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SENSITIVITY OF EXPLOSIVES V

TRANSITION FROM SLOW BURNING TO DETONATION IN CAST PENTOLITE

1 NOVEMBER 1957

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U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NAVORD Report 5758

SENSITIVITY OF EXPLOSIVES V

TRANSITION FROM SLOW BURNING
TO DETONATION IN CAST PENTOLITE

By

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ABSTRACT: Cast, highly confined charges of 50/50 pento-
lite were initiated by electrically heated Nichrome wires with
the energy input of 10 to 50 calories. Transition to detonation
occurred in many cases. Detonation and sub-detonation veloci-
ties were measured at different intervals along the charge by
means of ionization probes. It is concluded that transition
from slow burning to velocities of the order of magnitude of
1 km/sec. takes place within centimeters, or less, from the
igniter. The subsequent development to steady state detonation
may require tens of centimeters of travel. The latter portion
of the transition process is qualitatively similar to the build-
up of shock initiated detonation.

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CHEMISTRY RESEARCH DEPARTMENT
U. S. NAVAL ORDNANCE LABORATORY
White Oak, Silver Spring, Maryland

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Investigation of the basic mechanism of the initiation of explosives is cited in NAVORD 3906 "Key Problems in Research and Development, Part I" as a key problem under: Supporting Research, paragraph 7 of Section 7.7. This research was undertaken with the objective of increasing knowledge in this critical area. The results are considered preliminary and not as a basis for action. This project was supported by Task NO 301-664/43006/12040 and Task NO 800-667/76004/01040.

W. W. WILBOURNE
Captain, USN
Commander

Albert Lightbody
ALBERT LIGHTBODY
By direction

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SENSITIVITY OF EXPLOSIVES V

TRANSITION FROM SLOW BURNING TO DETONATION IN CAST PENTOLITE

I. INTRODUCTION

Until about a decade ago, our knowledge of the factors governing the spontaneous transition from slow burning to detonation was derived almost exclusively from experimental evidence of the phenomenon in gases (1,2,3,4). An extensive collection of quantitative transition data on primary explosives was presented only relatively recently by Bowden and Gurton (5) who found that impact-initiated unconfined primary explosives detonate, if at all, only after a clearly discernible stage of accelerated burning. These experiments on gases and primary explosives indicate that the difference between slow burning and detonation is more than simply one of degree. The evidence is twofold. First, while steady states can be realized both in slow burning (centimeters up to meters per second) and in detonation (kilometers per second), this is not true of intermediate burning speeds. Second, even though, both in gases and in primary explosives, the transition from slow steady burning to detonation is characterized initially by a continuous acceleration through lower intermediate burning speeds, the onset of detonation itself introduces a discontinuity in linear burning rate.

Some research on the transition to detonation in high explosives has been done. There is a well known example of a black powder initiated tetryl fuse which detonates within a short distance from the region of initiation (6). At the present time, transition experiments on high explosives are being conducted at the U. S. Bureau of Mines (7). There has also been a certain amount of classified research on transition properties of rocket propellants (8,9).

The work reported herein deals with the transition from slow burning to detonation in cast pentolite. The purpose of these preliminary experiments was:

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a. To find out if, and under what conditions, the thermally initiated high explosives can be brought to steady state detonation. Much of the known work on initiation of detonation was done on low density charges, which have been found to be detonated more easily than cast or highly pressed material. In the present experiments pentolite was chosen primarily because it is a common explosive which could be investigated in its cast, hence most difficultly detonable state. Also, pentolite is sensitive enough to be detonated with a standard detonator in case thermal initiation fails.

b. To learn, by means of velocity measurements, the manner in which the reaction accelerates and thus gain some knowledge of the mechanism of transition. Understanding of this mechanism is of primary importance to understanding burning stability and sensitivity of high explosives, propellants and primary explosives.

c. To develop methods for testing sensitivity properties of rocket propellants, such as burning stability and detonability.

Since initiation was purely thermal, confinement of the explosive was necessary to bring the reaction to detonation. That this is so, can be seen from the following consideration:

If slow burning is to develop into a detonation, two hydrodynamic conditions must be met: (a) the pressure behind the flame must exceed that ahead of the flame; and (b) the mass flow of the products of the reaction must be in the direction of the propagation of the flame. In other words, conditions for shock formation must be fulfilled. If the product gases are allowed to expand freely, these conditions will not be fulfilled and no shock will form. The rigor of confinement requisite for transition to detonation in any actual experiment will be determined by the strength of the shock necessary to start the detonation reaction. These matters were discussed somewhat more fully in a previous note (10).

II. EXPERIMENTAL

A. Equipment

Pentolite was cast into seamless cold-drawn steel tubes of following dimensions: 1.25 in. O.D., 0.5 in. I.D., 13.5 in. length (Figure 1). The upper end of the tube was open; the lower end was heavily plugged by a 5/8 in. - 11 threaded bolt, 1.5 in. long. The charge itself was thus a right circular cylinder, 12 in. long and 0.5 in. in diameter, encased in 3/8 in. thickness of steel.

The explosive was initiated by an electrically heated No. 24 Nichrome wire, situated at the lower end of the charge. The wire was mounted in one of two ways: In most experiments, one inch of the Nichrome wire was soldered to the leads of thin insulated copper wire which were taken out of the open (upper) end of the tube. A more satisfactory arrangement, employed in some of the later shots, is one in which the steel plug and the copper-beryllium leads are machined so as to serve as a pressure seal (11). This allowed the application of a larger current through the igniter, and hence shorter and less scattered delays to ignition. Resistance of the Nichrome igniter was about 0.1 ohm, the current employed 8 - 10 amps, and the total energy delivered to the explosive usually between 10 and 50 calories.

Detonation and sub-detonation velocities were measured by means of ionization probes, described elsewhere (12), placed along the walls of the tube. The signals from the probes were recorded on an electronic (Potter) chronograph and also on an oscilloscope (Tektronix 545). The circuitry, used with occasional minor modifications, is shown in Figure 2.

The violence of the reaction was estimated qualitatively by the degree of damage done to a 4 x 4 x 3/8 in. steel target plate placed in contact with the upper, open end of the charge. A detonator was placed in contact with the charge through a specially drilled hole for safety reasons (see Figure 1).

Several charges were fired with 1/2 in. rather than 3/8 in. confinement. Assuming 60,000 psi for ultimate strength of cold-drawn steel, the yielding pressure of these heavier tubes, calculated by the strain formula for the thick hollow cylinder, is 48,000 psi as compared to 43,500 psi for the usual 3/8 in. thickness.

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A few longer charges (34.5 in.) were fired with the usual 3/8 in. steel confinement.

B. Results

Thermal initiation of cast 50/50 pentolite under the conditions described above invariably (35 shots) led to explosions sufficiently violent to shatter the 3/8 in. (and the 1/2 in.) thick steel wall and to deform the 3/8 in. steel target plate.

Both qualitative and quantitative criteria for detonation were used. The size of the tube fragments is a fairly good indication of the violence of the reaction. A more exact qualitative criterion is the damage to the target plate. The degree of damage to the target plate was arbitrarily classified in four categories ranging from A - no damage, to D - detonation (Figure 3. See also Ref. 13).

Qualitative results, collected in Table I, show that the burning often developed into a steady-state detonation within 12 inches of travel. It always developed into a detonation over 34.5 inches of travel.

TABLE I

<u>Charge Length (in.)</u>	<u>Total No. of Shots</u>	<u>Developed to Steady State Detonation</u>	<u>Did not Develop to Detonation</u>	<u>Number Doubtful</u>
12	30	10	16	4
34.5	5	5	0	0

The delays, τ , measured from the time the current is turned on in the ignition circuit to the audible explosion, were quite erratic. They varied from 1 to 88 seconds with the

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average of 18 seconds for "Detonation" shots and 26 seconds for "No Detonation". Some representative values are given in Tables II and III. In some cases, the target plate damage evidence was supplemented by quantitative velocity measurements. These velocity data can be divided in three categories: (1) Measurement of steady detonation velocity of the confined 1/2 inch charge; (2) One-interval (two probe) data; (3) Three-interval (four probe) data.

1. Six detonator-initiated shots gave the average steady detonation velocity of 7.3 mm/ μ sec. (1/2 in. diameter, 3/8 in. steel confinement). The precision of these measurements was about 13%. The accepted value for detonation of cast pentolite is 7.5 mm/ μ sec.

2. Two-probe shots were of two kinds: those in which the start probe and hence the interval between the probes was far from the igniter and near the target plate; and those in which the start probe was near the igniter and the stop probe at varying distances along the tube. These data are given in Tables II and III, respectively.

TABLE II

Run No.	Delay \bar{T} (sec)	Dist. from Igniter to 1st Probe l (cm)	Distance Between Probes d (mm)	Velocity (mm/ μ sec)		Plate Damage
				Chronograph D_p	Oscilloscope D_s	
26	24	20	50	1.0	Instrument failed	B-C
27	55	20	50	6.7	7.1	D
29	78	20	50	2.3	Instrument failed	C
36	25	19	50	0.87	0.88	B

TABLE III

Run No.	Delay τ (sec)	Dist. from Igniter to 1st Probe l (cm)	Distance Between Probes d (mm)	Velocity (mm/ μ sec)		Plate Damage
				Chrono-graph D_p	Oscillo-scope D_s	
40	43	6	200	0.44	Instrument failed	D
43	14	5	230	1.91	1.92	C-D
45	26	5	230	2.71	2.74	D
46	8	5	230	Instrument failed	2.95	C-D
47	6	5	230	2.37	2.40	D
48	20	5	230	3.24	3.29	D
49	18	7	200	1.23	1.23	B
55	3	1	249	1.51	1.37 ?	C-D
58	10	1	241	Instrument failed	1.87	D
59	9	1	64	"	1.17	D

3. Data from two 4-probe shots are given in Table IV.

TABLE IV

Run No.	Delay τ (sec)	Dist. from Igniter to 1st Probe l (cm)	Dist. between Probes $d_{12} = d_{23} = d_{34}$ (mm)	Velocities (mm/ μ sec.)			Plate Damage
				D_{12}	D_{23}	D_{34}	
56	< 1	~ 1	89	2.3	3.1	8.0	D
57	< 1	~ 1	89	1.8	3.3	7.4	D

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Here, the distance between probes 1 and 2 is denoted by d_{12} , etc. The corresponding velocities obtained from the oscilloscope measurements, are D_{12} , D_{23} and D_{34} . In the shot No. 57 the velocity between the first two probes as recorded by the counter, $D_{12} = 1.9$ mm/ μ sec., is in good agreement with the oscilloscope value. In shot No. 56 the counter failed. The persistent increase of velocity between equidistant probes is illustrated by the oscilloscope record of shot No. 56 (Figure 4).

The data collected in Tables II, III and IV, represent only about half of the shots on which velocity measurements were attempted. In many cases the instruments failed. Damage to the probes during transportation and casting operations and other unavoidable mechanical deficiencies undoubtedly account for some failures. But it is probable that in other cases the probes simply did not respond to sub-detonation burning. Incorporation of a thyratron in the circuit (Figure 2) makes the triggering of the instruments fairly reliable, but does not eliminate malfunctions entirely.

The accuracy of the velocity measurements is rather low. The time intervals in steady-state detonations have been found reproducible only within two counts of the chronograph, or 1.25 μ sec. The oscilloscope records can usually be read within 5%.

III. DISCUSSION

A parallel use of the qualitative target damage criterion and the quantitative velocity measurements allows some insight into the phenomenon of transition to detonation. Several features of the process can be deduced by an inspection of the data presented in Tables II and III.

In Table II, where the interval between the probes, d , was relatively short and far removed from the heating element, there is good correspondence between velocity measurements and target plate damage, indicating that there was no appreciable change in burning speed once the first probe was reached. Final velocities, D_{34} , of Table IV can be used to supplement these data.

In Table III, on the other hand, where the measurements were made over an interval starting much nearer the igniter, the measured velocity does not correspond with target plate

damage. There is appreciable increase in burning rate between the start probe and the target plate as revealed by the damage to the target plate. But, even here, there is no evidence of a change of order of magnitude of velocity, once the first probe was reached. (Measurement of a possible exception, Run No. 40, Table III, is in doubt, because of an instrument failure.)

Hence it can be concluded from the data collected in Tables II and III that the transition from slow burning to velocities which are less than, but of the order of magnitude of, steady state detonation velocities takes place within a short distance from the point of initiation - a few centimeters at most, and probably much less. The subsequent build-up to steady detonation velocity may occur over a distance of tens of centimeters. This conclusion is supported also by the multiple probe data given in Table IV.

The existence of a fairly long, fast (kilometers per second) sub-detonation phase is in qualitative agreement with the results of shock-initiation experiments. Several workers (14, 15, 16) report that in shock-initiated charges of high explosives, the reaction, before developing into steady state detonation, propagates at lower velocities over measurable intervals. Although the sub-detonation intervals in our thermally initiated experiments are appreciably longer, the qualitative similarity of the two phenomena suggests that the build-up to detonation is similar in shock and thermal initiation. This gives support to the theory (10) that, even in the case of purely thermal initiation, the cause of detonation is a shock which must arise spontaneously in the burning medium, if there is back confinement. Confinement of the reaction products causes formation of a region of rapidly increasing pressure which generates a disturbance travelling along the tube. The front of this disturbance develops into a shock of increasing strength. This shock, presumably, is the direct cause of detonation.

IV. SUMMARY

It has been shown that confined cast high explosives can be detonated by purely thermal means. The build-up of steady state detonation is quite reliable if the explosive charge is sufficiently long. The process of transition to steady state detonation includes a relatively long (50 microseconds or more) interval of rapid sub-detonation velocities. The phenomenon is qualitatively similar to the build-up of shock-induced detonations.

V. PLANS FOR FUTURE WORK

The work to date suggests two avenues of approach in planning future experiments:

1. The velocity measurements and qualitative results described in this report, give little or no indication of the manner in which the pressure in the region of initiation builds up, and hence no information about growth of the detonation-generating shock wave. This very important information could be obtained by measuring the pressure-time history of the region of initiation during the pre-detonation delay, τ .

2. Several investigators (14, 15) report propagation of shock-induced "detonation" at a transient but constant velocity of about 2 km/sec., which subsequently changes to the steady state detonation abruptly and without a discernible stage of intermediate velocities. On the other hand, a detailed investigation, at this Laboratory, of shock-initiated detonation in several high explosives reveals a smooth transition to steady states (16). The preliminary measurements reported herein are not detailed enough to resolve this apparent discrepancy. The problem could be settled decisively only by a continuous measurement with high time resolution of the burning rate from initiation, or at least from an intermediate velocity of about 1 km/sec., to detonation.

Both the time-pressure and continuous velocity measurements on heat initiated, highly confined cast charges of high explosives are being planned as an extension of the work reported herein.

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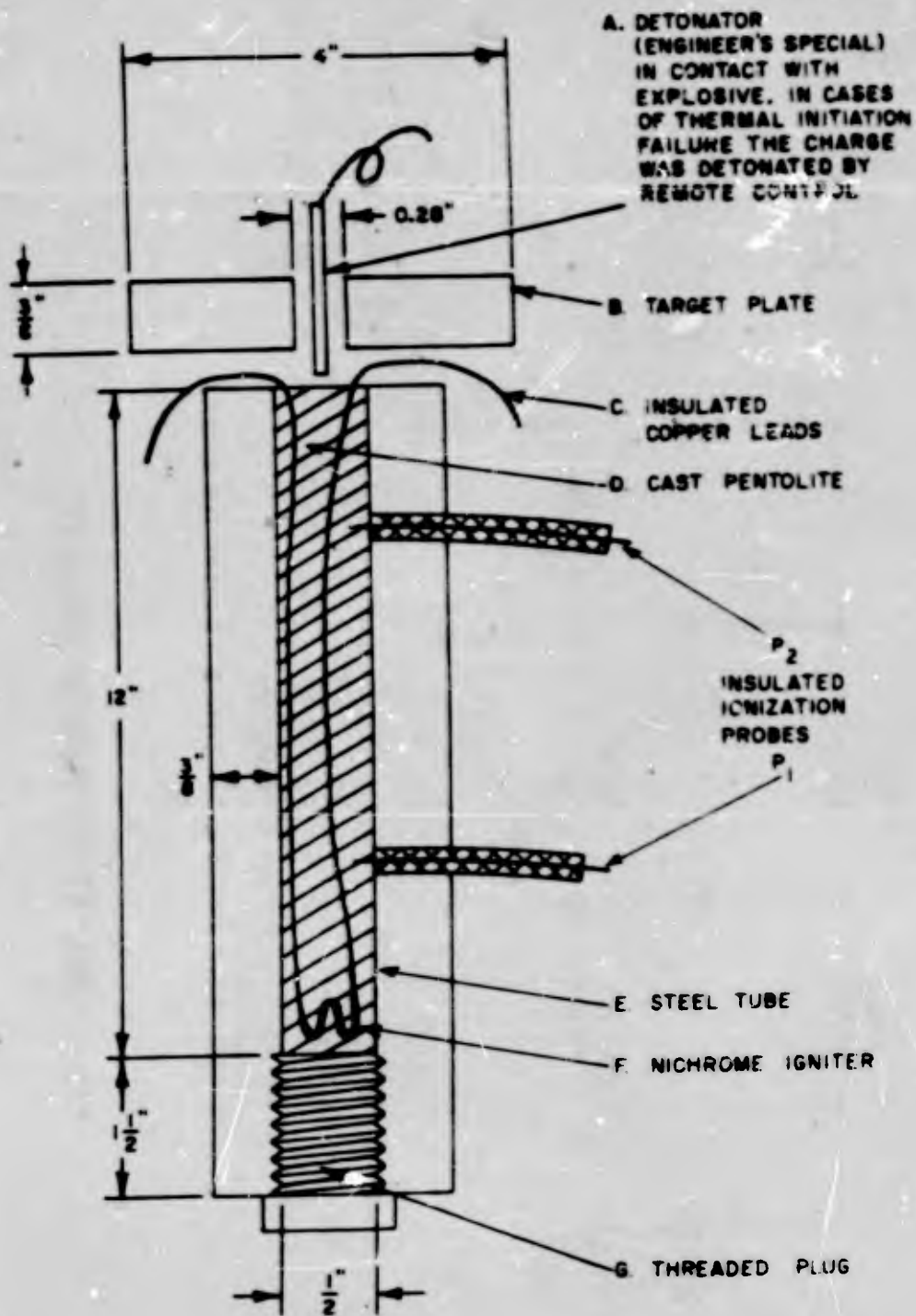
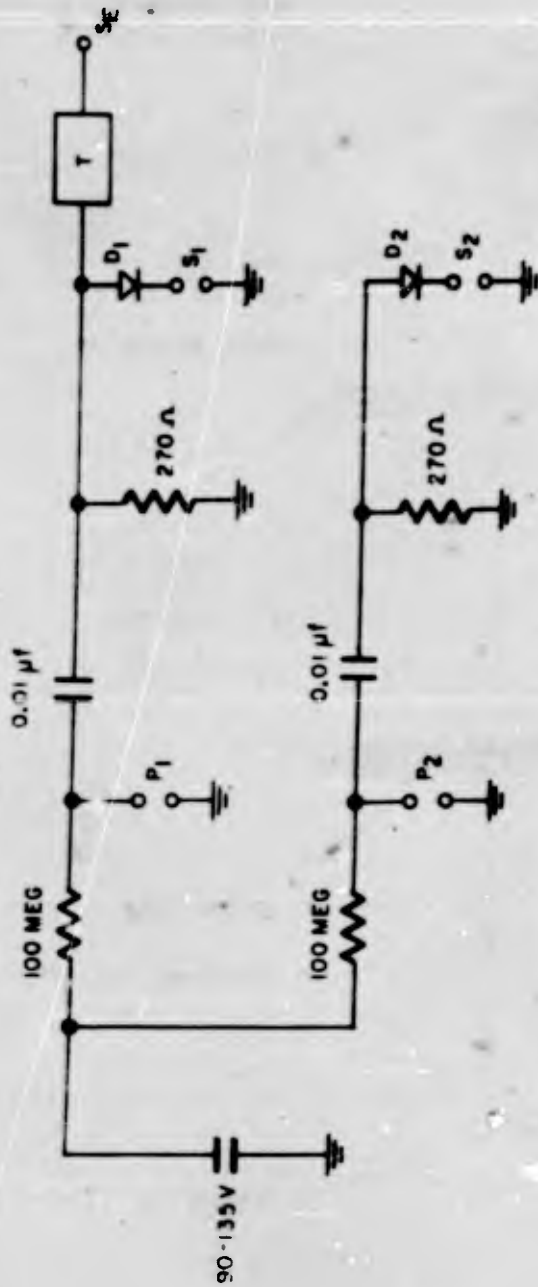


FIG. 1 CROSS-SECTION OF THE CHARGE



P₁, P₂ — IONIZATION PROBES

D₁, D₂ — CRYSTAL DIODES

S₁, S₂ — INPUTS (START AND STOP RESPECTIVELY) OF THE OSCILLOSCOPE AND CHRONOGRAPH

T — THYRATRON CIRCUIT

SE — EXTERNAL INPUT OF THE OSCILLOSCOPE (TO START THE SWEEP)

FIG.2 IONIZATION PROBE CIRCUIT

FACE OF PLATE
IN CONTACT WITH EXPLOSIVE
FRONT VIEW

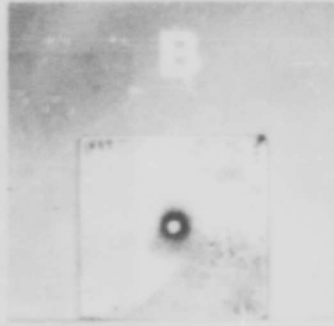
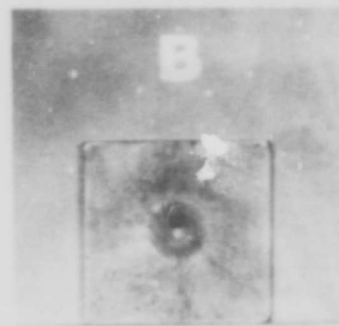
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SIDE VIEW

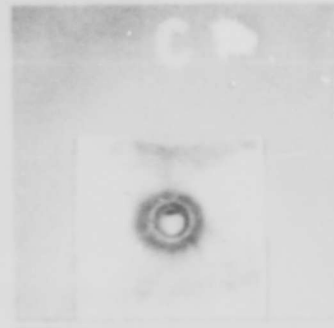
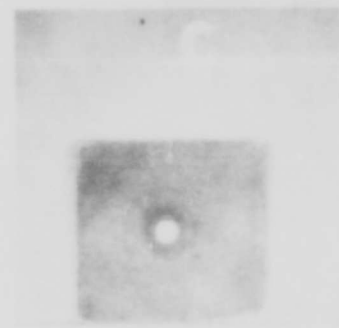
BACK VIEW



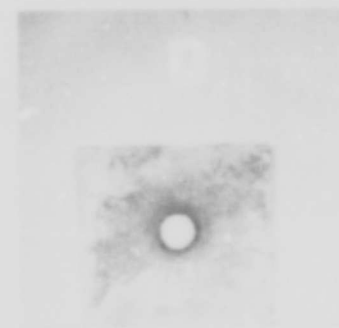
(A) NO DAMAGE DUE TO HIGH EXPLOSIVE SOME DAMAGE DUE TO DETONATOR



(B) SUB-DETONATION DAMAGE



(C) SUB-DETONATION DAMAGE

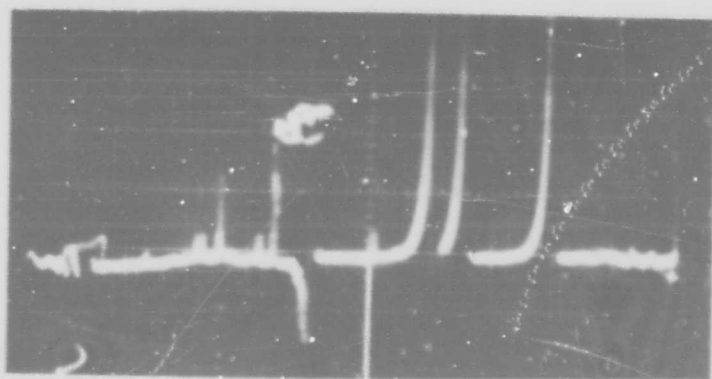


(D) STEADY STATE DETONATION

FIG. 3 TARGET PLATE DAMAGE

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SCALE: 1 CM = 20 μ SEC
DIRECTION OF THE SWEEP IS RIGHT TO LEFT
SIGNALS AT 0, 38, 67 AND 78 μ SEC.



↑
RECORD STOPS HERE

FIG. 4 4-PROBE OSCILLOSCOPE RECORD
OF SHOT NO. 56

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