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PROPAGATION FAILURE IN SOLID EXPLOSIVES UNDER DYNAMIC PRE-COMPRESSION

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PROPAGATION FAILURE IN SOLID EXPLOSIVES UNDER DYNAMIC PRE-COMPRESSION

By B. E. Drimmer and T. P. Liddiard, Jr.

ABSTRACT: Steady-state detonations were stopped on entering a zone in a solid explosive already under compression by a 5-20 kb shock. Tests with PBX 9404 and EL-506C indicate that such quenching of detonation may be a general phenomenon of explosives. This implies that energy-concentrating systems ("hot spots") are required even for steady-state detonations.

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The experimental work described in this report was accomplished under Project LACE at NOL for FY 1960 (Task NOL 260-60) and was supported by the U. S. Atomic Energy Commission through a contract with the E. O. Lawrence Radiation Laboratory, Livermore, California.

The bulk of the material under this task was reported in periodic progress reports. However, during the several years since this work was done, a number of peculiar incidents in various detonation experiments have occurred at this Laboratory, and elsewhere, which appear to be explainable by phenomena accompanying dynamic pre-compression of a detonating explosive. These incidents prompted the authors to extract all the data from the original progress reports which were pertinent to the subject of this report. These data represent the results of a relatively limited study of the quenching phenomenon, since the original aim of these experiments was slanted more toward the development of a "quick fix" which would prevent the quenching of detonation. They do show, however, that a detonation can be stopped by compressing the explosive beyond a critical pressure, and that the phenomenon of detonation quenching may be far more general than was suspected at the time the experiments were made.

The identification of commercial materials implies no criticism or endorsement by the Naval Ordnance Laboratory.

The authors acknowledge with gratitude the care and skill with which Mr. James Schneider performed these experiments. The many stimulating discussions with Dr. S. J. Jacobs and Dr. D. Price of this Laboratory also are acknowledged with appreciation.

R. E. ODENING
Captain, USN
Commander

I. KABIK
By direction

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I. INTRODUCTION

A series of experiments was run with solid explosives in which a fully developed detonation wave was quenched upon entering a zone in the explosive which was already under compression by another shock wave. These tests were made with EL-506C* and the plastic-bonded HMX explosive PBX 9404. Although the quantitative features of the results between these two explosives differ, they both exhibited the phenomenon of detonation quenching by dynamic pre-compression. In addition to these tests, the perplexing results of a single experiment on cast Octol (HMX 65%/TNT 35%), performed for a different reason several years ago, can now be explained on the basis of detonation quenching by the same basic mechanism of dynamic pre-compression.

Before describing in detail the tests and results obtained, a short definition of the term "detonation quenching by dynamic pre-compression" may be useful. In explosives science there is the well-known dependence of detonation velocity on the initial bulk density of the explosive. In general, this dependence is nearly linear, as the density increases from about 0.5 to 1.0 times the theoretical maximum, or voidless, density (TMD). One may well wonder if this linear relation continues beyond 1.00 TMD. The experiments to be described show that when the density of the undetonated explosive exceeds the voidless density by about 5 to 10 per cent, the detonation-velocity, density curve apparently leans all the way over, and the velocity of the wave drops to that of an inert shock; i.e., the detonation fails to propagate. Now, in some practical explosive configurations, it is possible for the forward part of a detonating explosive to experience a shock wave which compresses the explosive beyond its voidless density. When the detonation front collides with this high-density zone, the chemical reaction apparently stops and the wave velocity falls rapidly to that of an inert shock. This failure of a detonation to propagate through a zone of dynamically compressed explosive is termed "detonation quenching by dynamic pre-compression".

This phenomenon of detonation quenching has been observed by others. For example, Johansson[1]** recently discussed what he termed a "channel effect". He noted that if he placed a series of dynamite sticks in a metal tube, under certain circumstances some of the sticks near the end of the series would not detonate, even though a normal, steady detonation had been achieved in the

*A flexible sheet explosive, manufactured by E. I. duPont Co., Wilmington, Del., containing approximately 70% PETN plus 30% of an elastomeric binder.
** References will be found on page 8.

forward sticks. Pre-compression of these end sticks by a fast moving shock wave, traveling the annulus between the dynamite and the metal tube, apparently prevented propagation of detonation. Giltaire, et al, observed a similar effect in various mining explosives[2].

D. W. Woodhead[3], working with tubular charges, showed that in a sensitive solid explosive the strong air shocks within the cavity (he called these "cavity waves") can cause enhancement of detonation velocity. However, in an insensitive explosive, such as TNT. the presence of the "cavity wave" was found to cause some loss of explosive power or, in some cases, even complete detonation failure of part of the charge. This, as implied in his article, can be explained by the pre-compression of the material of the walls by the "cavity wave" moving ahead of the detonation front.

Campbell, et al[4], performed an experiment in which a wedge of plastic-bonded HMX was shocked twice. While still under compression from the first shock (39 kb) the explosive was subjected to another shock, moving in the same direction, of about 100 kb. With this experiment they were attempting to answer the question of whether or not the explosive traversed by the initial shock wave ever reacted completely. From their results they suggest that apparently the first shock had desensitized the explosive to the action of the second shock.

Other evidence indicates that the dynamic character of the pre-compression is not needed to cause quenching of detonation. All that is required is that an initial density above a critical value be achieved. In general, this critical value is dependent on the charge dimensions; the smaller the charge, the lower the critical density. For some explosives this density can be less than the TMD at atmospheric pressure. As examples, mercury fulminate and lead azide, under certain conditions, will not support a detonation of high velocity at densities near crystal[5]. The charges, shock initiated by electric detonators, were confined in thick-walled, brass containers. Charges with diameters of 3.8 mm or less would not support the usual high detonation velocity of about 5000 m/sec, but did support a reaction wave at 1200 to 1700 m/sec. Charges of 5.1 mm diameter yielded only the high velocity detonation. Nitroguanidine fails to detonate (51 mm diameter) at a density of 1.70 g/cm^3, or 95.5% TMD, even though it is confined in a thick-walled, steel cylinder and a PBX 9404 booster is used[6]. The detonation velocity in hydrazine nitrate falls off greatly with increasing density for unconfined charges of 42 mm diameter or less[7]. The effect may exist at a diameter of 65 mm or larger, since the maximum density here was 1.59 g/cm^3, or 94.6% TMD, at this diameter. The term "dead-pressing" has been applied to these in the past, but since we do not quite understand the phrase, in terms of modern detonation theory, we would prefer to describe these in more simple terms; i.e., as examples of failure to propagate because of excessive initial density. As we shall see below, although some progress has been made, it is still not clear at the present time how an excessive initial density prevents propagation of detonation in an explosive.

II. EXPERIMENTAL PROCEDURE

Most of the experiments* were run using the arrangement shown in Fig. 1. A mild detonating fuse+ ignited the EL-506C (donor) sheet, causing a shock wave to propagate through a layer of Plexiglas (6.4, 12.7, or 19.1 mm thick), the test explosive (acceptor), and finally a 25.4-mm thick layer of Plexiglas. A few microseconds after initiation of the donor sheet, the acceptor layer was initiated by another mild detonating fuse. As shown in the right-hand portion of Fig. 1, the detonation wave (D) in the acceptor moved down as the shock wave (U), transmitted to the acceptor, moved up with a phase velocity equal to the detonation velocity in the donor explosive. The collision point was adjusted, by appropriate delays, to be near the center of the acceptor. (In actual practice the required delays were obtained by using unequal lengths of fuse, initiated by a single U. S. Engineer's Special Detonator.) A high-speed smear camera viewed the events along an imaginary line, marked "Slit Image" in Fig. 1, on the free surface of the thicker Plexiglas layer. To improve the quality of the photographic record, a sheet of 0.015 mm thick, aluminized Mylar film was placed between the test explosive and the thicker Plexiglas layer. A properly placed exploding wire light source provided the required light. The 6.4-mm thick aluminum plate, backing up the EL-506C donor layer, served merely to provide confinement for that explosive.

In order to measure the amplitude of the pre-compressing shock wave, a set of calibrating tests were run. The experimental arrangement was essentially identical with the test arrangement, but with the test explosive replaced by Plexiglas; in other words, a continuous piece of Plexiglas formed the lower part of the set-up. In this case the smear camera viewed the Plexiglas at right angles to the propagation direction of the shock wave, with an exploding wire light source in the rear.

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*These experiments were described in qualitative terms in Ref. 8, which discussed the general subject of shock-to-initiation transition.

+A lead-sheathed explosive fuse containing RDX or PETN. The fuse used in these tests generally contains 10 grains of RDX per linear foot.

The data from the resulting shadowgraph were then reduced to give the shock velocity in the Plexiglas as a function of distance from the interface of the (donor) explosive and Plexiglas. Correlation of this velocity with the equation of state of Plexiglas (Reference 9) then gave the peak pressure in the shock as a function of the same distance. Having the pressure-distance dependence for the shock wave in Plexiglas, it was now necessary to determine the change in the pressure as the shock crossed the boundary, at a given Plexiglas thickness, into the test explosive. In order to do this, it was necessary to know the shock Hugoniot for the non-reacting test explosive. These shock Hugoniots were obtained by measuring the shock velocity and associated free-surface velocity of a thin specimen being shocked by a plane wave. With these shock Hugoniots it was now possible to estimate the peak pressures experienced by the test explosives under various experimental arrangements.

III. RESULTS

Typically, a photographic record, Fig. 2, showed the constant (phase) velocity shock wave from the detonation of the donor explosive, EL-506C (lower trace), and the constant velocity detonation wave from the test explosive (upper trace). On collision of the two waves, there was a sudden decrease in the velocity of the detonation wave, and finally a quenching of detonation. Closer inspection of some of the records shows that immediately after collision, the photographic trace of the detonation wave spread, as seen clearly in Fig. 2.

Though quenching of detonation occurred with the two explosives tested, details of the process differed from one explosive to another. For example, Table I shows the critical dimensions of seven tests, with EL-506C as the donor (or shock producing) explosive, and either PBX 9404 or EL-506C as the test explosive. Fig. 3 shows sketches of the resulting smear-camera records, with all records normalized to a common collision point and a common shock velocity (U) from the EL-506C donor. The traces for the four detonating EL-506C test explosives (D) all show a sharp break in slope, i.e., detonation velocity, immediately upon collision with the shock wave. The traces for the two PBX 9404 tests indicated that the detonation continued without significant change in velocity for about 10 mm after collision and then gradually slowed down.

Referring to Table I and Fig. 3, it can be seen that the response of the EL-506C test explosive was little altered by changing the thickness of the Plexiglas barrier from 12.7 to 18.8 mm, or by eliminating the aluminum backing. Actually, the acceptor pressures (P_a) used in th se tests were not low enough to pin-point the cut-off (crit al) value of P_a. For EL-506C the value probably is well under the lowest value (14.5 kb; shot no. 29) given in the Table, since the velocity degradation is very abrupt at this pressure. [There were a number of tests made in which the steady-state detonation of the acceptor explosive continued without interruption through the pre-compressed zone. In these cases the amplitude of the pre-compressing wave was made very small by a complex shock degrading system of alternate thin layers of plastic foam and steel or copper. Estimates of the pressures developed in the acceptor explosive in these tests ranged from 5 to 10 kb.] The critical value for the PBX 9404 (1.2-1.4 mm) acceptor apparently is only slightly under 17 kb, since the detonation (shot no. 48) showed little or no decay over 35 mm of travel after entering the shocked zone.

IV. DISCUSSION OF RESULTS

The results obtained with the two explosives appear to indicate a general rule for solid explosives: there exists for each solid explosive a characteristic density which if exceeded, will cause failure of the explosive to propagate detonation. The present results indicate that this characteristic density, for many of the military explosives, is about 8 (± 3) per cent above the "voidless" density. These densities can be reached by dynamically pre-compressing the explosive with a shock wave having a peak pressure of 5 to 20 kilobars.

The word voidless was placed in quotes to emphasize the fact that in these tests the compressed explosive contained many voids, even though the <u>bulk</u> density exceeded the density it would have had without voids, <u>at one atmosphere pressure</u>. An order of magnitude analysis shows this very simply. Assume an initial bulk density of say, 0.97 TMD. The 3 per cent of the volume therefore is made of a large number of tiny voids, whose volume distribution probably conforms to something like a Poisson distribution. To simplify the argument, we assume that the voids are spherical, and that they are filled with a gas obeying the ideal gas law. When the explosive experiences a shock of 8 kilobars these voids will simply contract, to a first approximation, until the volume is 1/8000 of the original volume, i.e., their diameters will decrease by a factor of 20. While these new voids are indeed much smaller now, the explosive is certainly not "voidless". It would therefore appear logical to believe that even during pre-compression there should still remain some voids whose diameters would be in the 0.1-1.0 micron range, even in a well-made charge.

Why voids of this size do not permit propagation of detonation is not clear at all. The fact that the quenching of detonation in some explosives, such as PBX 9404, does not occur immediately, would seem to imply that these few remaining sites may actually initiate detonation locally, but that there are not enough sites to continue the process. In other words, initiation may occur at one site, and tend to propagate outward, but not receiving support from a neighboring site, the process may ultimately degenerate and die. If this were true then it would imply that normal, steady-state detonation is basically an inter-crystalline process, at least in the sense that a shock wave of amplitude equal to its own Chapman-Jouguet pressure, or even its von Neumann spike pressure, is insufficient to break down the explosive molecule in the absence of some energy (pressure?) focussing system. Thus, such energy-focussing systems would appear to be necessary for steady-state propagation, as well as the transient process of build-up to detonation. Such a conclusion would have serious implications in detonation theory, for it indicates that the prevailing hydrodynamic theory of steady-state detonation of solid explosives, based as it is upon the dynamics of homogeneous gas reactions, will require significant modification. This modification will have to take into account the solid-state characteristics of the medium, as well as its thermal characteristics.

As already noted, the dynamic character of the pre-compression of the explosive does not appear necessary to this phenomenon of propagation failure. Nitroguanidine, hydrazine nitrate, lead azide, and mercury fulminate have already been cited as examples of explosives which fail to propagate if the bulk density exceeds a certain limit. A static test on EL-506C showed that this explosive would not propagate detonation if it were held at a pressure of 7-8 kilobars[10]. The 1.6 mm diameter charge was confined in a chrome-molybdenum tube, about a meter long, with an outer diameter of 11 mm.

An experiment was run to determine the role of the angle of incidence of the pre-compressing shock. Fig. 4 shows the arrangement for applying a plane shock normal to the propagation direction. Three Plexiglas thicknesses were used: 6.4, 12.7, and 25.4 mm. The EL-506C explosive layer was 1.0 to 1.3 mm thick, except for the case involving the 25.4 mm Plexiglas barrier: here the EL-506C was 3.15 mm thick. Quenching of detonation was observed in all of these experiments, yielding smear-camera records of the type sketched in Fig. 4.

In this connection this test reminded one of the authors of an experiment he ran in 1955. The experimental arrangement, shown in Fig. 5, involved a detonation that traveled around a Plexiglas barrier. The resulting smear-camera record, sketched on the right of Fig. 5, caused a great deal of puzzlement. The explanation now appears clear. The detonation wave ran around the Plexiglas while a shock wave went through the plastic, into the 12.7-mm thick Octol slab. The shock wave expanded somewhat spherically as the detonation approached from around the bend. Apparently the disc-shaped region of shocked Octol failed to support detonation, but the detonation continued to propagate around the disc. The projected image of the slit of the smear-camera, passing through the center of this compressed disc of Octol thus recorded the approach of the detonation wave, its disappearance within the disc , and its reappearance as the detonation swept around the disc and continued down the rest of the Octol layer. The significance of this interpretation of the experiment lies in the thickness of the explosive layer: 12.7 mm, a value considerably greater than the experimental failure thickness for explosive without pre-shock. For comparison the 65/35 Octol, of density 1.77 g/cc, without pre-compression, propagates in layers as thin as 1.8 mm when backed by aluminum sheet. EL-506C at 1.49 g/cc normally propagates detonation in 0.5 mm layers, while PBX 9404 at 1.83 g/cc normally propagates detonation in 0.8 mm layers. Quenching of the detonation, therefore, is not simply a question of squeezing a thin layer of explosive to less than its failure thickness; it must relate, instead, to an actual decrease in shock sensitivity in the denser material.

V. CONCLUSIONS

While this set of tests can hardly be considered exhaustive, it would appear that solid explosives have a critical density beyond which propagation of detonation will not occur in charges of rather large dimensions. For military explosives, in general, this density appears to be about 1.08 (±0.03) times the voidless density of the explosive, as measured at atmospheric pressure.

Such a conclusion, if proven to be general, would imply that steady-state propagation of detonation in solid explosives requires some kind of an energy-focussing mechanism: a mechanism which can be literally eliminated by pre-compression.

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10. R. Weingart (E. O. Lawrence Radiation Laboratory, Livermore, Calif., private communication.)

TABLE 1

QUENCHING-OF-DETONATION EXPERIMENTS ON EL-506C AND PBX 9404

(S_d, S_b, and S_a are the thicknesses of the donor explosive, the Plexiglas barrier, and the acceptor explosive, respectively. The peak pressure in the barrier and the acceptor at their interface, as the shock passed across it, are P_b and P_a, respectively.)

Acceptor Explosive	Shot No.	S_d (mm)	S_b (mm)	S_a (mm)	P_b (kb)	P_a (kb)
EL-506C	23	1.27	12.93	1.27	17.5	17.5
EL-506C	24	1.42	18.75	1.42	15.5	15.5
EL-506C	28	1.32	12.65	2.79	18.0	18.0
EL-506C	29	1.37*	12.65	1.37	14.5	14.5
PBX 9404	25	1.37	18.69	2.54	15.3	19.0
PBX 9404	26	1.37	12.14	2.54	18.6	23.1
PBX 9404	48	1.24*	13.00	2.59	13.9	17.2

*No aluminum backing

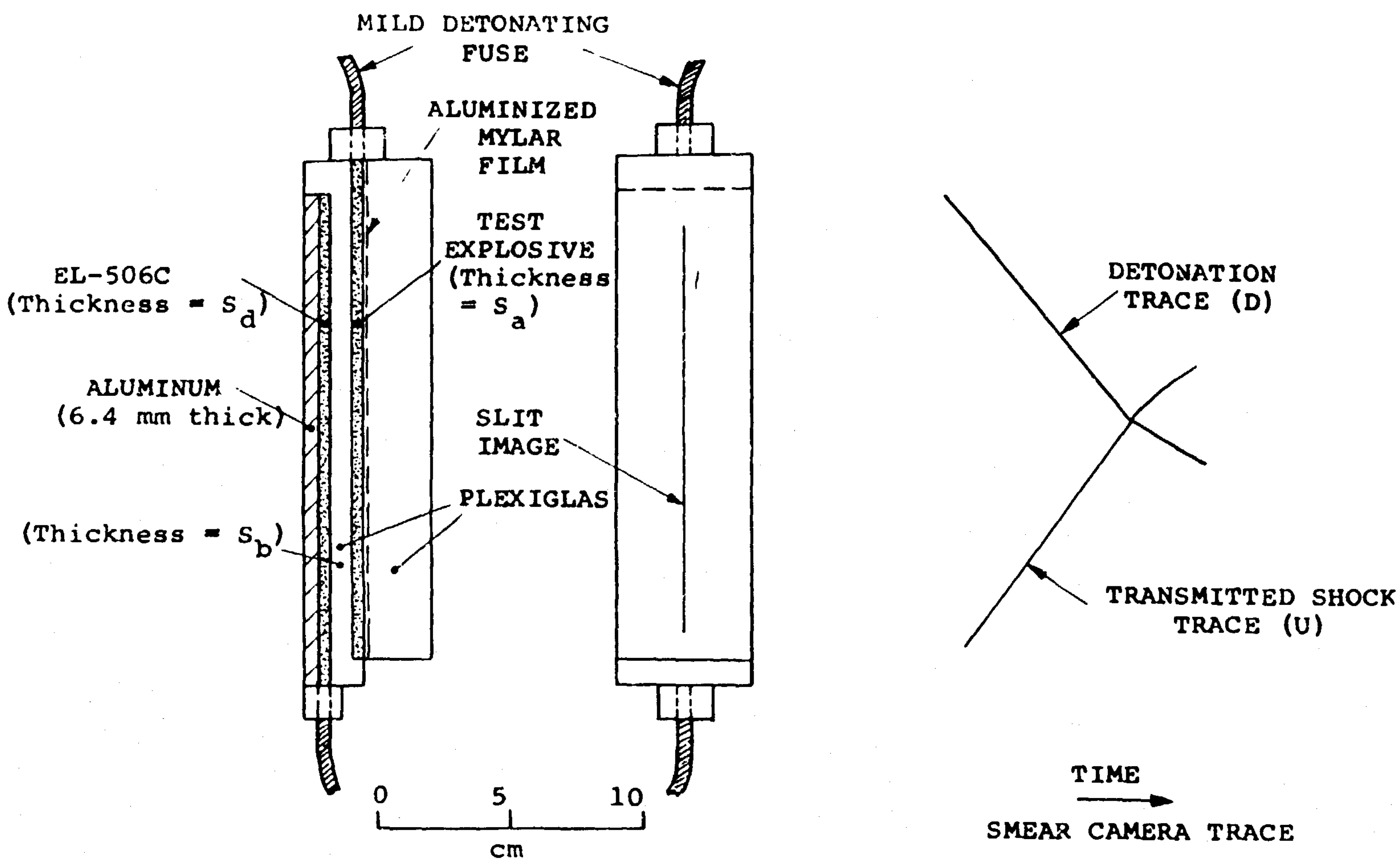

Fig. 1. TYPICAL ARRANGEMENT OF QUENCHING EXPERIMENT.

Fig. 2. TYPICAL SMEAR-CAMERA RECORD OF QUENCHING OF DETONATION

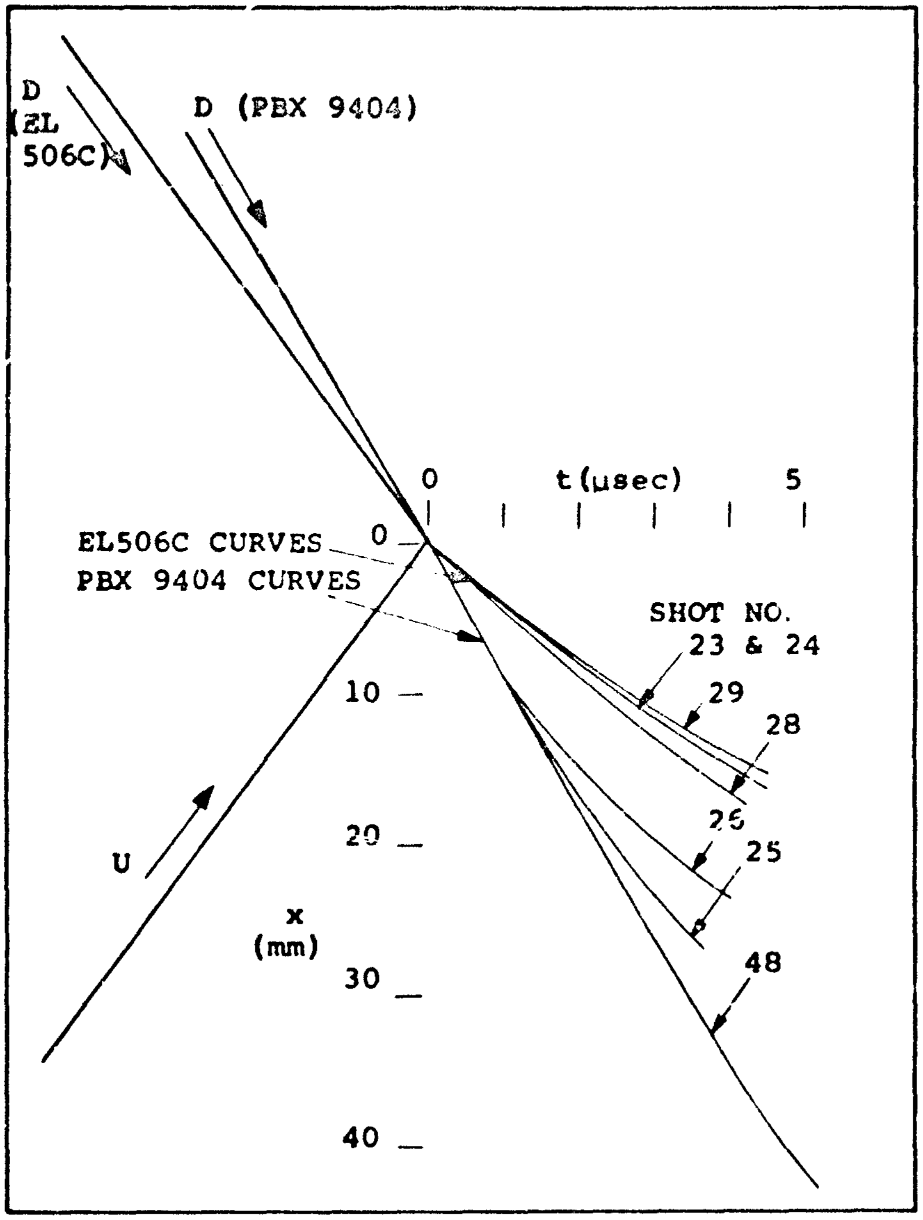

Fig. 3. SKETCHES OF SMEAR-CAMERA RECORDS OF QUENCHING OF DETONATION BY A SHOCK. (D is the detonation wave in the acceptor; U is the shock wave transmitted to the acceptor with a phase velocity equal to the detonation velocity in the donor.)

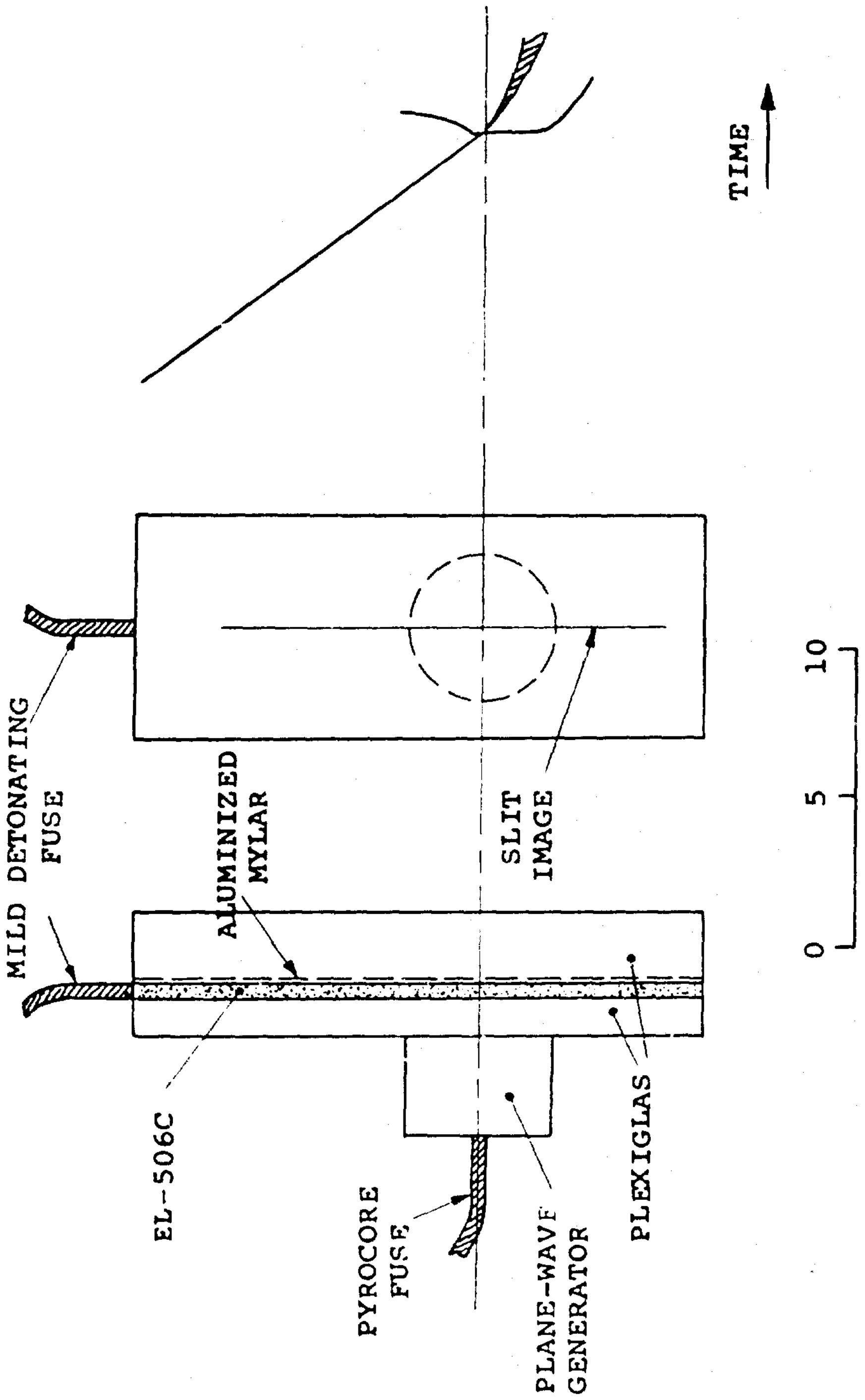

Fig. 4 QUENCHING OF DETONATION BY A NORMALLY APPLIED, PLANE SHOCK.

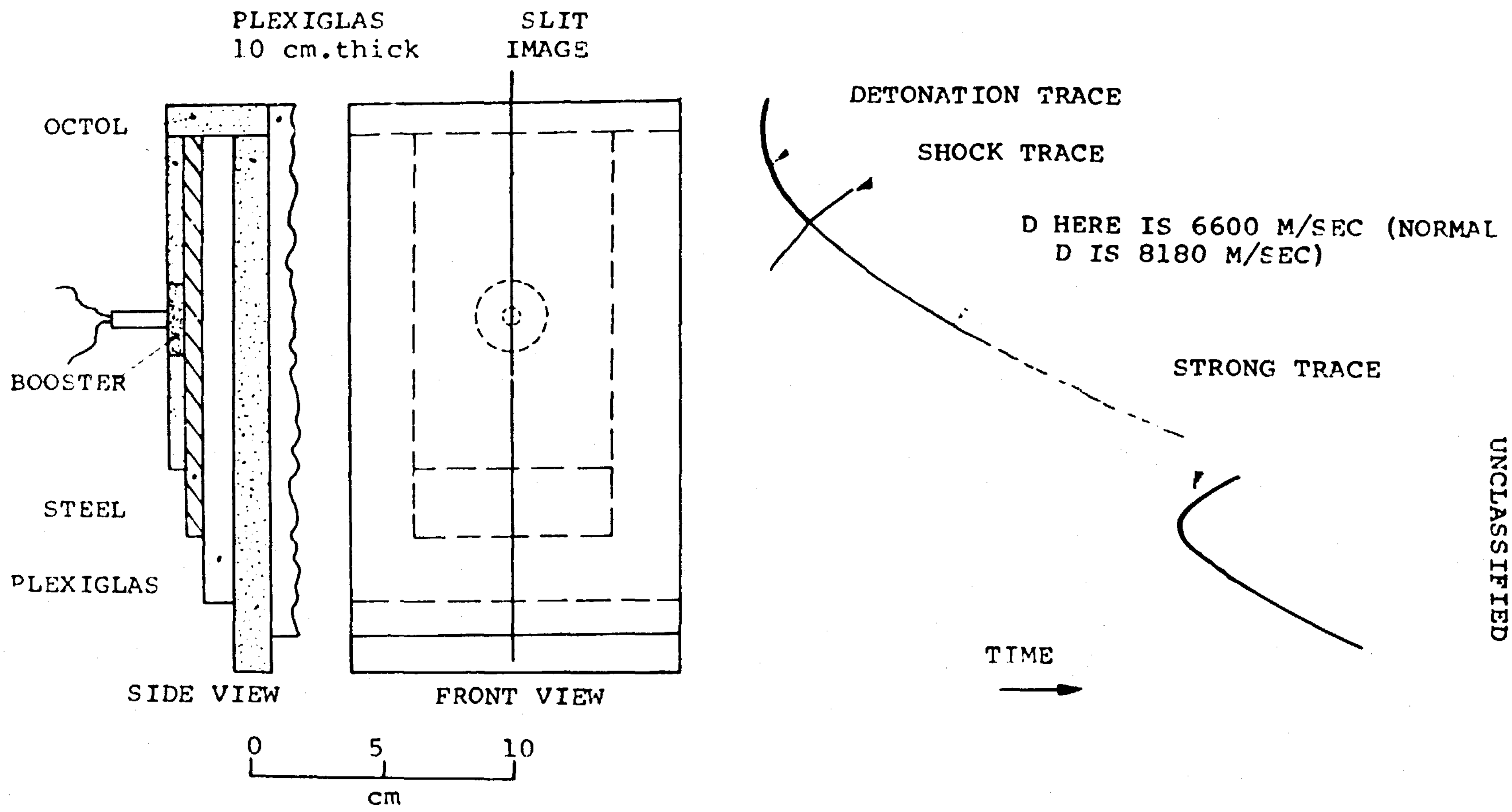

Fig. 5 EXPERIMENT OF 1955 NOW EXPLAINED BY QUENCHING OF DETONATION

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	DESCRIPTORS	CODES		DESCRIPTORS	CODES
SOURCE	NOL technical report	NOLTR	SECURITY CLASSIFICATION AND CODE COUNT	Unclassified - 20	UØ2Ø
REPORT NUMBER	64-60	64ØØ6Ø	CIRCULATION LIMITATION		
REPORT DATE	22 July 1964	Ø764	CIRCULATION LIMITATION OR BIBLIOGRAPHIC		
			BIBLIOGRAPHIC (SUPPL., VOL., ETC.)		

SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Failure	FAIL	Plastic	PLAS		
Solid	SOLI	Bonded	BOND		
Explosives	EXPL	PBX	PBXE		
Compression	COMR	EL	ELXX		
Propogation	PROO	Energy	ENER		
Detonation	DETO	Concentration	CNCT		
Dynamic	DYNA	Pressure	PRES		
Quenching	QUEN	Phenomenon	PHEO		
Hot spots	HOTS				
Steady state	STBI				
Shock wave	SHWV				
Shock	SHOC				

PRNC-NOL-5070.28 (5-62)

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 64-60)
PROPAGATION FAILURE IN SOLID EXPLOSIVES UNDER DYNAMIC PRE-COMPRESSION, by B. E. Drimmer and T. P. Leddiard, jr. 22 July 1964. 9p. illus., tables. NOL task 260-60.

UNCLASSIFIED

Steady-state detonations were stopped on entering a zone in a solid explosive already under compression by a 5-20 kb shock. Tests with PBX 9404 and EL-506C indicate this may be a general phenomenon of explosives. This implies that energy concentrating systems are required even for steady-state detonations.

1. Explosives - Detonation
2. Detonation - Quenching
3. Detonation - Propagation
I. Title
II. Drimmer, Bernard E.
III. Liddiard, Thomas P., jt. author
IV. Project LACE
V. Project

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