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Department of the Army Project No. 503-04-002
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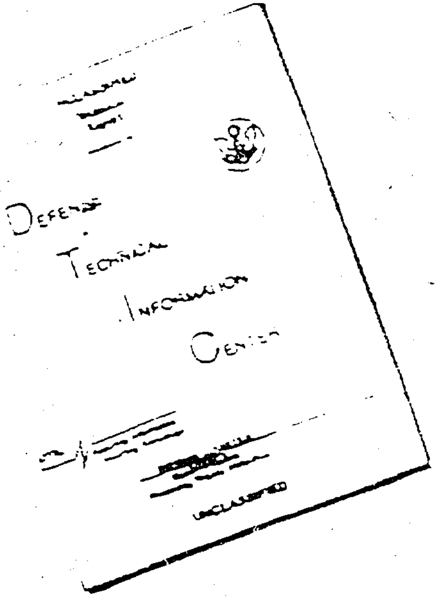
ABERDEEN PROVING GROUND, MARYLANI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MSultanoff, VMBoyle, JPaszek/lp
Aberdeen Proving Ground, Md.
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SHOCK INDUCED SYMPATHETIC DETONATION IN SOLID EXPLOSIVE CHARGES*

ABSTRACT

A study of the basic physical parameters for sympathetic initiation of high explosive receptor charges by the pressure pulse from a donor charge transmitted through barriers of air, steel, aluminum, lead, and copper has been conducted. A surface phenomenon, which has been shown to be a front of mechanical discontinuity supported by a chemically reacting core, has been observed to propagate at a constant, supersonic velocity. The core reaction is a "low-order" chemical decomposition which produces a pressure considerably less than that associated with high-order detonation, and propagates at a supersonic rate, but much slower than a high-order détonation. This reaction is confined to the central core of the explosive, and its rate of propagation is determined by the intensity of the incident wave. The propagation distances into the receptor and times required for the reaction to change abruptly to high-order detonation are uniquely determined, for a given explosive, by the intensity of the incident pressure wave. High-order detonation is first observed at the surface of the charge coincident to the front of the mechanical discontinuity. However, the shape of that front, on emergence, indicates that initiation originated in the reacting core.

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* This technical note, with minor revisions, is the paper presented at the Third Symposium on Detonation and included in the published transactions of the symposium (ONR Symposium Report ACR-52).

Invariably, for a considerable time after the beginning of the high-order reaction in the receptor charge, it propagates at a rate slightly greater than normal detonation rate.

While details of behavior vary with composition and geometry of the explosive, these qualitative features appear to be valid.

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INTRODUCTION

Studies have been made of the fundamental physical processes involved in the detonation reaction of solid explosives. These studies have led to an analysis of the parameters that control the sympathetic detonation of a receptor charge subjected to strong shocks transmitted through barriers of various materials. It is felt that these studies might lead to a better understanding of the detonation process, and could also indicate a criterion of sensitivity based on physical quantities directly related to the explosive charge. Continuation of the research project reported formally first in a Ballistic Research Laboratories Report(1)* in 1953 and subsequently in later reports(2,3) indicate the direction of this continued research with finer time and space resolution, employing new techniques for the investigation of the regime of transition from initiation to high-order detonation. Much of the earlier data were inferred from the observation of the surface conditions of receptor charges. The work covered by this report deals with the direct observations of the core reaction in the receptor. These new observations eliminate errors and uncertainties introduced by the earlier inferences.

EXPERIMENTAL PROCEDURE

Except for some preliminary experiments with internally cast resistance wires(4) all of the data were obtained from photographic records(5). Self-luminosity and auxiliary front lighting were used with streak-cameras, Kerr-cell single exposure shutters and multiframe, high repetition rate, framing cameras.

The charges were arranged as shown in Figure 1 and, except where noted, were cast 50/50 pentolite sticks of 3/4 inch square cross-section, 3 inches long. Barriers of air, steel, dural, copper, lead and plastic have been tested. However, most of the data presented in this report represent a variety of barrier thicknesses of air, lead and dural.

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* Superscripts refer to references at the end of the report.

Data for initiation by pellet impact were obtained with steel discs, driven intact, at velocities ranging from 500 to 1500 meters per second by metal-padded explosive sticks.

DISCUSSION-SPECIFIC RESULTS

As a result of the methods used for the determination of initial conditions in the receptor charges, the quantitative data obtained in these tests fall into three general categories, i.e. air-gap, metal barrier and pellet impact. However, the conditions leading to high-order detonation can be described by a single physical model.

1. Initiation by Shock Through Air Gaps

The earliest investigations of shock initiation were concerned primarily with air barriers, and the time "t" and distance "d" shown in Figure 2A, which is a typical streak-camera record, were the first observations made of the delay to detonation. More recent, front lighted records (Figure 2B) have shown that this time "t" consisted of at least two individual delays, i.e., the delay to ignition, and the delay to high-order detonation after ignition established a core reaction in the receptor stick. The direct measurements of the supersonic surface velocity(3) as a function of the width of the air gap in comparison with the velocities computed from the "t-d" data are shown in Figure 3. The velocities measured directly are always higher than those computed from the "t-d" data.

For detonation induced by the air shock it is necessary to separate the contributions of peak pressure, impulse and possibly heat, to the reaction in the receptor. The pressure in the air shock at the face of the receptor is directly obtained from the Hugoniot relations for air, which are well known for the velocities involved. The pressure so obtained, cannot be used directly to obtain the pressure in the receptor, however. Theory and experiment both show that the peak pressure occurs when the high density detonation products, which are following closely behind and driving the air shock, impact the face of the receptor charge. A single rough measurement made at these Laboratories, (by Mr. Boyd Taylor) of the pressure developed in a Plexiglas receptor separated by a one-inch air gap from a standard pentolite donor yielded an estimate of 300,000 PSI. At this gap distance, the pressure in the incident air shock is about 8,500 PSI and, allowing for a possible theoretical fifteen-fold magnification in the reflected shock from a perfectly rigid wall,(6,7) the pressure at the receptor face could be expected not to exceed 130,000 PSI as a result of the shock impact. The quantitative data presented relate the surface velocity and the delay to detonation in the receptor to the pressure in the incident wave. Recomputing to include the results of the single test with the Plexiglas receptor will increase the magnitude of this pressure, and will throw the air gap data into agreement with the metal barrier data.

2. Initiation by Shock Through Metal Barriers

The delay time and distance to detonation in receptor charges have been studied as functions of both the barrier thickness and barrier material with lead, dural, copper and steel. However, sufficient data for quantitative as well as qualitative analysis have been obtained only with the lead and dural barriers.

Direct measurements of the pressure induced in the receptor charges could not be made with existing instrumentation and techniques. However, once the pressure in the barrier at the barrier-receptor interface is known, this information can be used with the extended high pressure Hugoniot curve published by Los Alamos(8). By use of the pin technique, Dr. Floyd Allison at Carnegie Institute of Technology supplied the free surface velocities of barrier materials driven by contact donor charges. Using the relationship:

$$P = \rho_o U_s U_p$$

where: P is pressure (dynes/cm^2)

ρ_o is barrier density (gms/cm^3)

U_s is shock velocity in the barrier (cm/sec)

U_p is the barrier particle velocity (cm/sec),

and is approximately 1/2 the free surface velocity,

the pressure transmitted to the receptor charge is computed. The relationship of the delay to detonation for lead and dural is shown as a function of these computed pressures in Figure 4.

To date, the pressure profile, and consequently the impulse, delivered to the receptor charge have not been measured. With new pressure gauge techniques,(9) a program to determine values for this parameter is being initiated. However, the contribution of total impulse appears negligible in the comparison, shown in Figure 4, of data for two materials of widely different density and physical characteristics.

3. Initiation by Pellet Impact

Aluminum pads of various thicknesses were used on the ends of large explosive cylinders separating the charge and disc to be propelled. Tests were conducted with steel discs 1.5 inches in diameter and 0.125 inches thick weighing 28.32 grams with velocity of impact at the receptor ranging from 0.58 to 1.52mm/μsec. Earlier evidence that peak pressure, not total energy delivered to the receptor, controlled the delays and velocities in the receptor led to the treatment of the plate as a free surface. Computations identical to those for metal barriers were made and the plot shown in Figure 5 indicates the close agreement of these data to those in metal barriers.

It appears most likely that the excessive scatter in the impact data resulted from oblique collision of the plate with the end of the receptor. Additional testing of the effects of oblique impact is being conducted.

DISCUSSION-GENERAL RESULTS

An examination of the photographic exposures made in tests conducted with the air and metal barriers and impacting pellets made it immediately obvious that the initiation, the pre-detonation, and the "break-out" of high-order detonation have the same physical characteristics for all these methods of transfer of energy to the receptor charge. Four possible conditions have been found to exist in the impacted receptors:

1. Detonation occurs with no measurable delay at the impacted face of the receptor.
2. A measurable supersonic surface shock of mechanical discontinuity proceeds at constant velocity in the receptor, and eventually high-order detonation breaks out in this front.

3. A measurable supersonic surface shock of mechanical discontinuity proceeds at a constant velocity for the entire length of the charge and high order detonation does not occur.
4. A measurable supersonic surface shock of mechanical discontinuity is observed to gradually decay and be no longer observable as it approaches sonic velocity. High-order detonation does not occur.

The first of these conditions was not covered in this study, and the results which follow are only related to 2, 3 and 4 above.

The observations of a supersonic shock along the surface of the charge, proceeding at constant velocity, requires that energy be fed into that shock. This indicates that a chemical reaction has been initiated in the receptor. The lack of observations of this reaction at the surface does not preclude its existence. Figure 6 depicts the experimental arrangement used to study the propagation of this chemical reaction along the core of the receptor stick. A thin receptor is positioned as shown in Figure 6A. An argon bomb light source is used to illuminate the rear surface of this receptor. The streak camera views the rear surface as shown in Figure 6B. When a strong air shock hits the front surface of the thin receptor intense light is transmitted through the translucent explosive indicating the arrival time of this shock at the front surface. Some time later a reaction emerges from the rear surface; this reaction, though not itself highly luminous, is made visible by the use of auxiliary lighting. Figure 7 is a series of streak camera records of receptors of successively greater thickness. The profile of the core reaction can be observed to be changing shape in these records. Figure 8 is a plot of the velocity of the reaction (measured in the direction of the axis of the charge) at the center of the charge, and at various radial distances from the center, as indicated. The shape of the reacting core at any given time is directly related to the difference in velocity, which is highest at the axis of the charge and decreases with radial distance. The non-reactive surface shock is joined by a continuous extension of the shock profile of the reactive core, and has the lowest velocity observed during the pre-high-order detonation regime.

The velocity of the surface shock has been found to be constant in each record. However, the magnitude of this velocity is a function of the barrier conditions. The core velocity along the axis has been measured, and also shown to be constant from the photographic record of charges of different lengths and measured as constant in a given charge by the resistance wire method mentioned earlier(4). The magnitude of the axial velocity is also dependent on the barrier conditions.

The surface observation obtained for dural and lead barriers is plotted vs the transmitted pressure in the receptor charge (Figure 4), and it is indicated in this diagram that delay time and distance are directly dependent on the pressure. A similar graph, Figure 3, is shown for air barriers but, as described under "Discussion" the pressure shown is that of the incident air shock. Figure 5 shows the similarity of data for pellet impact to those for metal barriers.

In over three hundred tests conducted, the velocity of the high-order detonation that is induced in the receptor has been invariably about 1 1/2 per cent higher than the velocity of detonation in the donor stocks for each test. In two of these receptor sticks, the detonation velocity dropped abruptly to its normal value. A valid physical explanation for this observation cannot be made on the basis of information obtained in these firings.

CONCLUSIONS

It follows from the results obtained with the air gaps, metal barriers and pellet impact studies of sympathetic initiation that a single physical model may be established for all of these conditions.

Although the nature of the initiation of the reaction is not known, there is no evidence to contradict the hot spot theory of Yoffe and Bowden.(10) Allowing that the reaction does start by abiabatic compression of trapped gases, mechanical heating, or a combination of both, the volume of this reaction and, as a consequence, its pressure and propagation velocity, are functions of the pressure of the initial shock transmitted to the receptor. As this reaction propagates internally, as seen in the results presented here, the rarefaction wave from the boundary is sufficiently strong to prevent surface detonation. However, the pressure of this internal shock is sufficiently great to manifest mechanical surface changes in the solid explosives, observable by front lighting techniques. If the rarefaction loss rate is less than the energy release rate, the internal pressure builds up to a point at which a discontinuous jump to a high-order detonation occurs in a manner similar to that proposed by von Neumann.(11) However, in this case the reaction moves from the $n=k$ Hugoniot, in which $1 > k > 0$, to the $n=1$ Hugoniot when the pressure reaches a value equal to that at the intersection of the $n=k$ Hugoniot and the Chapman-Joguet plane. If the rate of energy release is such that the pressure does not build up at a rate higher than the rate of dissipation in the rarefaction, then the reaction either continues at a constant rate or at a decreasing rate until it is no longer detectable. It is also concluded that the contribution to this reaction by the shock from a donor charge passing through a barrier to the receptor charge is a function of the initial pressure in the receptor. Although the significance of the total energy in the pressure pulse is not evident in these experiments it is being investigated further to determine its role in the total reaction.

Morton Sultanoff
MORTON SULTANOFF

Vincent M. Boyle
VINCENT M. BOYLE

John Paszek
JOHN PASZEK

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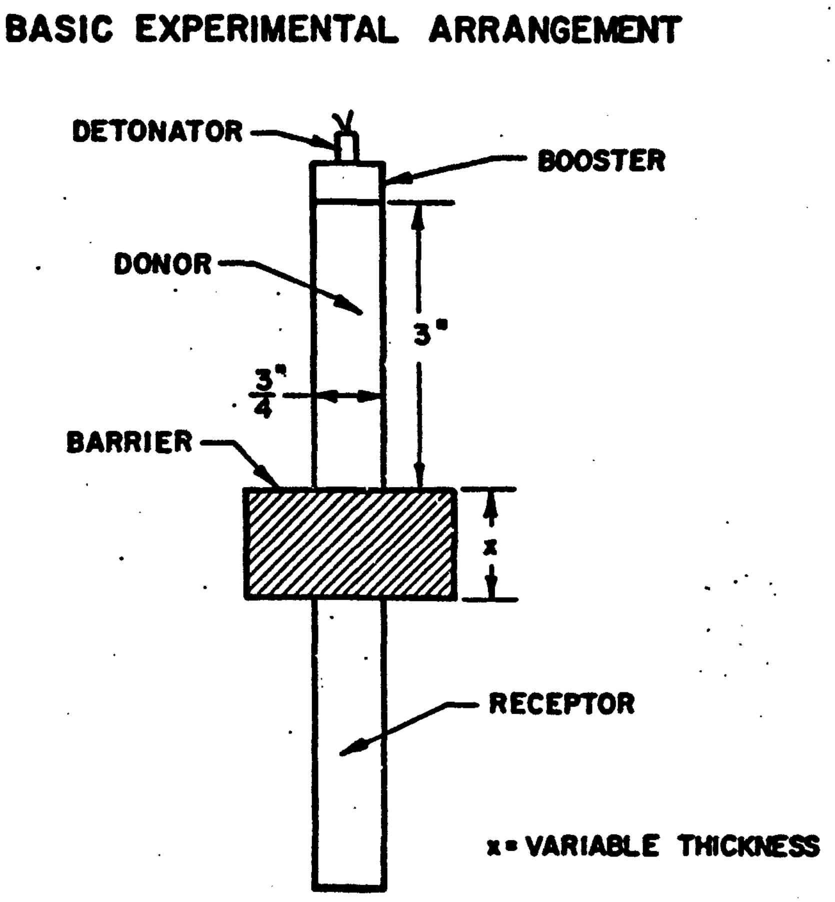


Figure 1: . Basic Experimental Arrangement

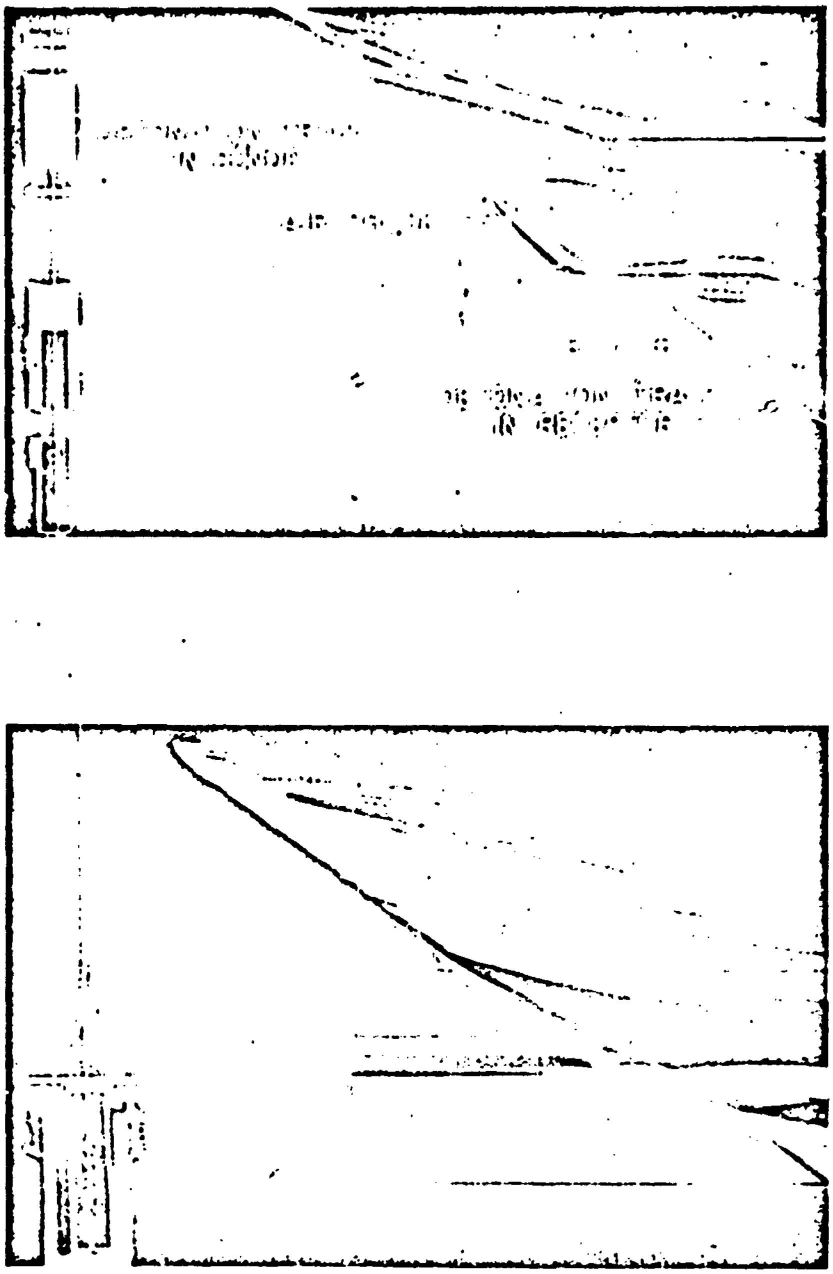


Figure 2: (a) Streak camera record of sympathetic detonation by air shock showing the distance and delay time to detonation; (b) front lighted record of sympathetic detonation by air shock showing the surface shock propagating along the receptor.

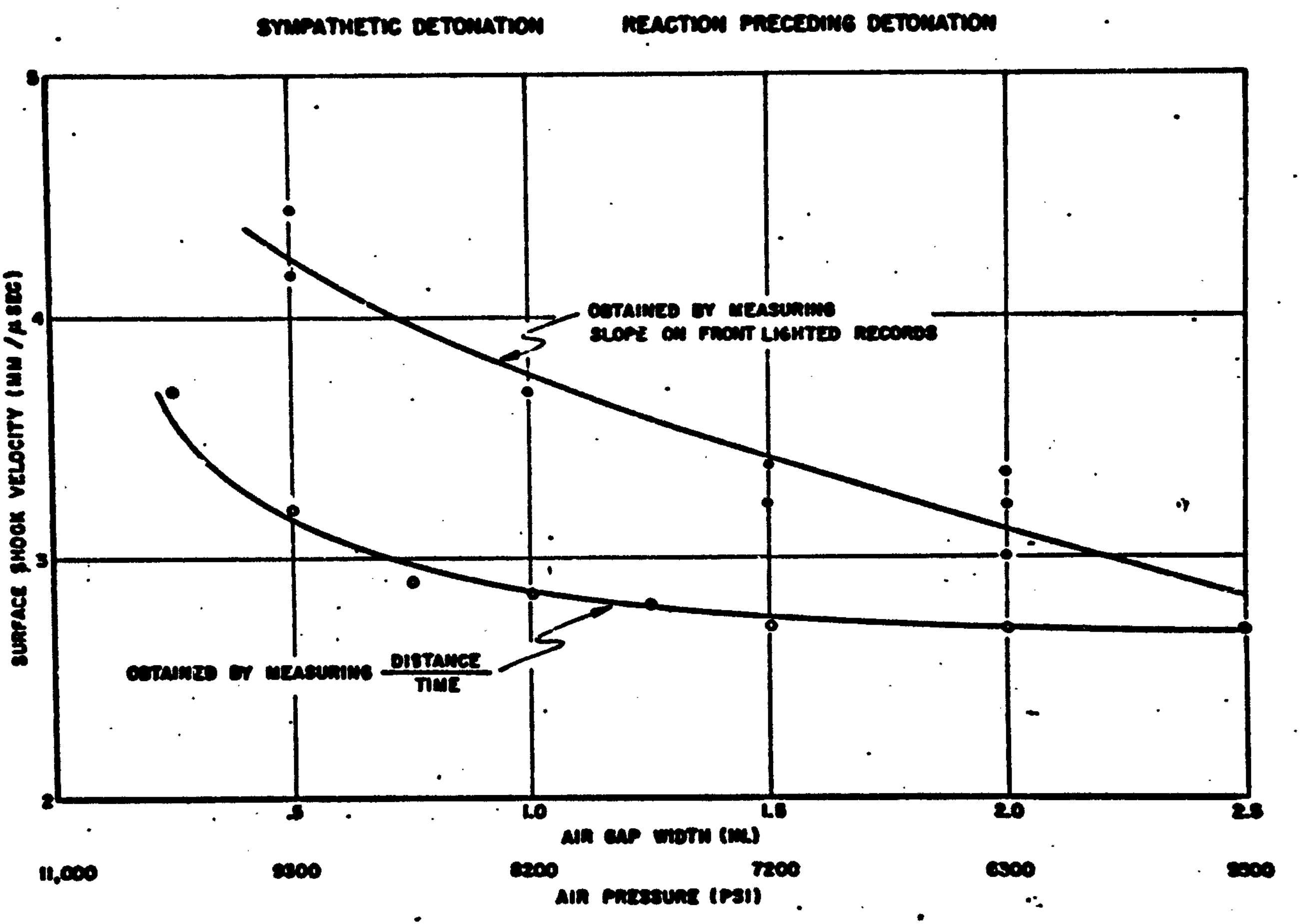
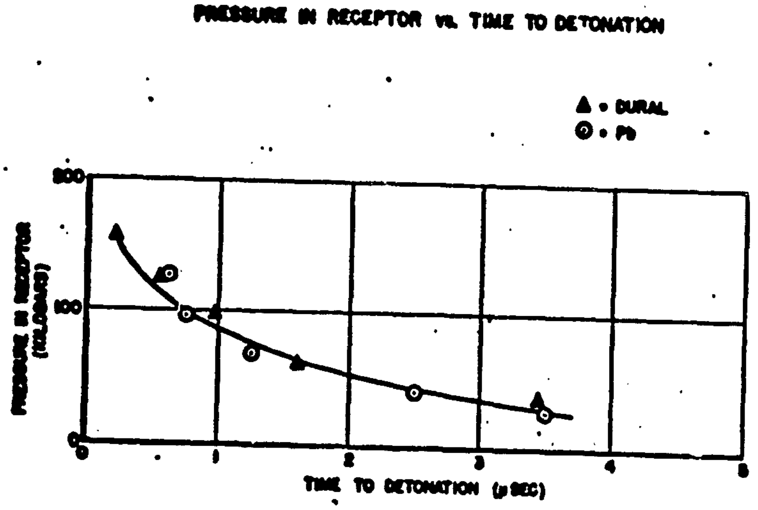


Figure 3: A comparison of front-lighted and distance/time measurements.


PRESSURE IN RECEPTOR vs. TIME TO DETONATION

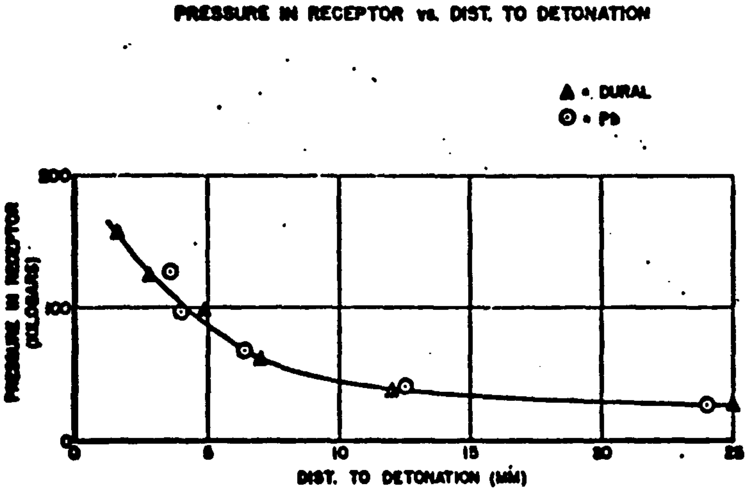

PRESSURE IN RECEPTOR vs. DIST. TO DETONATION

Figure 4: Pressure in receptor versus time to detonation, pressure in receptor versus distance to detonation.

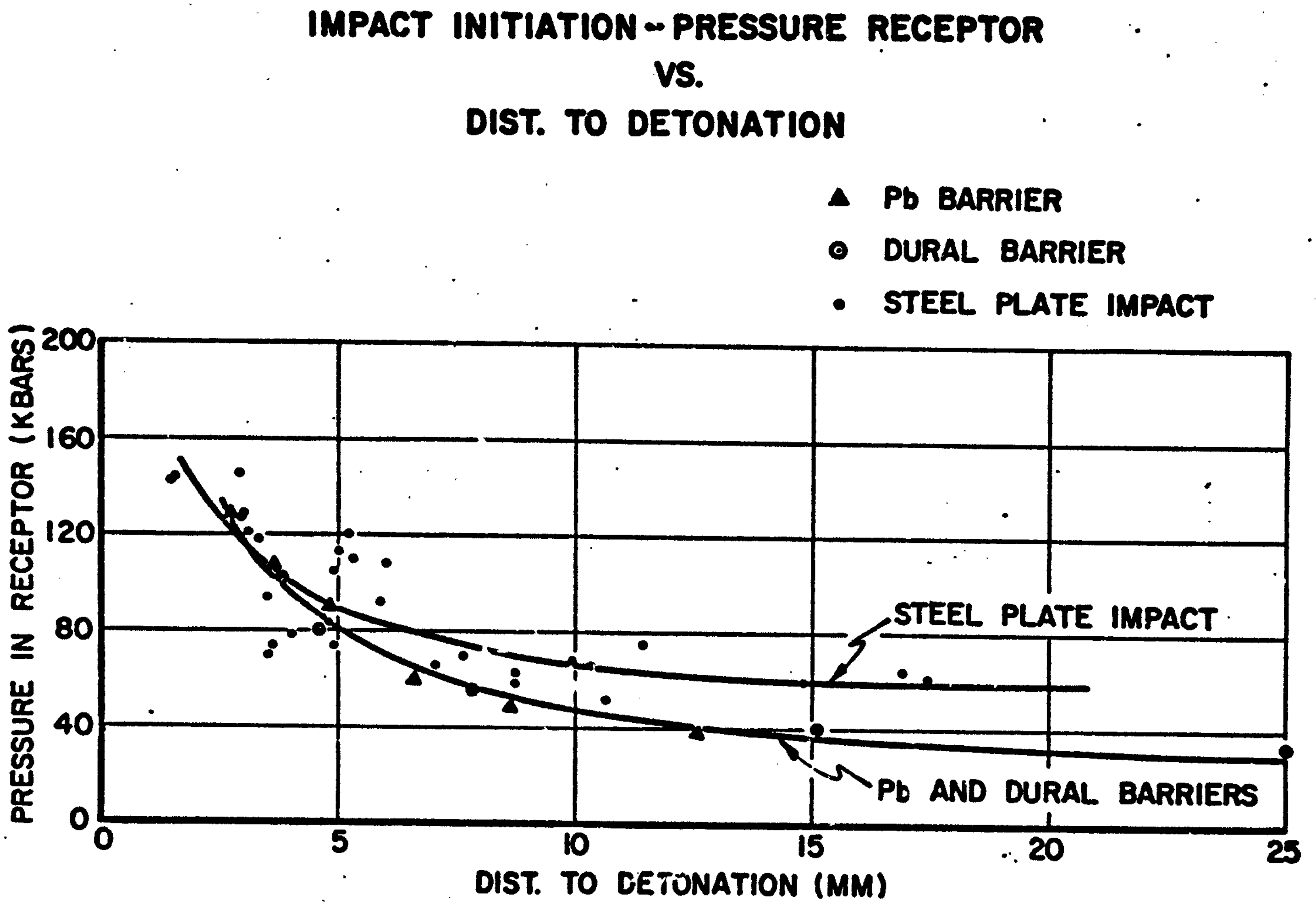
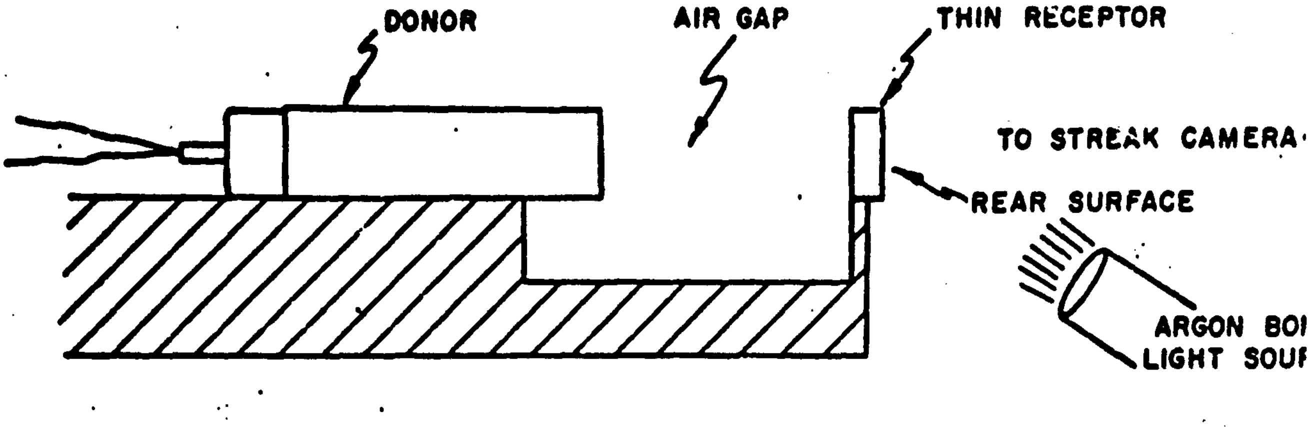
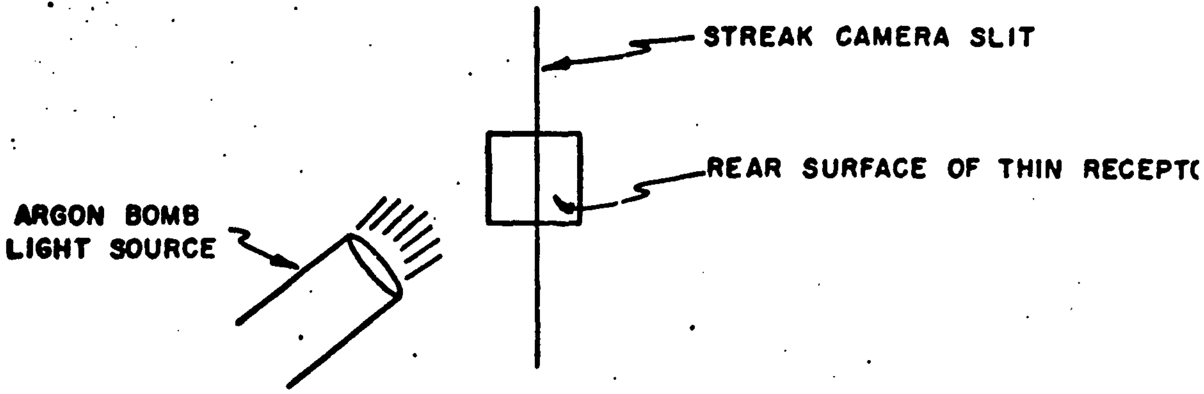


Figure 5: Impact initiation. Pressure in the receptor versus distance to detonation.

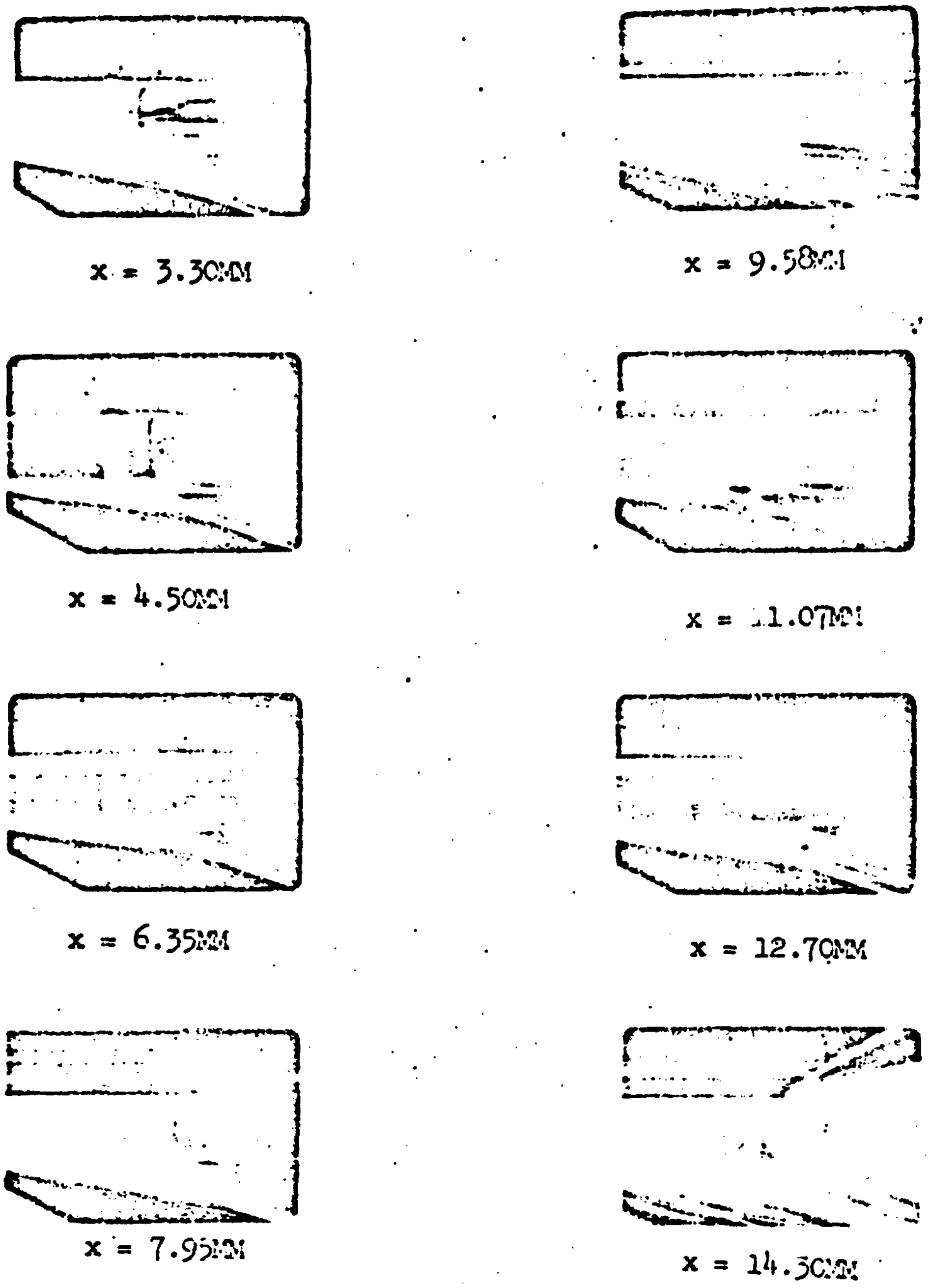


A. SIDE VIEW OF EXPLOSIVE ARRANGEMENT



B. IMAGE OF THE REAR SURFACE OF THE THIN RECEPTOR AS FORMED ON THE STREAK CAMERA SLIT

Figure 6: Experimental arrangement for observing the reaction at the core of a receptor explosive.



x = 3.30MM

x = 9.58MM

x = 4.50MM

x = 11.07MM

x = 6.35MM

x = 12.70MM

x = 7.95MM

x = 14.30MM

Figure 7: Series of streak camera records showing the core reaction emerging from the ends of short receptors (x=length of receptor).

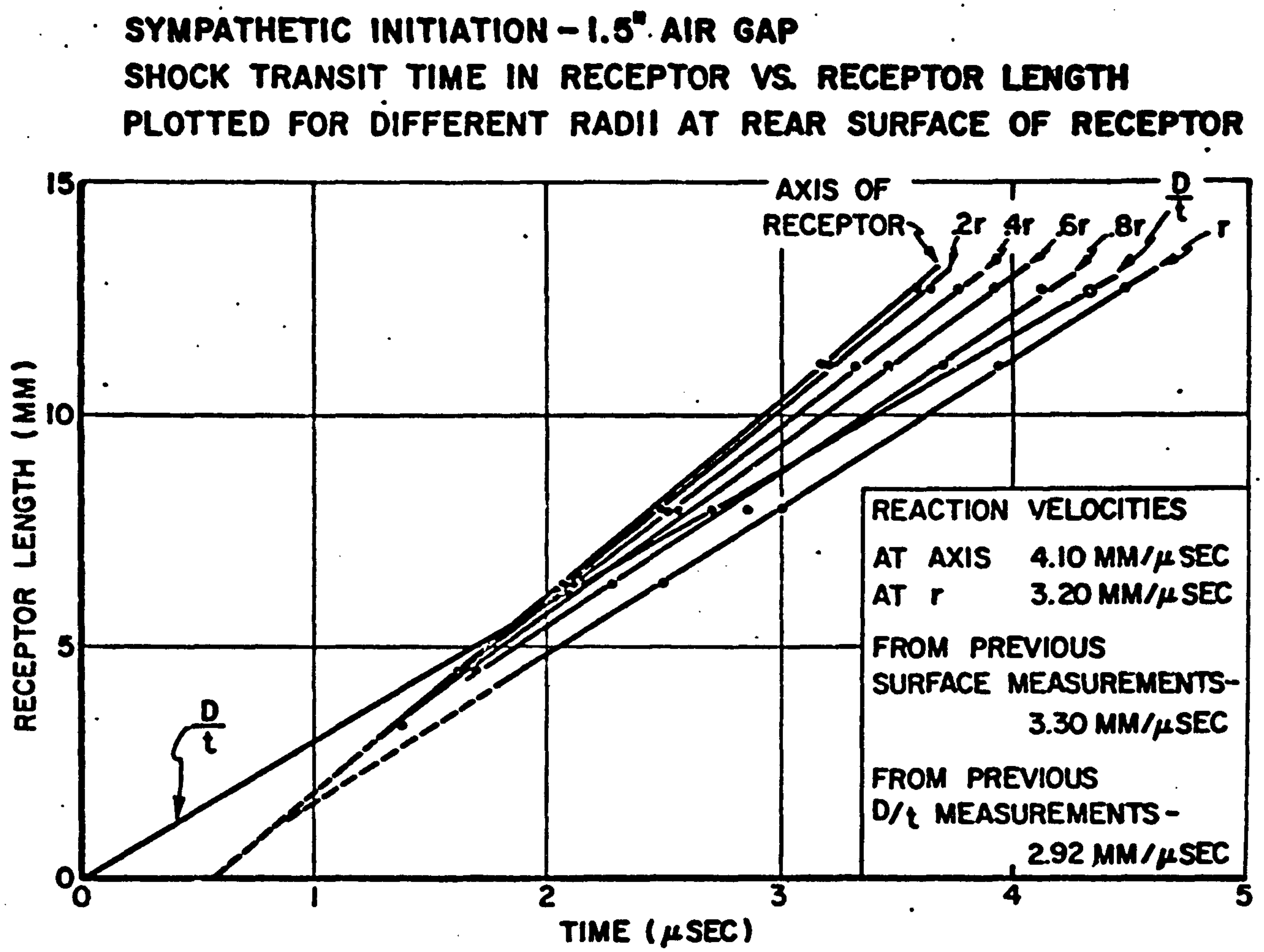


Figure 8: Sympathetic initiation - 1.5 in. air gap. Shock transit time in receptor versus receptor length plotted for difference radii at rear surface of receptor.