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ELECTRICAL TRANSDUCER STUDIES OF INITIATION OF LIQUID EXPLOSIVES

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ABSTRACT

Electrical signals are generated by initiation processes occurring in dielectric liquid explosives. A transducer utilizing this effect has been developed. Comparison of the results obtained with the transducer and with a smear camera shows that the transducer can measure the time of events occurring during the initiation process with high precision. The transducer technique is particularly useful in the study of those explosives in which, because of their low luminosity, the entire initiation process cannot be observed with a smear camera. Differences in the initiation behavior of nitromethane, solutions of TNT in nitromethane, molten DINA, and molten TNT are described.

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INTRODUCTION

The following thermal explosion model for one-dimensional shock initiation of liquid explosives^{1,2} adequately incorporates most of the experimental observations. A plane shock wave entering a liquid explosive compresses and heats it. After an induction time during which chemical reaction is occurring, detonation in the heated, compressed explosive begins near the interface where the explosive has been hot longest. This detonation travels as a supersonic wave through the compressed explosive, overtakes the initial shock wave, and overdrives a detonation in the unshocked nitromethane. This overdriven detonation decays to a steady-state detonation in a few microseconds.

These events can be photographed with a high-speed rotating-mirror smear camera. In an experiment of the kind shown schematically in Fig. 1, a smear camera is aligned so that its slit subtends a diameter of the charge and its optic axis is congruent with the charge axis. As initiation takes place, the camera records light successively from the flasher when the shock wave enters the nitromethane, from the detonation in the compressed explosive, from the strong interaction between this detonation wave and the overtaken shock wave, and finally from the steady-state detonation in the unshocked nitromethane. In some explosives, for example nitromethane, light from the supersonic detonation, although weaker than the light from steady-state detonation, is readily photographed. In others such as Dithelene 13,* molten TNT, and some solutions of TNT in nitromethane, light from the supersonic detonation has never been

* Nitric acid and nitrobenzene in the mole ratio 5 to 1, plus 13 w/o water.

detected. In all other respects the initiation behavior of these explosives is the same as that of nitromethane. No explanation for the lack of luminosity of the supersonic wave in these explosives has yet been confirmed.

The presence or absence of luminosity from the supersonic detonation in solutions of TNT in nitromethane is dependent on the TNT concentration. For a solution containing 30% by weight of TNT^{*} no light is observed. For solutions containing less than 20% TNT, light is observed, but it occurs later in the time scale of the initiation process than it does in pure nitromethane. Optical experiments with reflected light have shown that an opaque layer forms in shock-compressed TNT/nitromethane (30/70) shortly before it detonates. Nothing more is known about this layer, whether it is related to the non-luminosity or, if it is, how it can totally obscure the light from the detonation in the shock-compressed nitromethane.^{**}

Since optical techniques could not be used to study events occurring within the opaque layer, a new technique was needed if this problem were to be studied more thoroughly. Interest in this problem led to an investigation of other techniques and ultimately to the discovery of the charge generation phenomena associated with initiation processes.

The experimental device used to study the charge generation phenomena is a transducer in the form of an uncharged parallel-plate capacitor which has explosive as a dielectric. One plate is connected to the signal input terminal of an oscilloscope. The other plate, at ground potential, acts as part of the attenuator in the boosting system. When the shock

* Hereafter designated TNT/nitromethane (30/70).

** This problem is discussed more fully by Travis and co-workers (3).

wave in the grounded attenuator plate hits the explosive a voltage appears across the capacitor and a pulse is displayed on the oscilloscope.

The output of an explosive-filled transducer changes with time as the shock wave proceeds through it. The first experimental problem was to correlate the events already described which occur during initiation with the observed changes in the transducer signal. This has been done successfully for the explosives nitromethane, TNT/nitromethane, molten TNT and molten DINA (dinitroxyethyl-nitramine). Now that this correlation has been established, experiments can be performed in which the transducer results can be combined with results from optical and other electronic techniques to study some of the remaining unsolved problems in the initiation of explosives.

THE EXPLOSIVE-FILLED TRANSDUCER

Studies of the charge generation by shocks in inert dielectrics have been reported by Eichelberger and Hauver⁴ and Harris⁵ in recent publications. They have considered the effect to be due to mechanical polarization produced at the shock front. The voltage generated by a polarization transducer is a function of the nature of the dielectric material, increases monotonically with pressure until saturation occurs, is inversely proportional to the electrode separation, and is directly proportional to the effective area of the electrodes.

A schematic diagram of an explosive-filled transducer mounted in a charge assembly is illustrated in Fig. 1. The transducer was designed to meet conflicting requirements: (1) The diameter needs to be small so that the initiation phenomena occurring in the region near the probe can be photographed with a smear camera. (2) The spacing between the

probe and the ground plate needs to be great enough to allow sufficient time for coverage of the initiation phenomena. (3) The diameter must be large enough and the spacing small enough to give an adequate signal strength. Transducers with spacings of 5 and 6 mm and probe diameters of 7.5 and 12 mm have proven satisfactory, giving signals of a few tenths to a few hundredths of a volt across a 93 Ω RG-71/U signal cable.

Two oscilloscopes were used to record the waveform of the current in the transducer circuit which consisted of a small capacitance shunted by the small resistance of the signal cable. One of the oscilloscopes, a Tektronix 581, was set with a sweep speed of 0.1 or 0.2 $\mu\text{sec}/\text{cm}$ for optimum resolution of the events of interest. The other, a Tektronix 545, was used for long time coverage.

The design of the booster system was determined by the electrode spacing and was adjusted for each test explosive so that initiation would occur in less than one microsecond.

The output pulse from a polarization transducer has a characteristic shape for a given material. The pulse from Plexiglas, for example, rises sharply in the positive direction when the shock hits the Plexiglas, then rises slowly until the shock nears the signal probe at which time it rises rapidly to a height several times its initial height. The pulse from water starts with a large positive spike which decays rapidly before building up again as the shock wave approaches the probe. The output signal from liquid explosives is very different. A sample oscilloscope trace showing initiation polarization is reproduced in Fig. 2. The first short positive signal signifies the entry of the shock wave into the nitromethane. This is followed by a second positive pulse which occurs at the time the supersonic detonation starts in the compressed explosive. A sharp negative signal occurs a short time later when the

supervelocity detonation overtakes the shock wave. Correlation between the three parts of the signal and the initiation events has been demonstrated by comparing the transducer signal with the smear camera picture taken at the same time in many experiments. A smear camera picture reproduced below the transducer signal in Fig. 2 shows this correlation.

EXPERIMENTAL RESULTS

A. Relative Times of Occurrence of Initiation Events

Initiation polarization has been observed in four liquid explosives: nitromethane, molten DINA, TNT/nitromethane (30/70), and molten TNT. The qualitative appearance of the transducer signals obtained from the first three is the same as that shown in Fig. 2: two positive pulses followed by a negative one. But only the first positive pulse and the negative pulse are seen from molten TNT. Just as in the optical record no signal is detected from the detonation in the shock-compressed molten TNT, although the transducer does give a signal for TNT/NM (30/70) and the optical record does not.

The times of occurrence of the initiation events measured by both the transducer and optical techniques are given in Table 1. τ , the induction time, is the time from the entry of the shock wave to the time of the onset of detonation in the compressed explosive. The time, t , is the time from the entry of the shock wave to the time at which the detonation in the compressed explosive overtakes the shock wave. There is no doubt that the two techniques are detecting the same events.

Another experimental fact that demonstrates the validity of the interpretation is the constancy of the ratio τ/t . This ratio is dependent

Table 1

Comparison of Transducer and Camera Data

Explosive	Shot	Transducer			Smear Camera		
		τ (μ sec)	t	τ/t	τ (μ sec)	t	τ/t
Nitromethane	B5209	.114	.176	.648			
	B6086	.172	.246	.698	.174	.252	.690
	B6088	.213	.323	.660	.227	.328	.692
	B5203	.230	.332	.693			
	B5201	.325	.472	.667			
	B6093	.345	.500	.690	.340	.484	.703
	B5217	.424	.620	.684			
	Ave.			.677		Ave.	.695
Molten DINA	B6087	.160	.208	.769	.134	.171	.784
	B6089	.233	.305	.764	.265	.337	.787
Molten TNT	B6092	--	.122	--	--	.098	--
	B6091	--	.278	--	--	.296	--
TNT/Nitromethane ^(a)	B5220 (8/92)	.438	.632	.693	.563	.632	.888
	B5219 (15/85)	.820	--	--	1.11	1.15	.965
	B5211 (30/70)	.198	.286	.693	(b)	--	1.0

(a) Camera data taken on replicate shots - adjusted for comparison with the transducer results.

(b) No light detected.

only on the values of the velocity of the detonation wave in the compressed explosive and the shock and particle velocities of the initiating shock, which are all almost constant for the small range of shock pressures (85-90 kbar) used in these experiments.* τ/t as reported by Campbell and co-workers¹ is equal to 0.672 for nitromethane. The average value obtained from seven transducer measurements was 0.677 with a mean deviation of ± 0.016 .

The values of τ/t given in Table 1 for solutions of TNT in nitromethane are the same within experimental error as the value of τ/t for pure nitromethane. Therefore, the initiation events occur at the same relative times in the TNT solutions as in pure nitromethane. However, the optical technique shows that light from the detonation in the compressed TNT/nitromethane starts relatively later or is not seen at all. The conclusion from this is that detonation starts at the interface at the proper time in TNT/nitromethane, but must emerge from the growing dark layer before it can be observed. Apparently, when the TNT concentration is 30%, the entire volume of shock-compressed explosive has become opaque before the supersonic detonation overtakes the shock wave.

In a few experiments with molten DINA, no light from the supersonic detonation was detected, but in others, including those listed in Table 1, light from this wave was unmistakably observed, although the same camera exposure was used. The results obtained with the transducer agree fairly well with the camera results of Table 1. τ/t for DINA is greater than for nitromethane, which indicates that the wave velocities are quite different in the two explosives.

The agreement between the transducer and camera results for molten TNT is likewise good. Only the entry of the initial shock wave and the

* A complete analysis is given in Reference 1.

overtake of the shock by the detonation in the compressed explosive are observed. The onset of detonation in the compressed explosive is not detected by either method. Except for the absence of a signal either from the transducer or the optical method, the experimental evidence agrees with the initiation model. The size of the change in t as the initial pressure is changed, the intensity of the photographed light at its onset relative to that from steady-state detonation, and the sensitivity to the presence of solid inclusions or bubbles all confirm the proposition that molten TNT initiates in the manner described in the introduction.

Several polycrystalline solid explosives (Composition B, for one) were tested in the transducer with disappointing results. A positive pulse was observed when the shock entered the explosive, but the succeeding parts of the signal were not reproducible and, therefore, not interpretable.

B. Measurement of the Initiating Shock Pressure

Another capability of the polarization transducer, besides precision time measurement, is measurement of the pressure of the initiating shock wave. In Table 2 are given the heights of pulses from the three steps in the initiation process for the four explosives. With a few exceptions, the pulse height decreases monotonically with increasing τ ; that is with decreasing pressure. τ is a very sensitive indicator of the initiating pressure. In nitromethane, the range of pressures is less than 5 kbar for the range in τ of 0.1 to 0.45 μsec .

Before the pulse-height measurement can be used as a measure of pressure, it must be calibrated by determining the pressure in the shock

Table 2
Transducer Pulse Height Data

<u>Explosive</u>	<u>Shot</u>	<u>τ (μsec)</u>	<u>Pulse Height^(a) (volts)</u>		
			<u>Shock</u>	<u>Detonation</u>	<u>Overdrive</u>
Nitromethane	B5207	(.093) ^(b)	--	.042	>.05 negative
	B5209	.114	.042	.044	>.05 negative
	B6086	.172	.032	.032	-.044
	B5203	.230	.027	.033	>.046 negative
	B5201	.325	.018	.020	-.023
	B6093	.345	.022	.020	-.034
	B5217	.424	.021	.018	-.025
Molten DINA	B6087	.160	.186	.082	off scale negative
	B6089	.256	.146	.054	-.224
Molten TNT	B6092	.122	.084	(c)	-.058
	B6091	.278	.078	(c)	-.072
TNT/Nitromethane	B5211 (30/70)	.198	.008	.004	+.007
	B5220 (8/92)	.438	.019	.011	-.024

(a) Normalized to the B6000 series by $V = 41 V_{\text{meas}} (s/AZ)$ where V_{meas} is the voltage measured across a cable of impedance Z (Ω), s is the spacing (in.), and A is the electrode area (in.²).

(b) Calculated from a measurement of $t - \tau$.

(c) No signal.

wave in nitromethane and the pulse height in the same experiment.

Although this has not been done, it can be.

The ratios of the pulse heights of the different events have different values for each of the four explosives tested. In nitromethane, the pulse generated when detonation starts has about the same amplitude as the shock pulse, but in DINA it is only slightly more than half as high. The pulse generated when the supersonic detonation overtakes the shock wave is very large in DINA, but has an amplitude only slightly larger than the first pulse in nitromethane and molten TNT. The shapes, heights, and signs of the pulses must be related to the molecular properties of the explosive and to the changing state of the explosive in the initiation process, but the details of the mechanism that generates the electric charge must be better understood before an interpretation can be made.

ADVANTAGES AND LIMITATIONS OF THE TRANSDUCER TECHNIQUE

In the preceding section, measurements were presented which showed that initiation events can be identified and studied with an electrical transducer. The transducer technique has advantages over optical technique for some kinds of experiments. First, the time of the shock entry is measured on the same axis as are the later events. To do this with optical techniques requires great experimental complexity - the addition of an external light reflected from the driving plate, for example. Second, the precision of time measurement is very great (≈ 1 nanosecond resolution). It is limited by the rise time of the signal, which is determined by the planarity of the wave. As a result, very short induction times can be measured accurately. Third, the

pressure of the initiating shock wave can be measured directly once the calibration has been made for each explosive to be studied.

Some of the limitations of the use of the transducer should be mentioned. Since only an insulating material shows the effect, conducting explosives, such as those containing nitric acid, cannot be studied. The rise time and height of an output pulse is influenced by the quality of the shock or detonation wave. For precision measurements the waves must be planar and parallel to the electrodes. The length of the induction zone that can be studied is limited by the minimum detectible signal, because the signal amplitude decreases as the transducer is made longer.

CONCLUSIONS

Unusual electrical phenomena have been found which occur as part of the initiation process in liquid explosives. Their study has already shed some light on initiation behavior, but the mechanism by which the observed electrical signals are produced is not really known. Polarization by mechanical orientation or deformation of the molecules within the thickness of the shock or detonation front is postulated as the primary mechanism.* The following hypothetical model is proposed to explain the electrical phenomena observed during the course of initiation of detonation in nitromethane.

As the initial shock wave enters the liquid explosive it polarizes the molecules in a thin layer near the interface. As a result an induced charge appears on the plates of the transducer. As the shock proceeds through the nitromethane it continues to polarize a thin layer of molecules,

* Proposed by Eichelberger and Hauver (4) and Harris (5) for inert dielectrics.

but the polarization behind the front relaxes rapidly. No additional charge is induced on the plates, so the output pulse drops to zero. When detonation starts at the attenuator interface, it repolarizes a thin layer of molecules near the attenuator in the compressed explosive. This newly-polarized layer induces additional charge on the plates giving rise to the second observed pulse. Chemical reaction taking place immediately behind the detonation front in the compressed explosive destroys the polarization, but the reaction products form a conductive path between the detonation front and the grounded attenuator plate. The output pulse drops quickly to a value determined by the electrical properties of the reaction products. Charge continues to flow in the external circuit because the electrode spacing is being reduced (and thereby the electric field strength is increased) by the increasing layer of conducting reaction products. When the detonation in the compressed explosive overtakes the initial shock wave, the signal drops sharply in the negative direction. This must indicate that the amount of polarization between the electrodes has been reduced suddenly. Charge flows in the opposite direction and a negative signal appears across the shunt resistance. This suggests that the polarization produced by the overdriven detonation (and subsequently by the steady-state detonation) in the unshocked nitromethane, although still having the same sign, is less intense than the polarization produced by the initial shock wave. A possible inference to be drawn from this is that decomposition (with little polarization) occurring at the higher pressure of the detonation wave is a more rapid process than the polarizing deformation caused by the initiating shock. As the detonation wave nears the probe the pulse rises rapidly because of

the rapidly increasing field strength resulting from the decreasing effective electrode spacing.

It is recognized that there are many causes for the appearance of charge in detonating systems. The proposed model has in no way been proved, nor does it explain all the observed facts, but is put forth only as an aid in planning additional experimental and theoretical programs.

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FIGURE CAPTIONS

- Fig. 1. Schematic diagram of transducer mounted in a charge assembly. The probe shield is electrically connected to the grounded attenuator plate, to the wall of the explosive container, and to the ground lead of the signal cable.
- Fig. 2. Transducer and smear camera records of initiation phenomena in nitromethane.

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Fig. 1

Fig. 2