline{t}$ is time after the shock struck the corner of the wall and $\underline{r}$ and $\underline{\theta}$ are polar coordinates with pole at the corner, instead of by three variables such as $\underline{r}$, $\underline{\theta}$, and $\underline{t}$. It also means that for purposes of comparison of the experimental measurements of angles with those predicted by any theory of local conditions at the triple point, it is best to specify the angular positions of shocks and slipstream from the line of motion of the triple point rather than from the wall. The only angles with which we shall be concerned here are the angles $\underline{\omega}$ and $\underline{\omega'}$ between the line of motion of the triple point and the incident and reflected shocks, respectively. In regular reflection $\underline{\omega}$ and $\underline{\omega'}$ are identical with the angles $\underline{\alpha}$ and $\underline{\alpha'}$ measured from the wall. In Mach reflection $\omega = \alpha - \chi$, $\omega' = \alpha' + \chi$.

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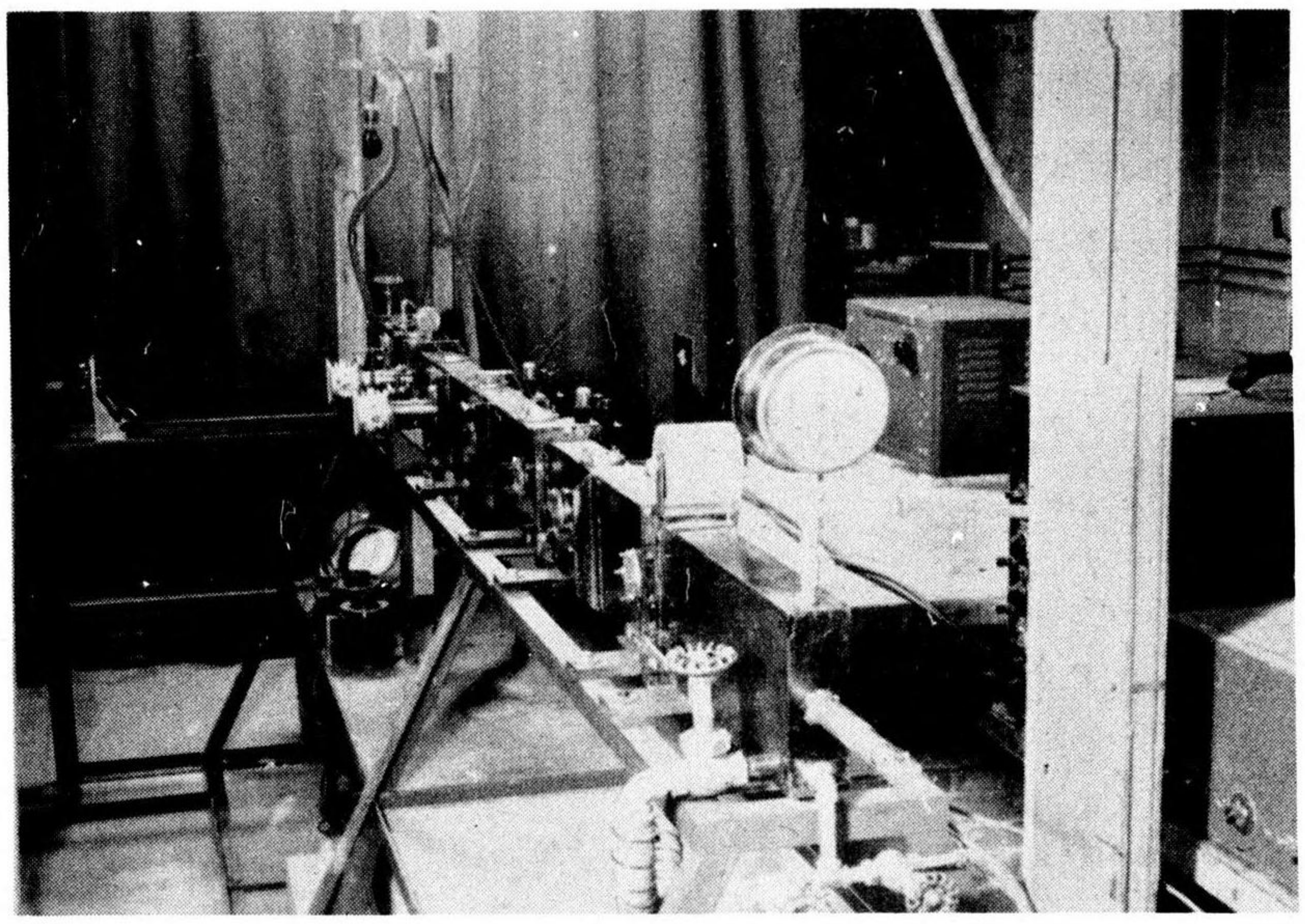
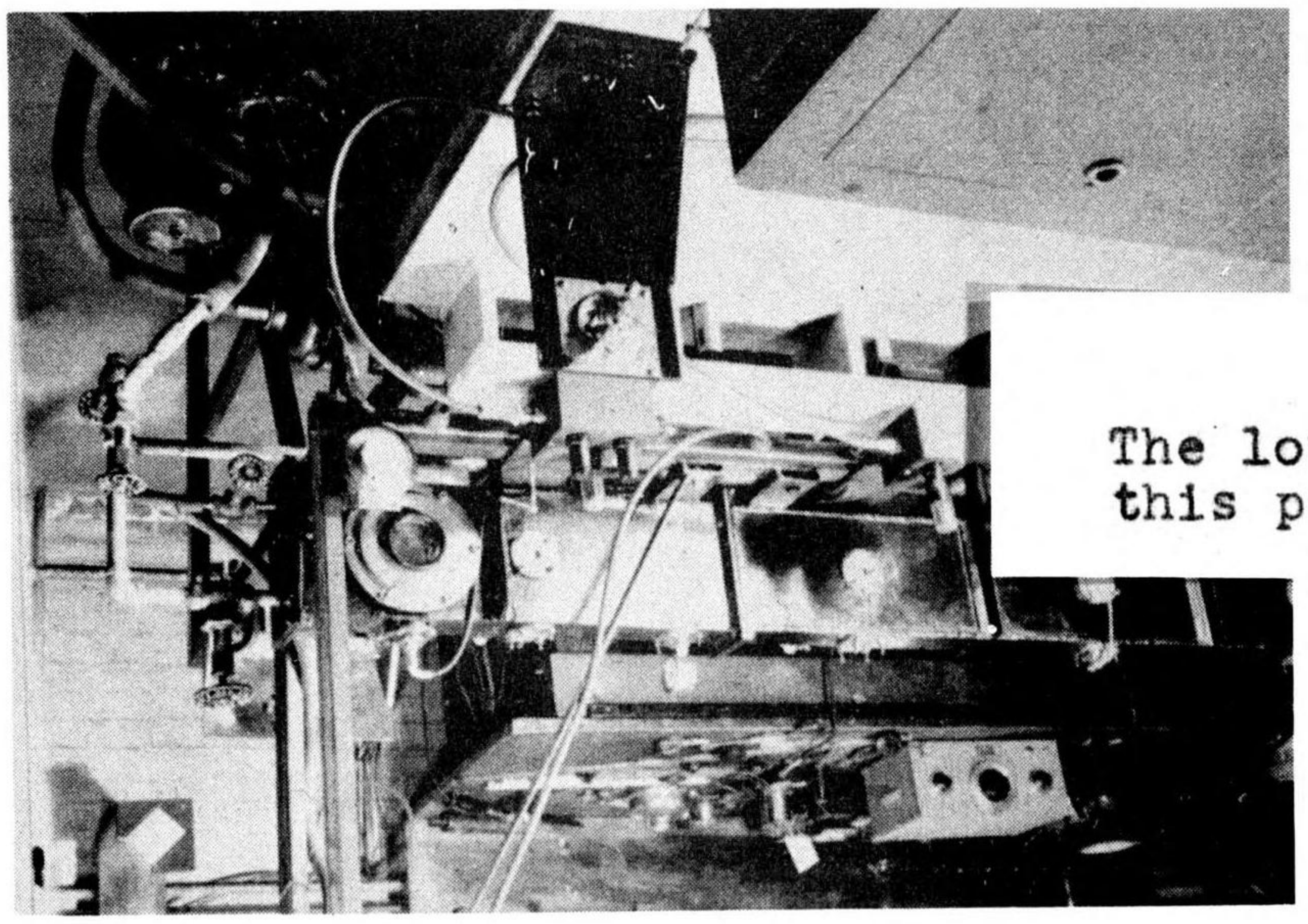
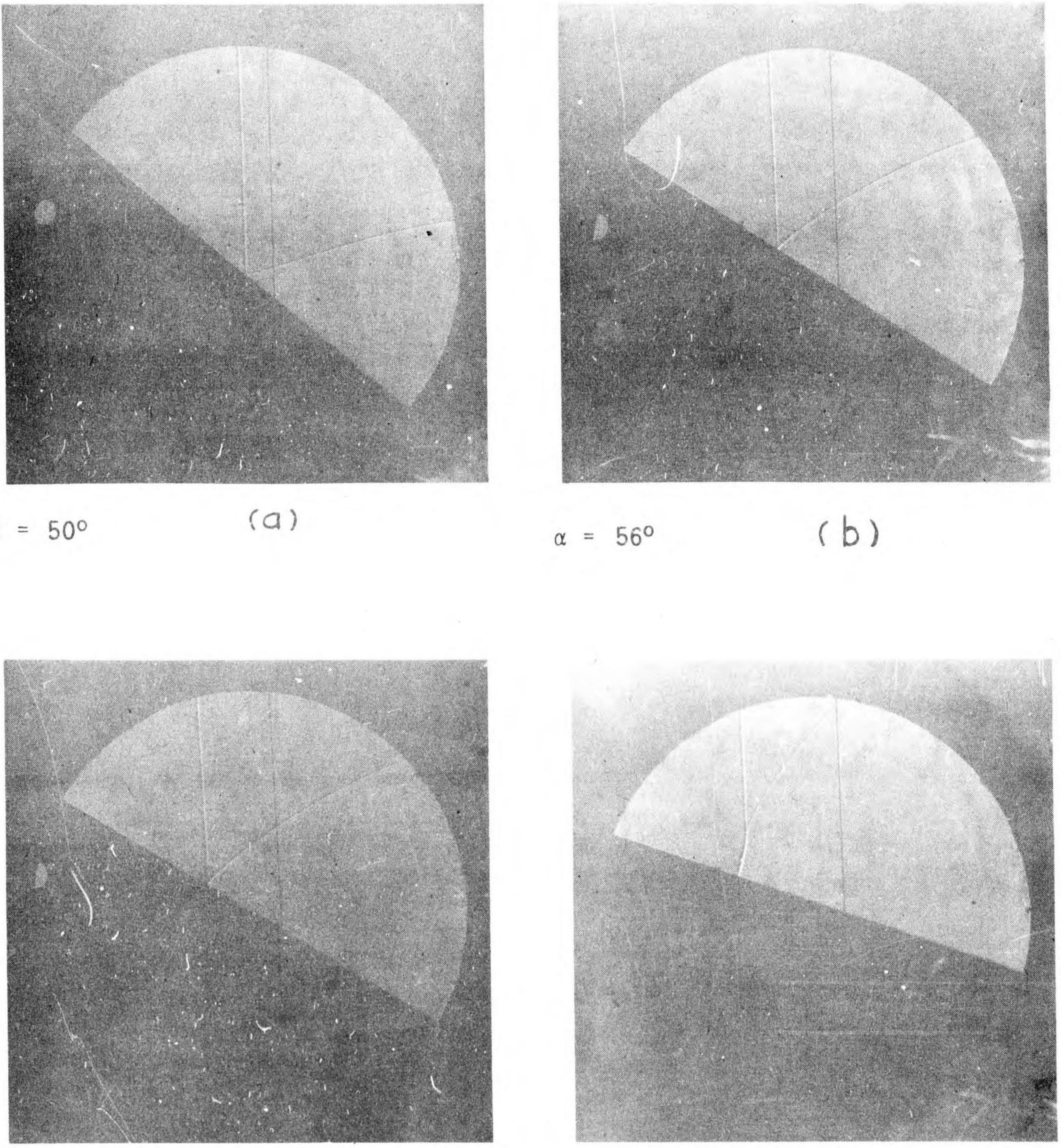
[11] Short base line projectile velocity measurements, by R. J. Emrich and L. A. Delsasso, NDRC Report A-89 (OSRD-927), Confidential.





The lower photograph on this page is inverted.

Figure 27. PHOTOGRAPHS OF THE SHOCK TUBE.



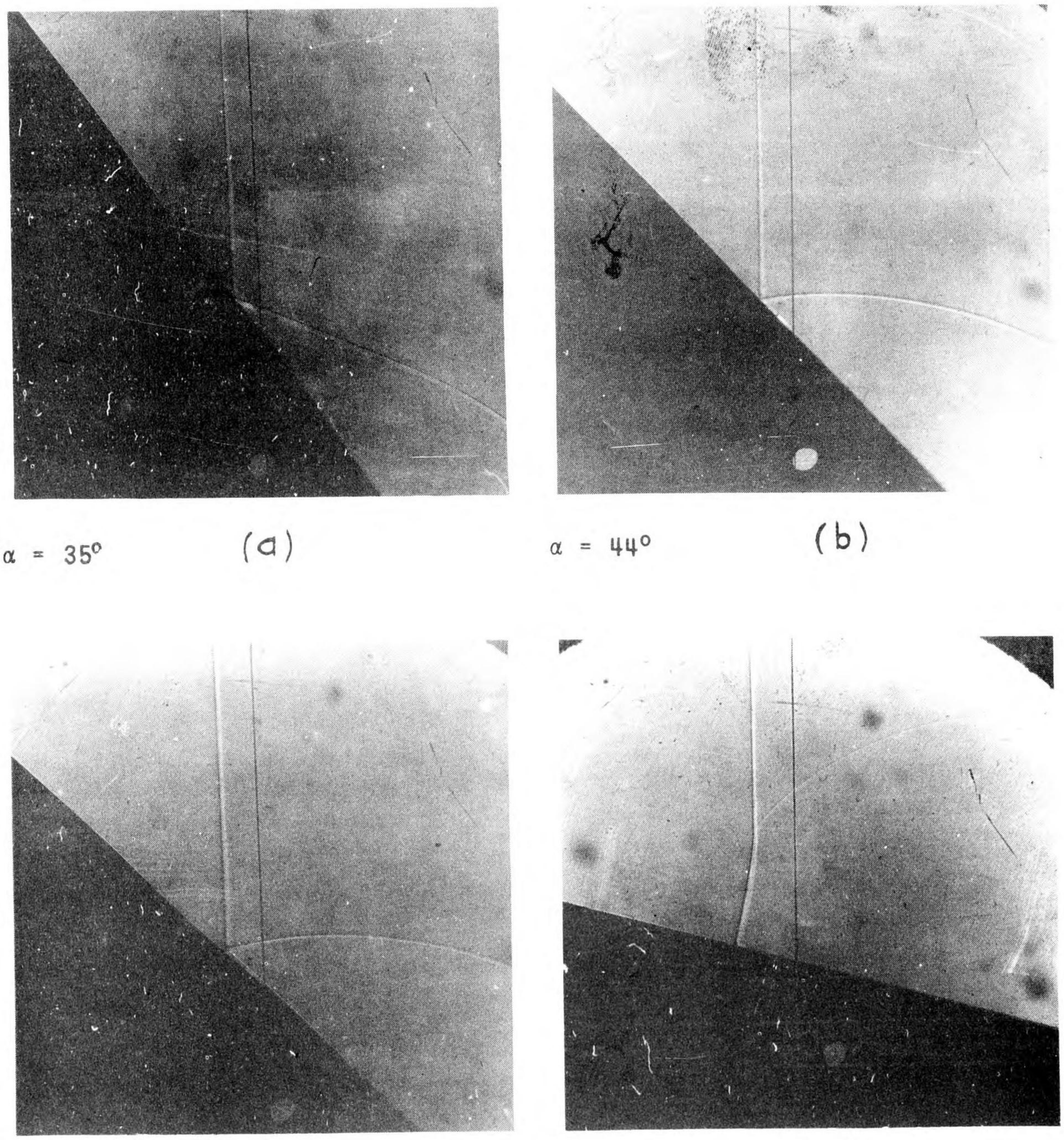
$\alpha = 50°$ (a)

$\alpha = 56°$ (b)

$\alpha = 57°$ (c)

$\alpha = 70°$ (d)

Figure 28. PARALLEL SHADOW PHOTOGRAPHS - $\xi = 0.8$.
The incident shock is vertical and moves to the left. The dark vertical line is made by a plumb line outside the tube.



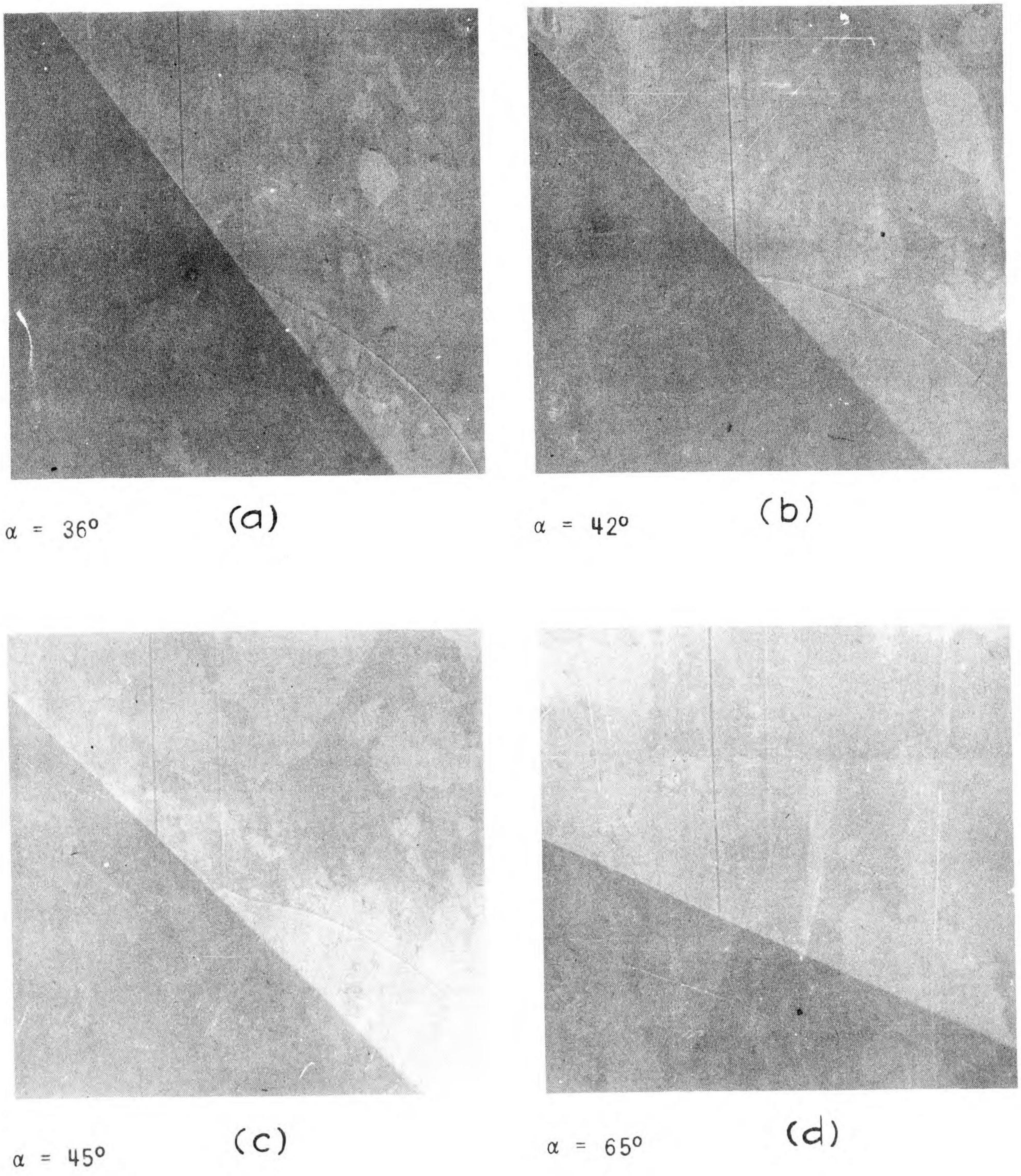
α = 35° (a)

α = 44° (b)

α = 46° (c)

α = 75° (d)

Figure 29. PARALLEL SHADOW PHOTOGRAPHS - ξ = 0.5.
The incident shock is vertical and moves to the left. The dark vertical line is made by a plumb line outside the tube.



α = 36° (a)

α = 42° (b)

α = 45° (c)

α = 65° (d)

Figure 30. ORDINARY SHADOW PHOTOGRAPHS - $\xi = 0.15$.
The incident shock is vertical and moves to the left. The dark vertical line is made by a plumb line outside the tube.

2. Comparison of results with theory

In Fig. 31 is shown a set of theoretical curves of $\underline{\omega}'$ as a function of $\underline{\omega}$. The "two-shock" curve is the ordinary regular reflection curve predicted by von Neumann[12] and worked out for an ideal gas of $\gamma = 1.40$ by Polachek and Seeger[13] with the lower branch of which the experimental points (crosses) agree very well. The dashed curve marked "normal to $\underline{Z}'$" gives the values $\underline{\omega}'$ would have if the reflected shock, $\underline{R}$, were normal to the flow $\underline{Z}'$ behind the incident shock as seen by one at rest on the triple point. For any value of $\underline{\omega}$ less than the extreme sonic value, ω_{es}, which is the abscissa of the doubly circled point of Fig. 31, there are two limiting positions for $\underline{R}$ symmetrically placed about the normal to $\underline{Z}'$ position such that the component of $\underline{Z}'$ normal to $\underline{R}$ is just sonic. The corresponding values of $\underline{\omega}'$ are given by the dashed curve $Z'_{\perp} = C'$. It is theoretically impossible for any reflection phenomena whatever to exist for points on the convex side of the curve $Z'_{\perp} = C'$. For $\omega > \omega_{es}$, $Z' < C'$ and no reflection phenomena may exist for any value of $\underline{\omega}'$. The curve ε_{max} shows the values $\underline{\omega}'$ would have if $\underline{R}$ produced the maximum turning of the flow toward the wall (downward) while the curve ε_{min} shows the values of $\underline{\omega}'$ for maximum upward turning of the flow by $\underline{R}$. We note that ε_{min} intersects the two-shock curve at the extreme point (ω_e, ω'_e); that is, for $\omega = \omega_e$ the maximum possible upward turning of the flow by $\underline{R}$ is just adequate to compensate the downward turning by the incident shock, while for $\omega > \omega_e$ it is not adequate.

Also shown in Fig. 31 is a "three-shock" curve calculated by Polachek and Seeger.[13] It is evident that the experimentally measured angles for Mach reflection do not agree with the predictions of this theory. While it is true that measurements of $\underline{\omega}'$ are subject to considerable uncertainty because of the curvature of the reflected shock near the triple point, the measured values of $\underline{\alpha}$ and $\underline{\chi}$ and thus of $\underline{\omega}$ cannot be in error by more than a few tenths of a degree. Since the measured values of $\underline{\omega}$ extend nearly to ω_{es}, which is 14° larger than the largest value for which three-shock

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[12] Bureau of Ordnance Explosives Research Report No. 12, Confidential.

[13] Bureau of Ordnance Explosives Research Report No. 13, Confidential.

solutions exist, there can be little doubt that such solutions cannot represent Mach reflection in two dimensions for weak shocks.[14/]

There is considerably better agreement of the experimental measurements of $\underline{\omega}'$ versus $\underline{\omega}$ with three-shock theory for strong shocks, as an inspection of Fig. 32 for $\xi = 0.15$ shows. The agreement is not quite as good in the case of the angles of the Mach shock and slipstream (not shown) but it is perhaps within experimental uncertainty. A discrepancy between experiment and theory in the case of regular reflection at $\xi = 0.15$ has not been explained though it has been repeated on numerous occasions with various arrangements of the reflecting wall. This discrepancy exists only for $\xi = 0.2$ and $\xi = 0.15$.

In order to explain the complete failure of the "three-shock" theory to account for the Mach effect for weak shocks, it has been proposed that the assumption made in this theory of constant conditions of pressure, temperature, and so forth, in the angular domains between shocks be abandoned and that one assume that angular variations of the Prandtl-Meyer type exist in one or more of these angular domains. The best schlieren photographs thus far obtained (Fig. 33) show that a continuous pressure rise follows the reflected shock and a continuous rarefaction follows the Mach shock. Each of these, however, appears to extend approximately uniformly for some distance along the shock from the triple point and thus neither appears to be an angular variation. Thus if such variations exist we are forced to the unpleasant conclusion that their extent is so limited that they are undetectable with the resolution at hand.

Since it seems likely that the reflected and Mach shocks are the first signals informing the gas they meet that a wall is present, it is more likely that a Prandtl-Meyer variation should follow one of these shocks than that it should precede one. Now in any Prandtl-Meyer variation the component of flow normal to a radius vector must be exactly sonic at all points. Thus for such a variation to follow a shock, since the component

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[14/] A second branch of the three-shock solution is not shown in Figs. 31 and 32 since it exists only for smaller $\underline{\omega}$ values.

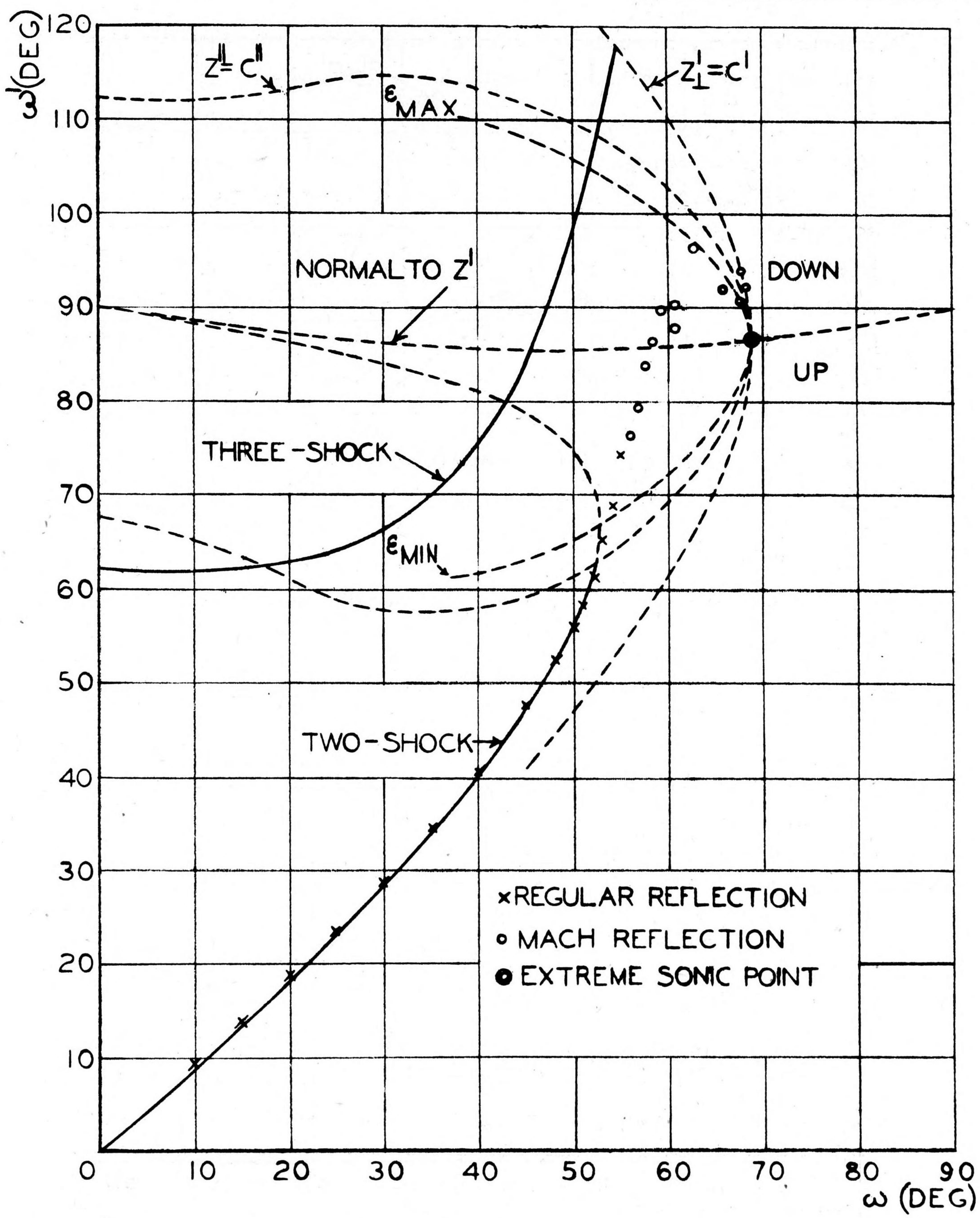

FIG. 31. THEORETICAL CURVES OF ω' AS A FUNCTION OF ω FOR $\xi = 0.80$.

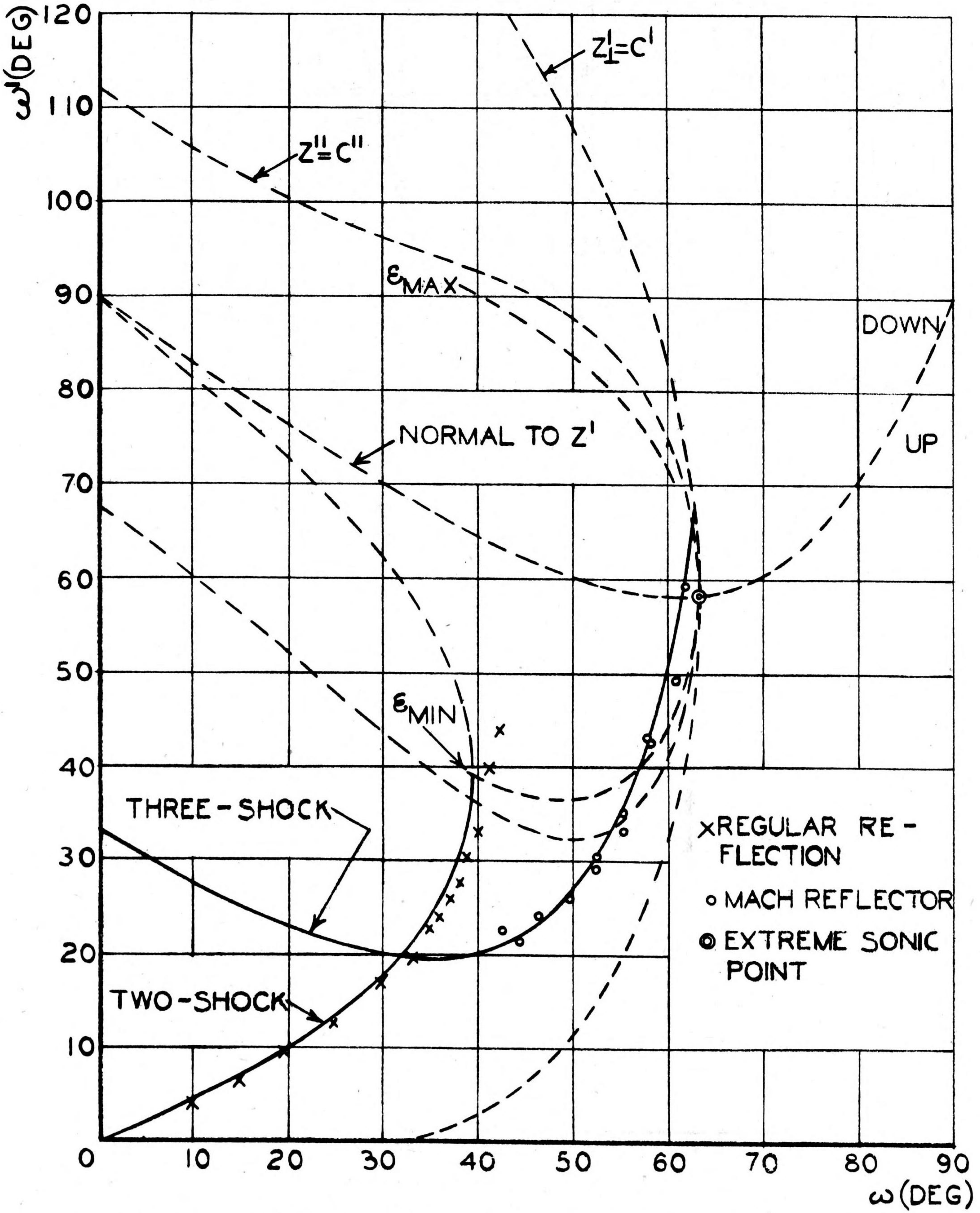

FIG. 32. THEORETICAL CURVES OF ω' VERSUS ω FOR ξ=0.15.

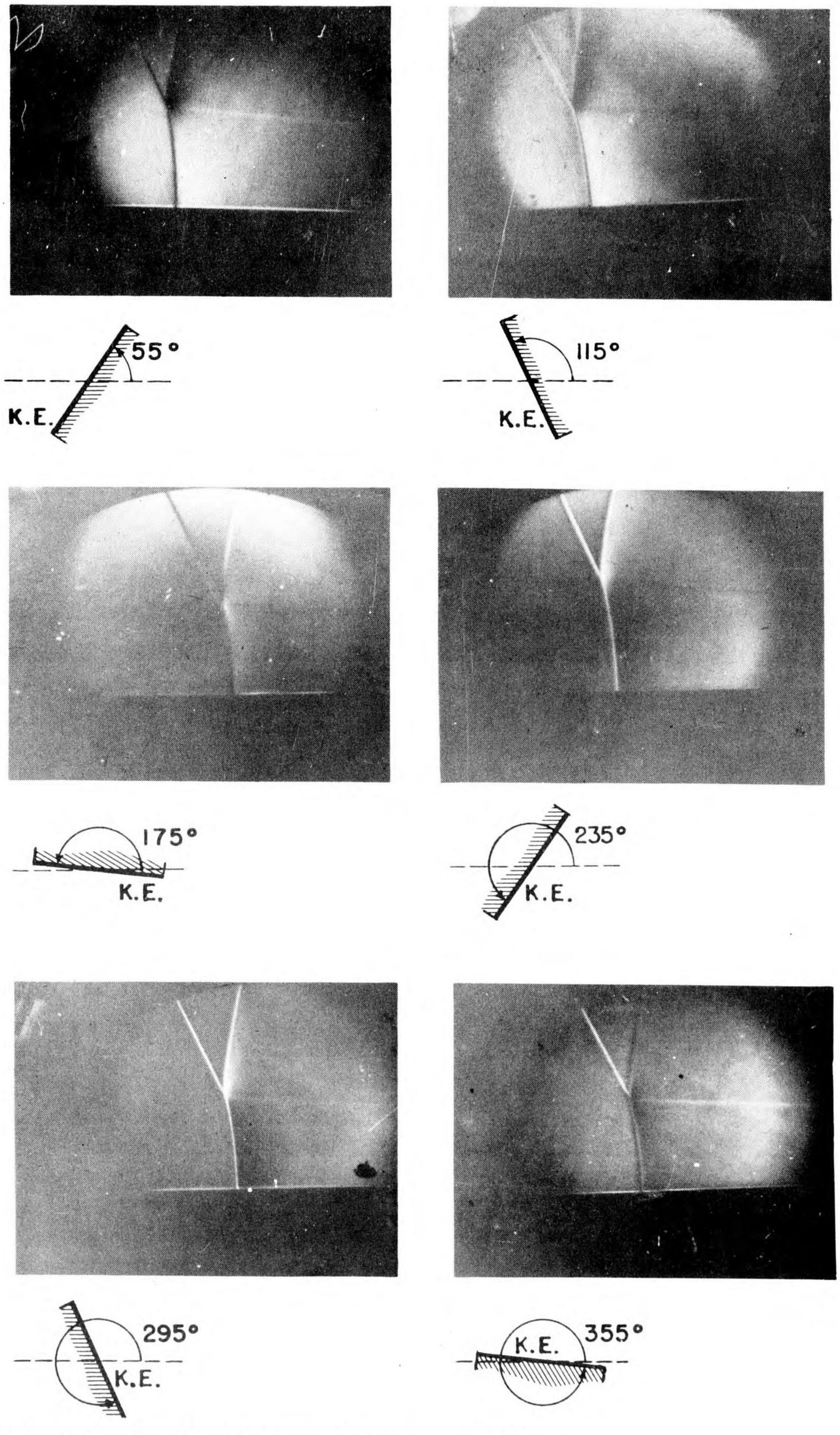

Figure **33.** SCHLIEREN PHOTOGRAPHS - $\xi = 0.8$, $\alpha = 65^\circ$.

The reflecting wall is horizontal and the incident shock moves to the left and downward. The density of blackening on these (positive) prints increases with the component of gradient normal to and toward the knife edges (KE) of flow normal to a shock is always subsonic behind the shock, the total flow behind the shock must be supersonic and the radial component must be directed toward the triple point so that at some angular distance behind the shock the component normal to a radius vector is just sonic. For values of $\underline{\omega}'$ and $\underline{\omega}$ for points on the curves of Figs. 31 and 32 marked $Z'' = C''$ the flow behind $\underline{R}$ is just sonic and is supersonic only for points between these curves and the curves $Z'_{\perp} = C'$. Furthermore only for points between the upper branches of the curves $Z'' = C''$ and $Z'_{\perp} = C'$ is the radial flow component directed toward the triple point. Thus if an angular variation is to follow $\underline{R}$ the values of $\underline{\omega}'$ for $\underline{R}$ must be such that the corresponding points fall between the upper branches of the curves $Z'' = C''$ and $Z'_{\perp} = C'$. Figures 31 and 32 show that so far as the required conditions behind $\underline{R}$ alone are concerned, solutions involving a Prandtl-Meyer variation behind $\underline{R}$ are possible for all values of $\omega < \omega_{es}$, but that the values of $\underline{\omega}'$ are much larger except near $\omega = \omega_{es}$ than the measured values. If such a variation does indeed follow $\underline{R}$ we must assume that a much greater curvature of $\underline{R}$ near the triple point exists than the photographs reveal. Numerical calculations by D. Montgomery have shown that solutions involving a Prandtl-Meyer variation behind $\underline{R}$ do exist for all values of $\underline{\omega}$ between ω_e and ω_{es}.

There is little doubt that the Mach shock turns the flow toward the wall (downward) and hence that the component of flow normal to a radius vector behind $\underline{M}$ is directed away from the triple point. This is clearly indicated by the photographs and is substantiated by the argument that no combination of shock and Prandtl-Meyer variation between the incident shock and the slipstream can result in an upward turning of the flow sufficient to contract the downward turning by the incident shock if $\omega > \omega_e$. (The flows on the two sides of the slipstream must be parallel.) Thus no Prandtl-Meyer variation can occur following $\underline{M}$.

A Prandtl-Meyer compression (which does not reach its maximum pressure) could occur preceding either $\underline{R}$ or $\underline{M}$. The compression would start at a value of $\underline{\omega}'$ for the upper branch of the curve $Z'_{\perp} = C'$ if it preceded $\underline{R}$ and at a corresponding position such that the component of $\underline{Z}$ normal to a radius vector was sonic if it preceded M.[15/] Montgomery has been unable to find solutions involving a Prandtl-Meyer compression preceding R. However, he has found solutions in which such a compression precedes M. The values of the angles obtained are much closer to the measured values than for the case of a variation following R.

3. Determination of pressure on the wall

Geometrical measurements of photographs have yielded values of the pressure on the wall as a function of the strength ξ of the incident shock and of the angle of incidence α. These agree well with the pressures predicted by the two-shock theory for $\alpha < \alpha_e$, the extreme angle, except at $\xi = 0.2$ and $\xi = 0.15$, where the experimental pressures are slightly lower than the theoretical. For Mach reflection the relative velocities of Mach and incident shocks are determined from the relative distances moved by the shocks normal to their front in the interval between the striking of the corner of the reflecting wall by the incident shock and the flashing of the spark. From this, by simple application of the Rankine-Hugoniot relations, one can predict the pressure on the wall due to passage of the Mach shock over it since one knows the pressure jump in the incident shock.

Typical curves giving the overpressure ΔP in terms of P_0, the pressure ahead of the incident shock, as a function of α for $\xi = 0.8$, 0.5, and 0.15, are shown in Figs. 34, 35, and 36. The curves for $\alpha < \alpha_e$ are taken from the two-shock theory[12, 13/] while the solid curves are drawn through the experimental points for $\alpha > \alpha_e$. The two curves do not join, and it is uncertain how they should be joined. We shall not discuss here the dashed curves or the experimental results indicated by crosses in Fig. 34.

[15/] Solutions in which a rarefaction starting for ω' on the lower branch of the $Z_{\perp}' = C'$ curve or in the corresponding position for M are possible, but seem highly unlikely as they involve no reflected or Mach shock at all. (A shock cannot follow an angular rarefaction because the radial flow component during and after a rarefaction is directed outward.)

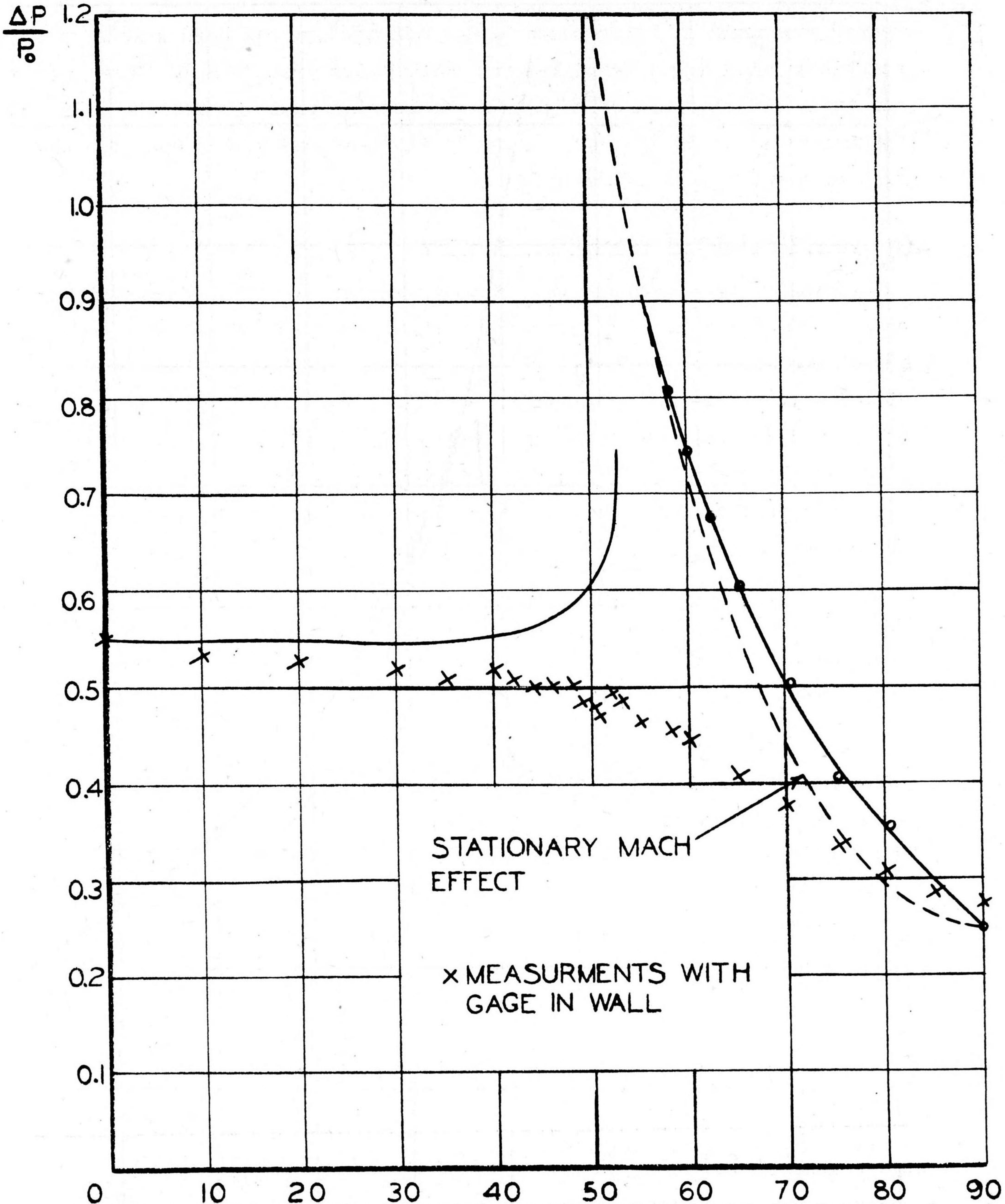

FIG. 34. ΔP/P₀ VERSUS FOR ξ=0.8.

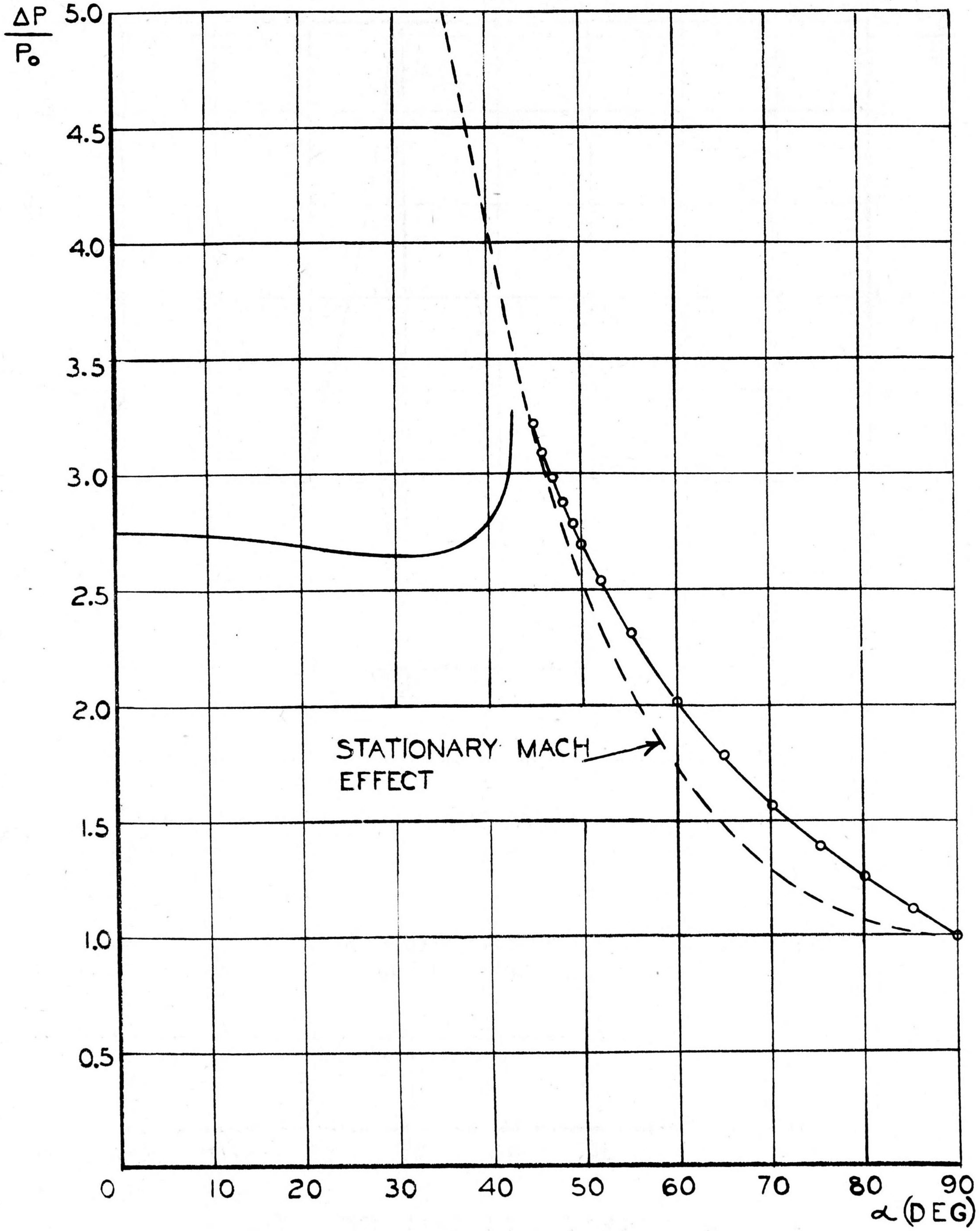

FIG.35. $\Delta P/P_0$ VERSUS α FOR $\xi=0.50$

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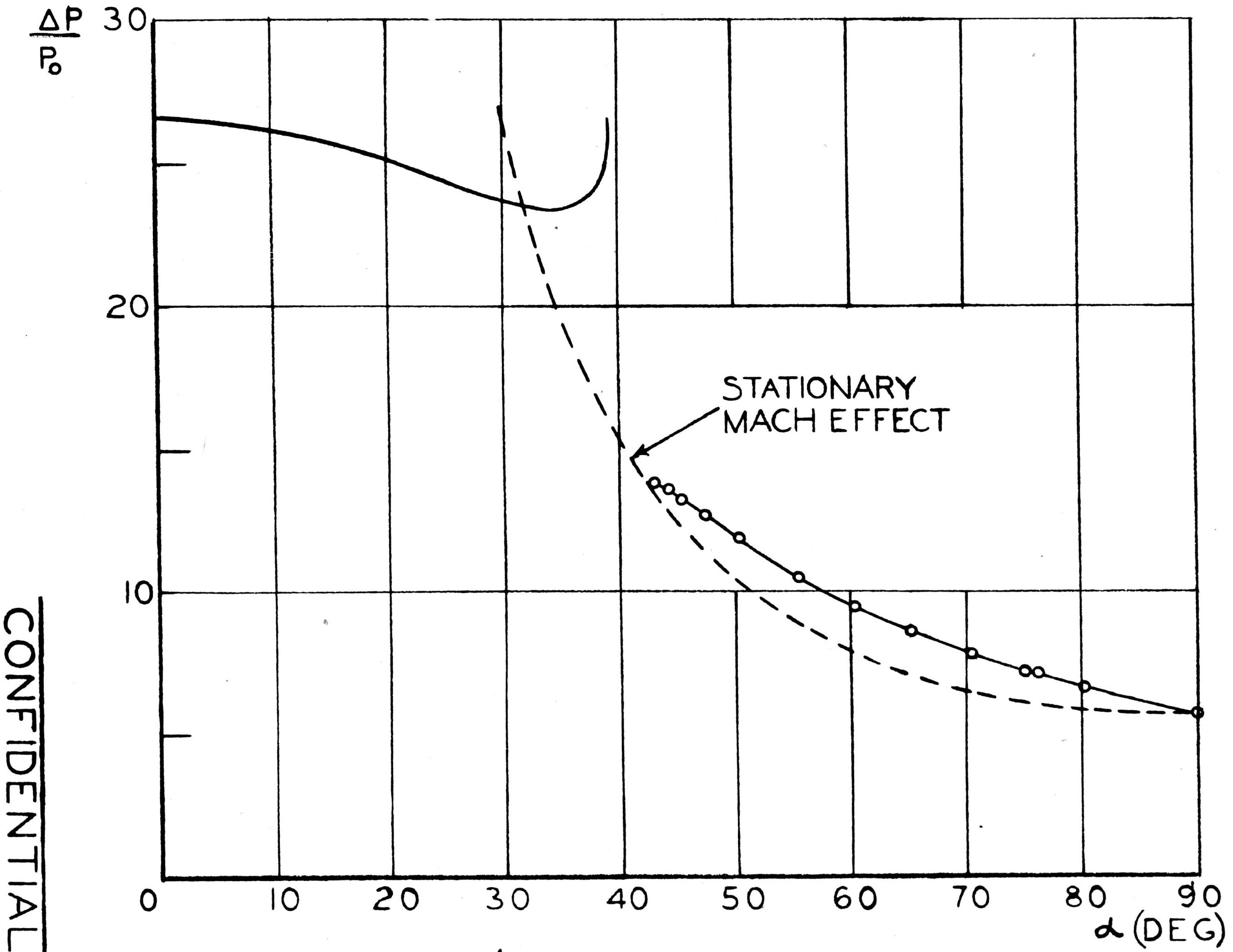

FIG. 36. $\Delta P/P_0$ VERSUS α FOR $\xi = 0.15$.

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C. AN EMPIRICAL METHOD OF CORRELATING AIR-BURST DATA*

by R. R. Halverson
Underwater Explosives Research Laboratory

1. Introduction

The pressure-time measurements on air-burst charges obtained at the Underwater Explosives Research Laboratory[16] have been analyzed in an attempt to correlate the results with the theory of oblique regular reflection as well as with the results obtained in the shock tube at the Princeton University Station[17] and to extend the range of variables by the use of empirical generalizations.

2. Empirical generalizations for time-interval data

In what follows, all data have been reduced to the basis of 1 lb of TNT by dividing all times and linear distances by the cube root of the charge weight actually used. To apply the results to any other charge weight, the times and distances of this report need only be multiplied by the cube root of the charge weight. Note that all lengths (charge height, gauge height, charge-to-gauge distance) must be so transformed.

By examining the time between the arrival of the direct and reflected waves at a gauge as a function of gauge height and charge height, it was possible to calculate the height of the triple point (junction of direct, reflected, and Mach waves) as a function of charge height at two charge-to-gauge horizontal distances. The curves in this form are different at the

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*This is a summary of a more complete report, "The effect of air burst on the blast from bombs and small charges, II. Analysis of experimental results," by R. R. Halverson, NDRC Report A-320 (OSRD-4899), Apr. 1945.

[16] Experimental results used in this report are reported in (a) "The effect of air burst on the blast from bombs and small charges, I. Experimental results," by W. D. Kennedy, OSRD Report 4246, Sept. 1944, and (b) "The effect of height of detonation on peak pressure and positive impulse measured close to the ground," by W. D. Kennedy and R. F. Arentzen, included in AES-5 (OSRD-4514), Dec. 1944.

[17] "The reflection of shock waves in air," by L. G. Smith, included in AES-1 (OSRD-4076), Aug. 1944.

two horizontal distances, but it is possible to express the results in variables such that the distance seems to have little effect. Let ϕ be the angle between the horizontal and the chord joining the triple point (at the given distance) with the point where the triple point first left the ground. See Fig. 37, in which the shock configuration produced by a 1-lb charge detonated at a height h_c above the ground is shown at three successive times.

Let α be the angle made by the incident wave with the horizontal at the triple point. The angle α_{extreme} is the value of α when the triple point first leaves the ground, and can be calculated from the work of Polachek and Seeger[18] if a pressure-distance law is assumed[19]. It was then possible to convert the plots of triple-point height versus charge height at different horizontal distances from charge into a plot of ϕ versus $\alpha - \alpha_{\text{extreme}}$. The empirical result was then observed that this curve of ϕ versus $\alpha - \alpha_{\text{extreme}}$ was independent of the horizontal distance from charge insofar as the available data are concerned. There appears to be no theoretical justification for this result, and therefore it cannot be relied upon at distances far beyond the range of the experiments. Nevertheless, it does provide a reasonable method of expressing the experimental data and extrapolating them to other distances.

This curve of ϕ versus $\alpha - \alpha_{\text{extreme}}$ was used to compute the path of the Mach triple point for various charge heights. The results are shown in Fig. 38 (a plot of the height of stem versus horizontal distance from charge for several values of charge height). These curves enable a prediction to be made of the height of charge required to cause the triple point to pass through a point of given height at a given horizontal distance.

A second empirical generalization shows that the height of charge which produces maximum pressure at a given point in space is about 9/10 of the charge height which causes the triple point to pass through that point.

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[18] "Regular reflection of shocks in ideal gases," by H. Polachek and R. J. Seeger, Bureau of Ordnance, Explosives Research Report No. 13, Feb. 1944.

[19] A free-air pressure-distance law for 1 lb of TNT was taken as $P = 3.25\left(\frac{15.9}{R}\right)^{1.5}$, where P is in pounds per square inch and R is in feet [see Ref. 16(a)].

C	Charge
I	Incident shock wave
R	Ground reflection
Stem	Mach shock, front of Mach region
S	Slipstream
M	Triple point
ℓ-ℓ	Locus of triple point
D	General horizontal coordinate
D_o	Horizontal distance from charge to point where **M** leaves ground
h_c	Charge height
α	Angle made by incident shock and the horizontal at the point of reflection
α_{ext}	Value of α at D_o
ϕ	Angle made by horizontal and the chord of ℓ-ℓ from D_o to any point on ℓ-ℓ

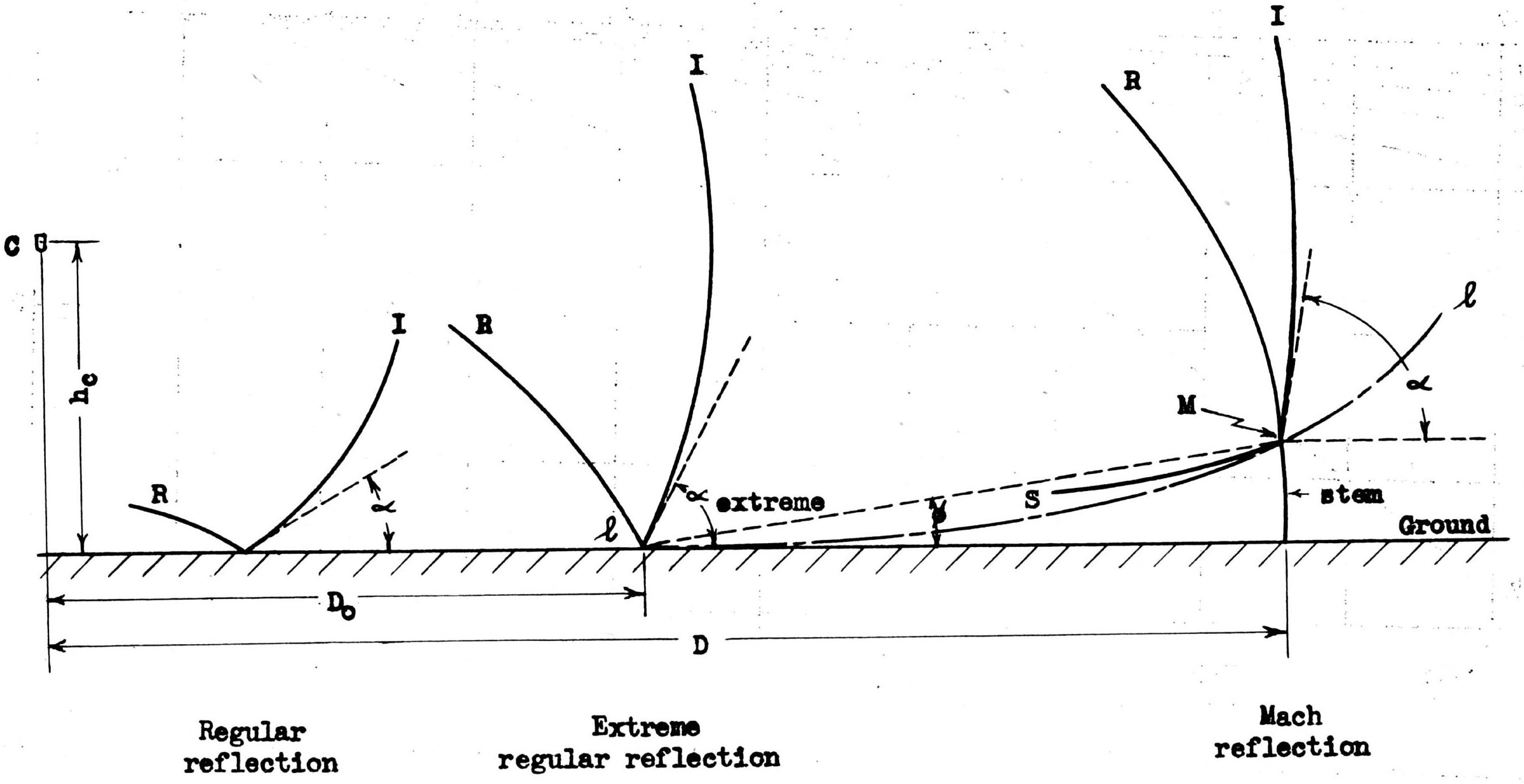
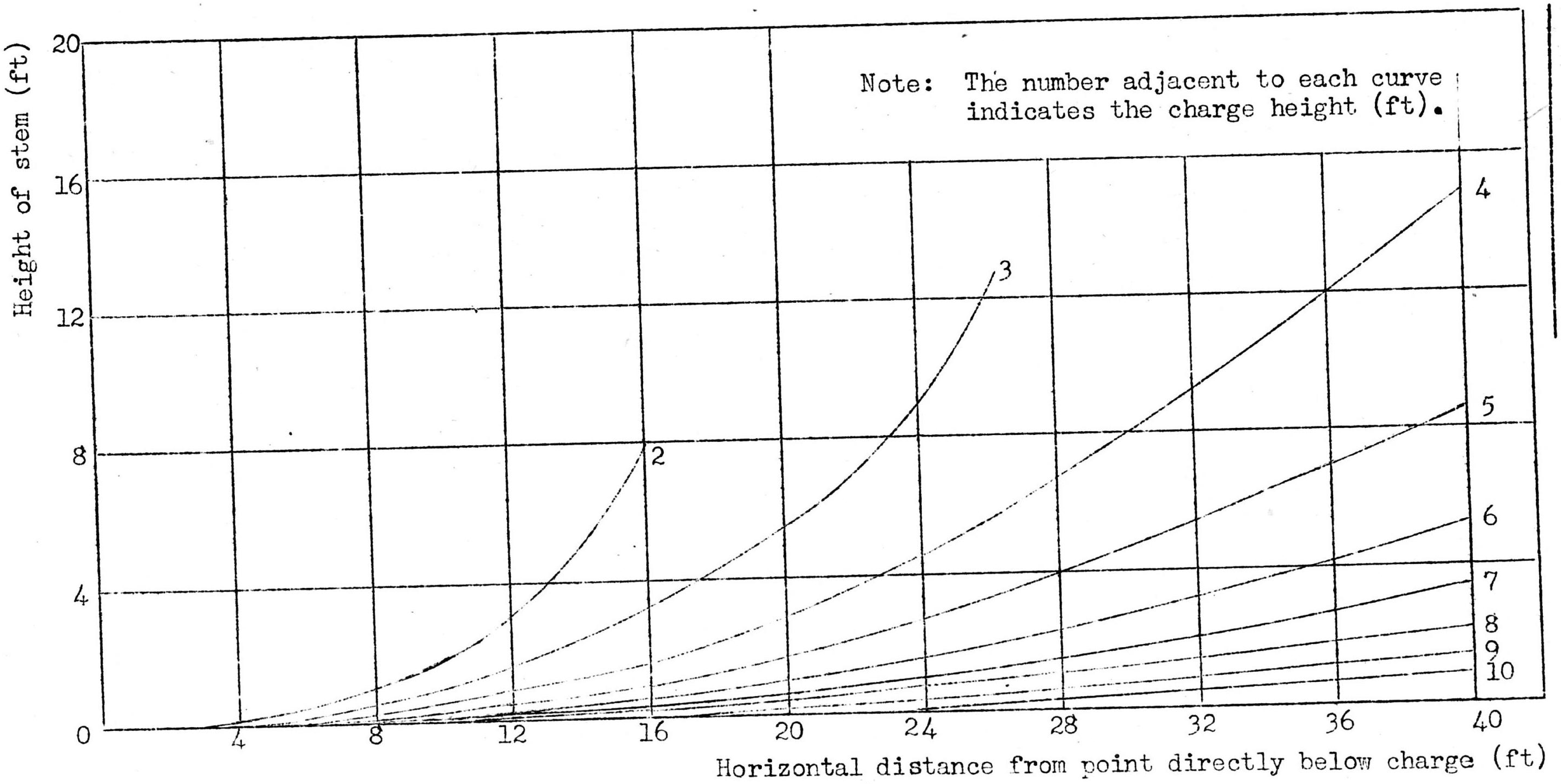


Fig. 37. Successive shock configurations from 1-lb charge.



Note: The number adjacent to each curve indicates the charge height (ft).

Fig. 38. Calculated values of height of stem versus horizontal distance from charge for various charge heights. All units reduced to basis of 1 lb TNT.

Unfortunately there does not seem to be as simple a relation for the maximum impulse.

3. Representation of pressure data

A similar representation in terms of relative variables was made in the case of the peak-pressure data of the pressure-time records obtained at the Underwater Explosives Research Laboratory. Two types of records were obtained, (i) for the gauge above and (ii) for the gauge below the triple-point height for the given charge height and horizontal distance of the gauge.

In the first case a double-peak record results, the first shock being the incident shock of peak pressure P_P and the second shock being the reflected shock of peak pressure P_R. The following variables are defined:

P_i, pressure in incident shock at the time the reflected shock strikes the gauge,

P_r, pressure behind reflected shock.

P_r is calculated on the assumption that the incident shock has not decayed; that is, P_r is taken as the pressure rise in the second shock (from the minimum pressure behind the incident shock to the peak of the second shock) plus P_i, the pressure immediately behind the incident shock at the time of comparison of the incident and reflected shocks.

For this case -- gauge above triple-point height -- the relative pressure variable used was P_r/P_i. The angular variable taken was $\alpha - \alpha_{extreme}$, where $\underline{\alpha}$ is measured at the triple point at the time of comparison of the incident and reflected shocks and $\alpha_{extreme}$ (Fig. 37, a function of charge height only) can be calculated as discussed in Sec. 2. Dependence of P_r/P_i on an additional variable was found. This was taken as an actual reduced distance variable R_{gM}, the length of the chord of the reflected shock from the triple point to the point on the reflected shock which strikes the gauge.

The corresponding variables for the gauges below the triple point where single-peak records are obtained are:

(i) P_M/P_F, where P_M is the peak pressure of the Mach shock which strikes the gauge, and P_F is the free-air pressure that would have been recorded by that gauge in the absence of the ground.

(ii) $\alpha - \alpha_{extreme}$, where now $\underline{\alpha}$ is defined arbitrarily as the angle that the incident shock makes with the horizontal at a point directly above the gauge on the proper triple-point path for the given charge height.

(iii) $(h_g - y)/y$, a relative distance variable, where h_g is the height of the gauge and $\underline{y}$ is the height of the stem. This is taken as -1 at the ground and zero at the triple point. It is taken as zero if $h_g = 0$, and the point of reflection is at the ground.

Plots were made of P_r/P_i versus R_{gM} and P_M/P_F versus $(h_g - y)/y$ for several ranges of $\alpha - \alpha_{extreme}$. Figure 39 is an example of such a plot for the range $\alpha - \alpha_{extreme} = -2^\circ$ to 4°. The sharp rise in this curve at the ground indicates that, for the oblique regular reflection of spherical

Legend for Figs. 39 and 40.

$\underline{D}$ is the reduced horizontal distance from charge to gauge.

Symbol	$\underline{D}$ (ft)	Laboratory	Type of Charge	Weight of Charge (lb)	Reference
○	15.9	UERL	Bare GP bomb	2, 12.4, 41.7 500, 1000, 2000	16 (a)
ó	15.9	UERL	Bare (low gauges)	4.15	16 (b)
□	10.4	UERL	Bare GP bomb	12.4, 41.7 500, 1000, 2000	16 (a)
×	39.8	UERL	Bare	2	16 (a)
Δ	5 to 10	Princeton	Bare	$\frac{1}{2}$	20
$\bar{\Delta}$	10 to 15	Princeton	Bare	$\frac{1}{2}$	20
▲	15 to 20	Princeton	Bare	$\frac{1}{2}$	20
∇	20 to 25	Princeton	Bare	$\frac{1}{2}$	20
$\underline{\nabla}$	25 to 30	Princeton	Bare	$\frac{1}{2}$	20
▼	30 to 35	Princeton	Bare	$\frac{1}{2}$	20

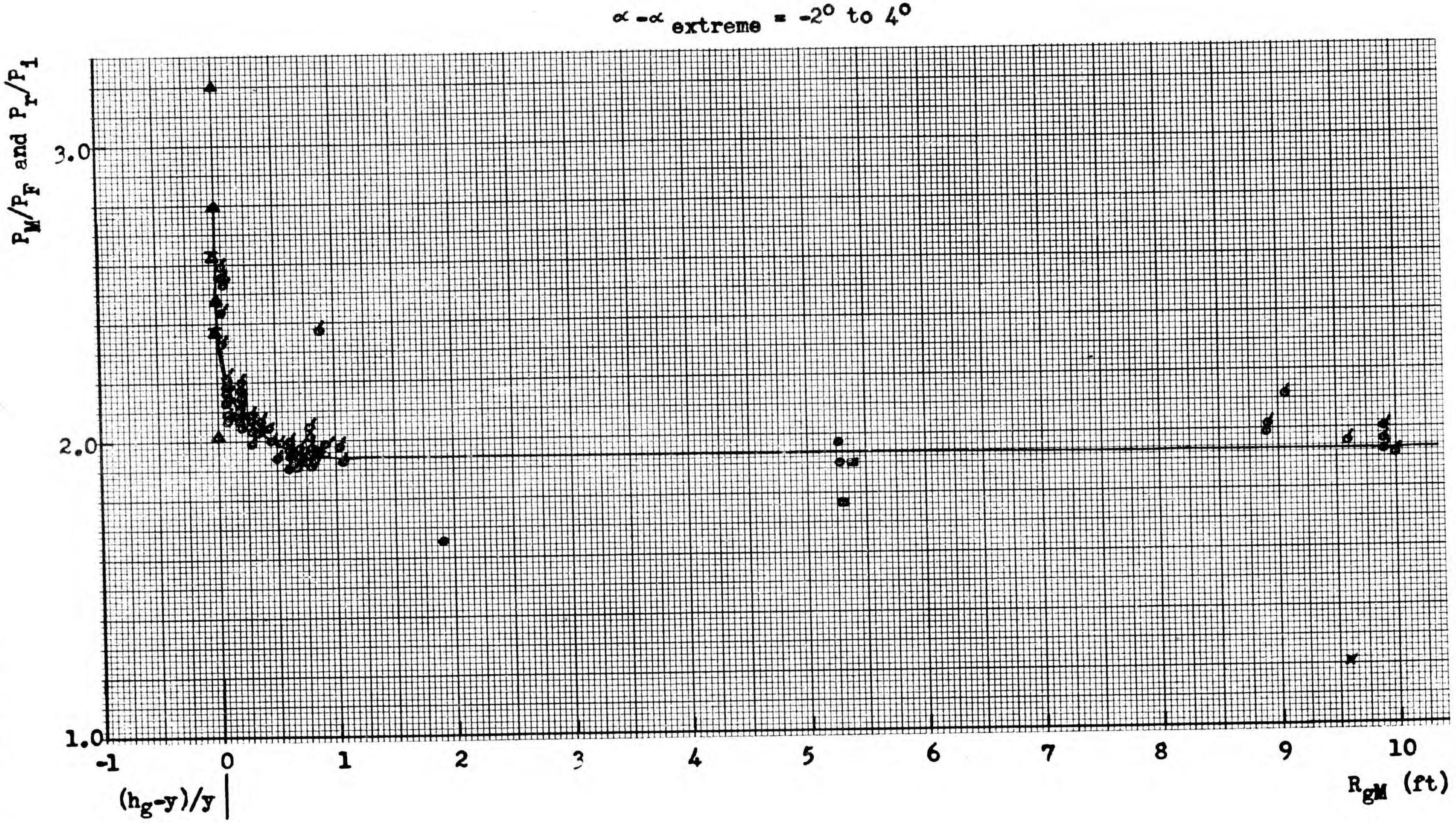


Fig. 39. P_r/P_i versus R_{gM} (gauges above triple point) and P_M/P_F versus $(h_g - y)/y$ (gauges below triple point). All units reduced to basis of 1 lb TNT.

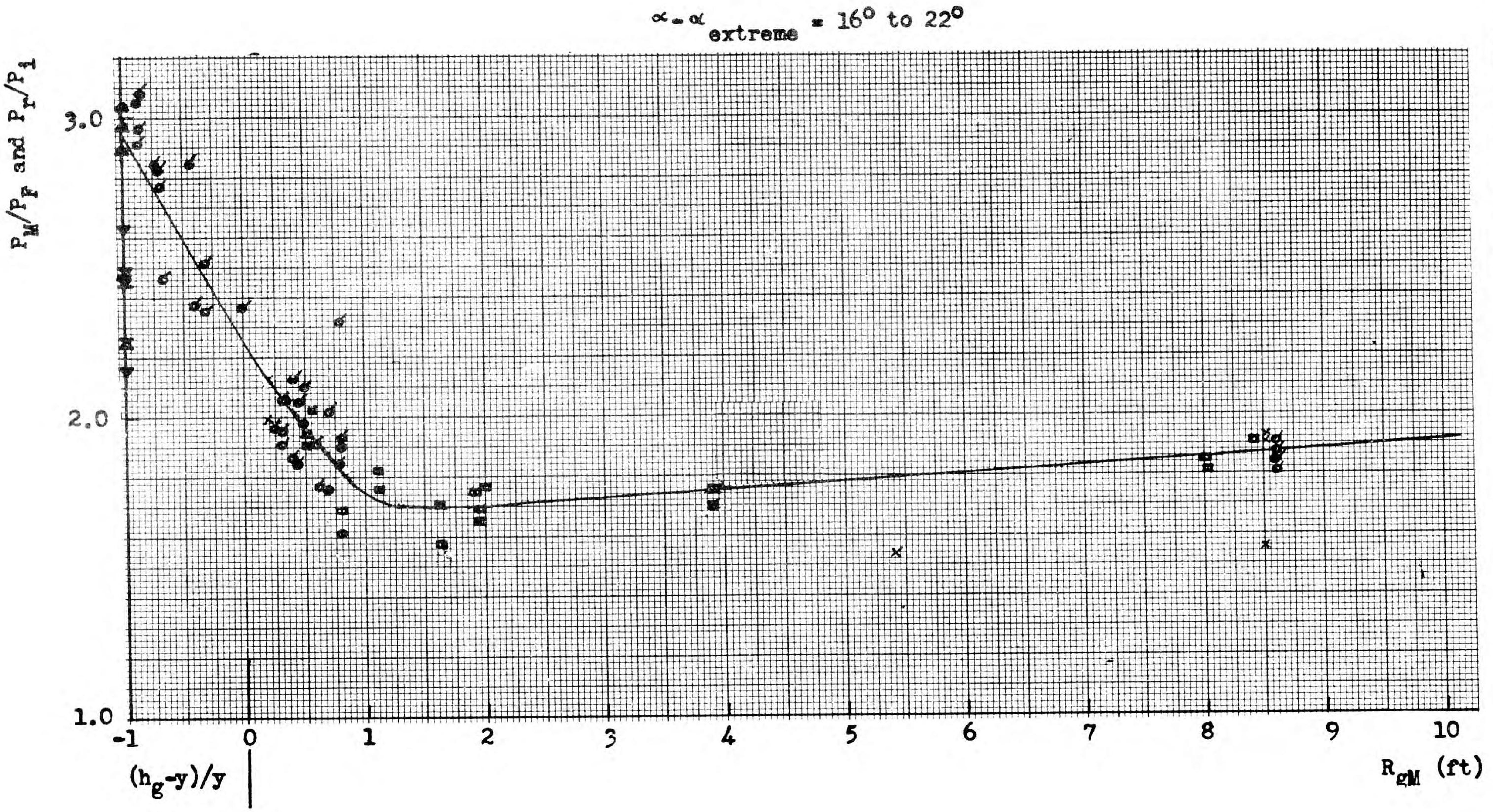


Fig. 40. P_r/P_i versus R_{gM} (gauges above triple point) and P_M/P_F versus $(h_g - y)/y$ (gauges below triple point). All units reduced to basis of 1 lb TNT.

decaying shocks and for very early Mach reflection for which the height of stem is still zero, the high overpressure at the ground is an extremely local phenomenon. Figure 40 is a similar plot for the range $\alpha - \alpha_{extreme} = 16^\circ$ to 22°. This is the region of the Mach type of reflection, and thus there are data for $(h_g - y)/y$ in the range from 0 to -1.

Figures 39 and 40 indicate that these variables represent the data satisfactorily with no noticeable systematic trend with charge height or horizontal distance from charge. For this reason these curves could be used together with interpolated data on reflection times, time-decay of pressure behind the incident shock, and free-air pressure data for the incident shock. to calculate curves of pressure versus charge height at constant gauge height and horizontal distance from charge. In this manner the data on which curves of the types of Figs. 39 and 40 are based can be interpolated and to some extend extrapolated.

Figure 41 is a typical set of curves calculated in this manner for a horizontal distance D of 20 ft and a gauge height h_g of 4, 2, and 0 ft. The peak pressure of the Mach shock, P_M, and the incident peak pressure P_P, as well as the reflected peak pressure P_R, are shown as a function of charge height in these curves. The x's on the curve for $h_g = 0$ ft represent the results calculated by Taub[20/] on the basis of the theory of regular reflection and on the basis of the results obtained in the Princeton shock tube for the Mach reflection range. These data are based on the free-air pressure-distance law given by Taub, which differs very little in this range from the UERL curve used in the calculation of these predicted pressure versus charge height curves. Thus, good agreement of the predicted curves with the theoretically obtained results is shown.

20/ "Peak pressure dependence on height of detonation," by A. H. Taub, included in Division 2 NDRC Monthly Report AES-1 (OSRD-4076), Aug. 1944.

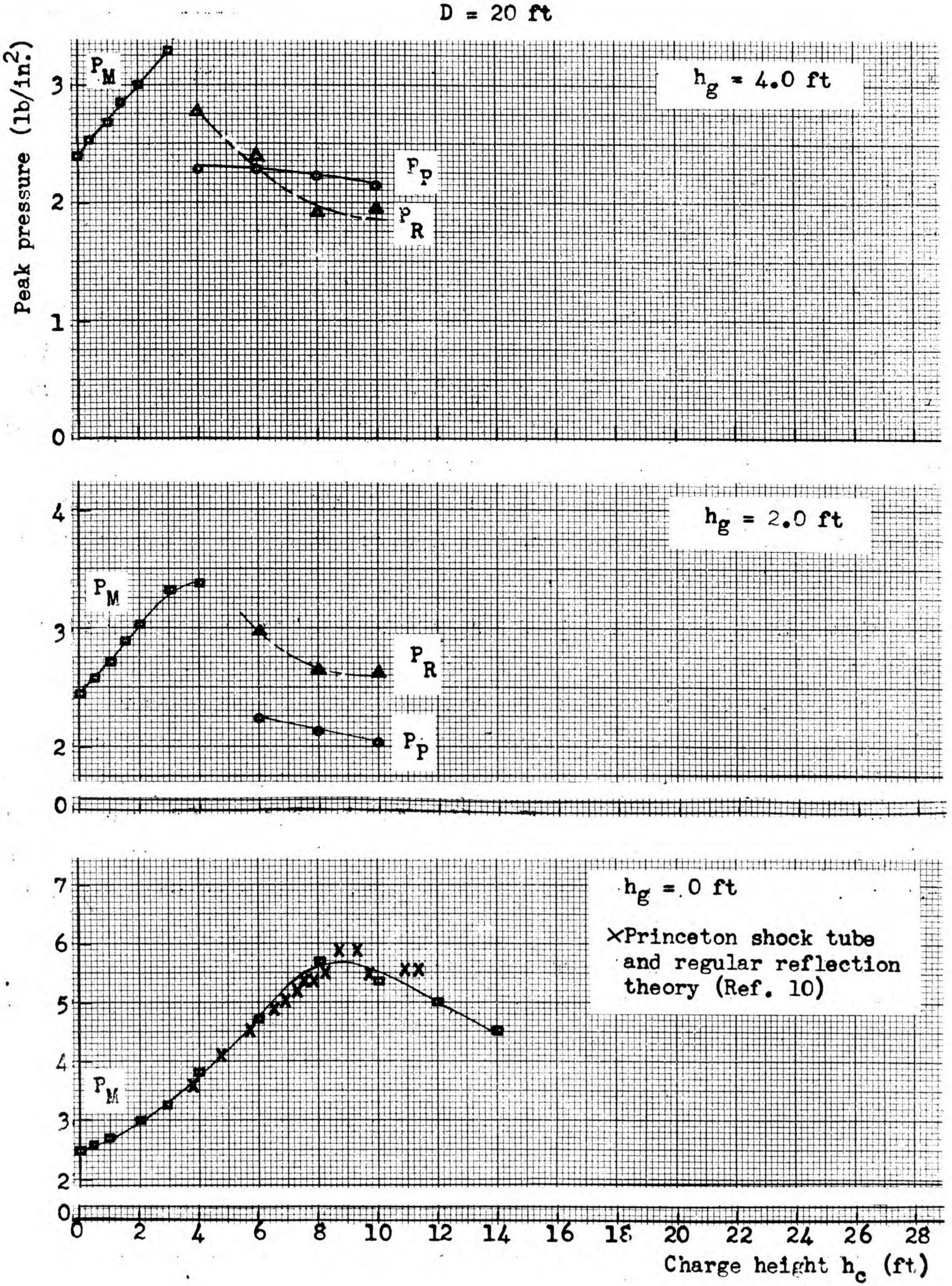


Fig. 41. Predicted pressure versus charge height. All units reduced to basis of 1 lb TNT.