AD No. 234290
ASTIA FILE COPY

NAVORD REPORT 6759

10 cys

TRANSITION FROM SLOW BURNING TO DETONATION: FLAME FRONTS AND COMPRESSION WAVES DURING GROWTH OF DETONATION

XEROX

23 November 1959

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NAVORD Report 6759

TRANSITION FROM SLOW BURNING TO DETONATION: FLAME FRONTS AND COMPRESSION WAVES DURING GROWTH OF DETONATION

By

ROYCE W. GIPSON
ANDREJ MAČEK

Approved by: EVAN C. NOONAN, Chief
Physical Chemistry Division

ABSTRACT: A group of experiments is described which elucidates details of propagation of flame fronts, pressure fronts and shock fronts during build-up of steady state detonation. The experimental evidence gives further support to the previously proposed theory that the transition proceeds essentially through two steps, shock formation and shock initiation of detonation. The measurements demonstrate the existence of a flame front which propagates at a fraction of the detonation velocity (1-2 mm/μsec) for as much as 60 μsec and then goes over into steady state detonation within a few microseconds. A proposed explanation of the transition phenomenon is given and discussed.

Published March 1960

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

NAVORD Report 6759 23 November 1959

In the study of explosive sensitivity the sequence of events from ignition through steady state detonation is of critical interest. This report gives quantitative measurements on the transition phenomenon which will be recognized as applicable to many of the tests for explosive sensitivity.

This research was carried out under Task 800-667/76004/01 and FR-59.

JOHN A. QUENSE'
Capt. USN
Acting Commander

Albert Lightbody
ALBERT LIGHTBODY
By direction

TABLE OF CONTENTS

FIGURES

TABLES

TRANSITION FROM SLOW BURNING TO DETONATION: FLAME FRONTS AND COMPRESSION WAVES DURING GROWTH OF DETONATION

I. INTRODUCTION

The purpose of the research program on transition from slow burning to detonation is a general elucidation of the phenomenon, especially as applied to solid explosives and propellants. The main idea tested has been the hypothesis that the transition is due to a precursor shock which arises because of a rapid pressure increase behind the flame front and then propagates into unburnt explosive. Previously reported work with two high explosives, pentolite and diethylnitramine dinitrate (DINA), revealed the following features of the phenomenon (1,2,3):

a. Thermally initiated slow burning will under strong confinement go over into steady state detonation even in charges of moderate dimensions. Under specified experimental conditions detonations were found to develop between 6 and 18 cm from the point of thermal ignition of cast explosives.

b. Theoretical considerations show that the experimentally found rate of pressure increase in the region of initiation is such that a strong shock must be expected to form at a distance between 10 and 15 cm from the region of thermal initiation.

Results a. and b. tend to confirm the original postulate that the course of transition proceeds essentially through two steps, shock formation and shock initiation of detonation. The theoretical mechanism of shock formation is discussed in Ref. 3, while the subject of shock initiation of detonation has been dealt with rather extensively in recent years (4,5,6). Thus it appears promising to seek an explanation of the largely unknown transition phenomenon in terms of better known processes.

The present report is concerned mainly with additional experiments designed to verify in a somewhat more detailed fashion the applicability of the above concepts to the problem at hand, and especially to elucidate the details of propagation of flame fronts, pressure fronts and shock fronts prior to development of steady state detonation. The experimental evidence presented herein demonstrates the existence of a low velocity stage which propagates for as much as 60 μsec and then goes over into steady state detonation within a few microseconds. It also shows that during the transition stage a pressure wave (or possibly a series of pressure waves) precedes the burning front as anticipated. These facts, along with some extraneous experimental evidence, suffice to construct a probable scheme of the transition phenomenon.

II. EXPERIMENTAL

Experimental work has continued on explosives (DINA and 50/50 Pentolite) cast into heavy (0.375 inch wall thickness) steel tubes of 0.5 inch inside diameter, twelve inches long. The charges were ignited by means of a Nichrome resistance bridge incorporated in a bolt-igniter which also provides back confinement. Figure 1 of Ref. 2 is a cross-section of the complete charge.

The charges were instrumented with three types of measuring devices: (a) ionization probes placed at intervals along the charge to record times of arrival of the flame front; (b) pressure indicating collapse probes which record times of arrival of a pressure front; (c) resistance wires, imbedded axially in the explosive charge, designed to give a continuous record of the location of the flame front as a function of time. The two types of instrumentation (b) and (c) were developed by A. B. Amster and co-workers in the propellant sensitivity group at NOL.

A. Propagation of the Flame Fronts

Previously reported velocity data were obtained by means of four ionization probes placed at intervals of 1.5, 4.5, 7.5, and 10.5 inches from the base of the charge. In general, the three intervals over which average velocities were thus determined yielded a low velocity (1-2 mm/μsec) over the first interval, an intermediate velocity (usually 3-6 mm/μsec) over the middle interval and the steady state detonation velocity (7-8 mm/μsec) in the third interval, nearest the top of the charge. These results suggested a continuous and steady acceleration from deflagration to detonation.

In an attempt better to define the time-distance relationship of the propagating flame front, additional probes were added to the charge to decrease the interval between probes. Probes placed at one inch intervals provided data which indicate the presence of two distinct regimes: (1) a fairly steady, low velocity front which propagates for up to sixty microseconds over a distance of several centimeters; and (2) a region of steady state detonation. The transition from low to high velocity occurs within one of the inch long intervals. A further attempt to look into the transition from low to high order regime by using one-half inch intervals between ionization probes resulted in detonation failure (six shots); the tube fragments were large and were evidently the result of the tube splitting along the line of the probe-admitting holes. To minimize the tendency of the tube to split and vent before the critical stage of transition could be attained, in subsequent shots eleven probes

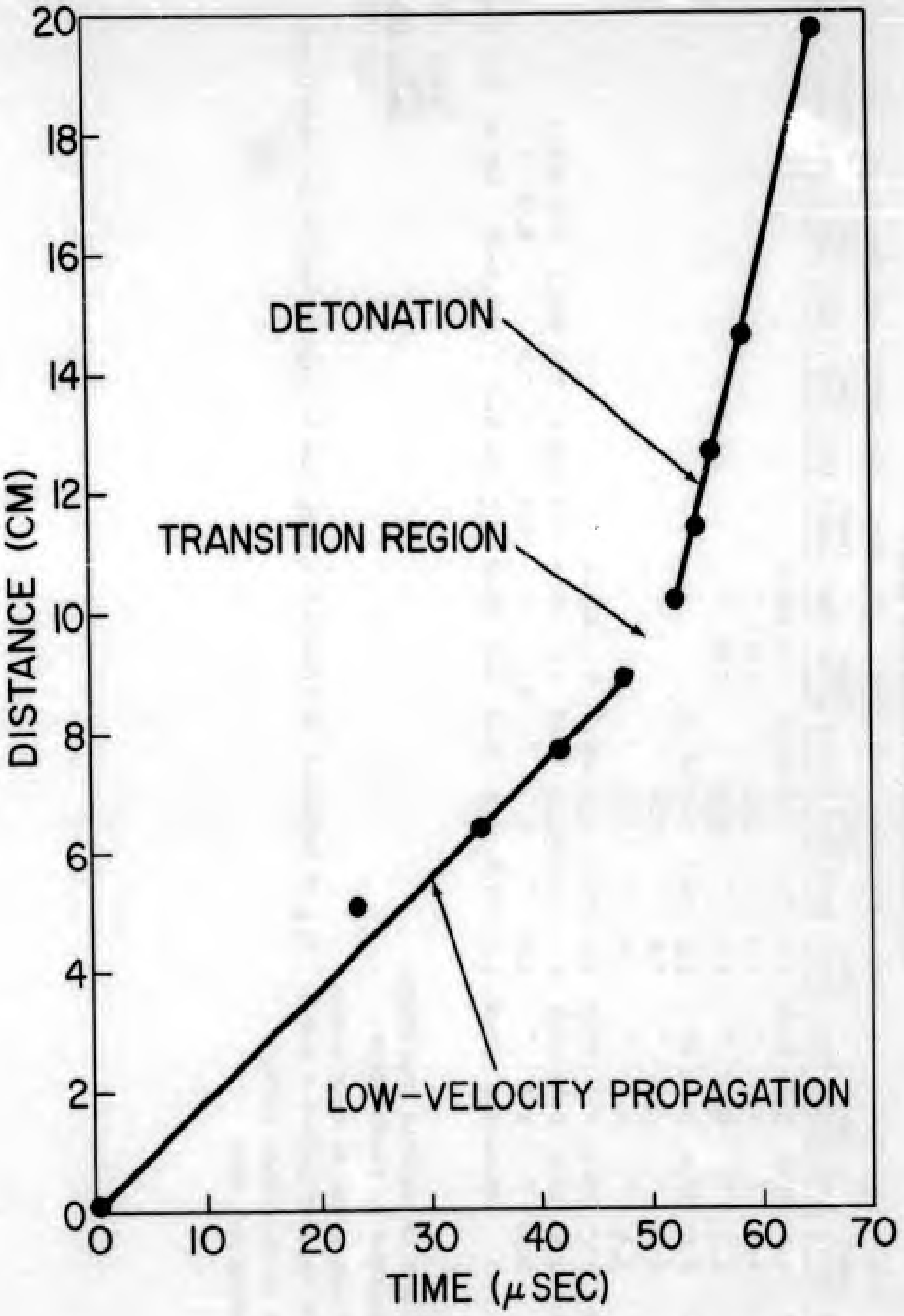


FIG. I ABRUPT ONSET OF DETONATION

TABLE I

ACCELERATION OF IONIZATION WAVES

Shot No.	τ (sec)	ℓ (mm)	D12 (mm/ µsec)	d2 (mm)	D23 (mm/ µsec)	d3 (mm)	D34 (mm/ µsec)	d4 (mm)	D45 (mm/ µsec)	d5 (mm)	D56 (mm/ µsec)	d6 (mm)	D67 (mm/ µsec)	d7 (mm)	D78 (mm/ µsec)	d8 (mm)	D89 (mm/ µsec)	d9 (mm)	D910 (mm/ µsec)	d10 (mm)	D_{1011} (mm/ µsec)	d_{11} (mm)
CWIN1-1	1.5	~32	1.1	25.4	$\underline{2.3}$	50.8	7.3	76.2	7.6	152.4	7.6	228.6										
CWIN1-2	2.2	"	1.1	"	1.8	"	2.0	"	$\underline{3.7}$	"	7.6	"										
CWIN1-3	2.3	"	1.0	"	0.89	"	1.4	"	$\underline{4.8}$	"	7.6	"										
PIN1P-6*	1	~38	2.0	19.1	2.3	44.5	$\underline{3.5}$	95.3	7.8	146.1												
PIN1D-14	1	"	1.3	"	$\underline{2.0}$	"	7.6	"	8.0	"												
PIN1D-18	~2	"	$\underline{2.4}$	"	7.3	"	7.8	"	7.8	"												
PIN1D-12	~3	~32	F**	19.1	1.1	44.5	1.7	69.9	$\underline{3.2}$	120.7	7.1	171.5										
D-56	2	~20	1.6	12.7	0.82	38.1	F	63.5	$\underline{>2.1}$	88.9	7.7	114.3	7.7	139.7	7.7	165.1	7.6	241.3				
D-58	2.5	"	0.91	"	1.2	"	1.3	"	F	"	$\underline{>2}$	"	5.4	"	7.9	"	8.9?	"				
D-70	1	"	F	25.4	~2.2	50.8	1.1	63.5	1.7	76.2	2.0	88.9	$\underline{3.0}$	101.6	~7	114.3	~8	127.0	7.0	146.1	7.5	196.9

τ - delay from ignition to audible explosion.

ℓ - distance from igniter to first probe.

d_i - distance from first probe to i-th probe.

D_{ij} - average velocity between probes i and j. D_{ij} in interval of transition from low to high velocity is underlined.

* - Pentolite; DINA in all other shots.

** - F denotes recording failure.

were positioned spirally up the charge at the one-half inch intervals; steady state detonations developed. The data (Shot No. D70, Figure 1) show that, again, there is only one interval in which the transition is indicated by an intermediate velocity. These and other results obtained by use of multiple ionization probes are collected in Table I (see also Tables IV A and B). While these data are compatible with those obtained earlier with four probe shots, it now becomes evident that the transition from a fairly constant low velocity propagation to steady state detonation takes place within as little as one-half inch of travel. It also appears that the flame front is approximately planar and perpendicular to the charge axis since there is little irregularity in the time-distance plot of the spirally placed probes.

Since multiple probe data showed that the transition to steady state detonation is quite abrupt, the limit of usefulness of the ionization probe method had been reached; an attempt to obtain a continuous velocity record was made by adapting the continuous wire method of Amster et. al. (7) to fit the test conditions for thermally initiated deflagration-detonation studies. The system is based upon a high resistance Nichrome wire (No. 40, AWG; 2.267 ohms/cm) running axially through a cased charge of cast high explosive (see Fig. 2a). The ionized flame front shorts the wire to the grounded charge case thereby completing a circuit. A constant current supply provides a current of approximately 200 milli-amperes to the wire at all times (after the flame front has completed the circuit). The progress of the front is then recorded as a function of the change in resistance of the Nichrome wire as its effective length decreases; it is therefore necessary to have accurate values for the current and the resistance per unit length of the wire. With this information and the voltage-time record, assuming that the ionized front has negligible resistance, it is in principle possible to draw a continuous time-distance plot for the flame front. Also incorporated in these charges were several ionization probes to be used as check points (Fig. 2a). The first of these probes was used to trigger two oscilloscopes, one for the wire record and one for the ionization probe record, so that the two types of events had the same time reference. Figures 2b and 2c are the ionization probe and the continuous data taken simultaneously from a single shot (CWI2). A comparison of the two figures confirms the results of multiple ionization probe tests insofar as it indicates an abrupt transition to steady state detonation.

An inspection of Fig. 2c shows that the wire circuit is not following the progress of the front prior to onset of steady state detonation. This is so because a diode bias in the system does not allow a voltage drop across the wire unless the sum of resistances of the wire and of the burning front is less than 150 ohms (in some cases a bias corresponding to 450 ohms was used);

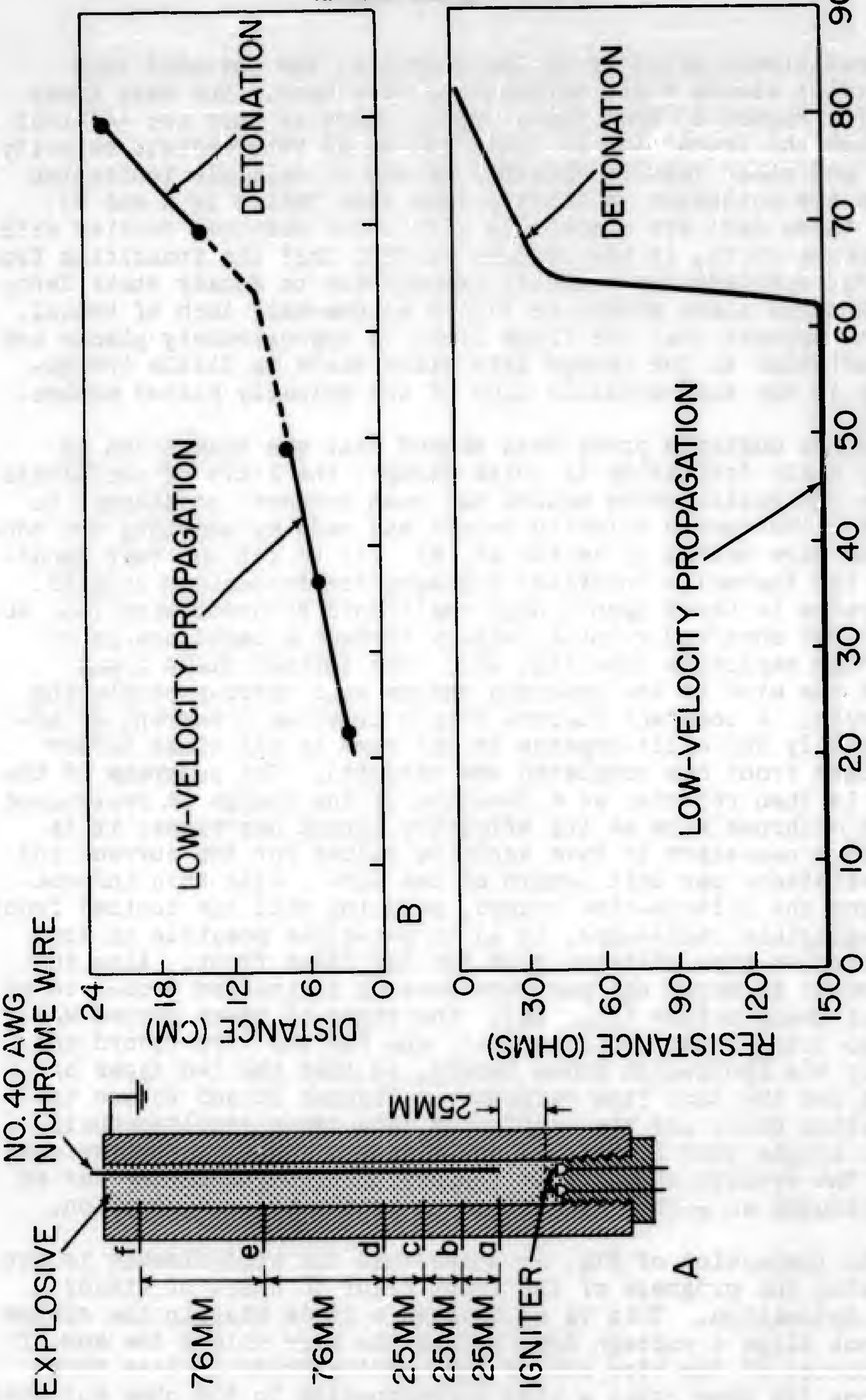


FIG. 2 CONTINUOUS MEASUREMENTS (SHOT CWINi-2)

during low velocity propagation the condition evidently is not fulfilled. This means that the resistance in low velocity regime is at least 100 ohms. However, the ionization probes do function in such a low conductance front, as seen in Fig. 2b, and consequently a satisfactory comparison of the two measurements can be made: In Fig. 2c the point at which the trace becomes a straight line (steady state detonation) is 66 μsec and 10 cm from the first probe, while the ionization probe record places the front between the probes at 7.6 and 15.2 cm from the trigger probe at this time. Upon linear extrapolation, the low and high velocity regimes measured by the ionization probes are found to intersect also at about 10 cm and 65 μsec from the first probe.

In a further attempt to obtain continuous records of the phase intermediate between the low velocity stage and steady state detonation the following experimental arrangement was used (7): In addition to the high resistance Nichrome wire, a very low resistance copper wire was cast into the explosive charge parallel to the Nichrome wire and connected to a duplicate circuit. Since resistance of the copper wire is negligible, the duplicate circuit measures resistance of the ionization front alone. Hence the difference of the two circuit resistances is the resistance of the Nichrome wire; the rate of its change then must give the true velocity of the ionization front. Three shots (CWW1-3) were fired with this arrangement; the transition from low to high velocity stage was too rapid for quantitative resolution, but in two out of three shots both wires placed the transition region at the same distance from the base of the charge (in one shot the circuitry of the copper wire failed).

Thus all three ionization methods — point probes, high resistance and low resistance wires — reveal an abrupt transition from the low to the high velocity regime. Furthermore, good quantitative agreement as to time and location of the transition region is obtained from simultaneous measurements with probes and high resistance wire in one set of experiments, and with high and low resistance wires in another. All continuous wire data are collected in Table II.

B. Propagation of Pressure Fronts

In the study of build-up of detonation it is important to know the relationship of the pressure (shock or compression) fronts to the flame front. An effort was made to study the relationship with the use of a collapse probe (8) in conjunction with the ionization probe. The collapse probes are activated when a pressure wave (shock or compression) collapses the outer copper sleeve against an inner axial wire. The probes were

TABLE II

CONTINUOUS WIRE DATA*

Shot No.	Low Velocity Region (μsec)	Interval Between Low And High Vel. (μsec)	Region of Steady State Detonation (μsec)	X_d (mm)	Bias Resistance (ohms)
CWINi 1	0 - ~35	~35 - ~38	~38 - ~62	~37	150
CWINi 2	0 - 62	62 - 66	66 - 86	100	150
CWINi 3	0 - 80	80 - 82	82 - 92	136	300
CW-W 1	0 - 49	49 - 52	52 - 63	173	450
CW-W 2	0 - 16	16 - 19	19 - 40	79	450
CW-W 3	0 - 39	39 - 42	42 - 57	153	450

X_d - distance from first probe to detonation. First probe is about 25mm from igniter.

* DINA in all shots. For corresponding ionization probe data see Table I.

statically tested and found to be actuated at approximately 12,000 psi.

In a preliminary series of shots, a conventional card gap test arrangement was used. The test charge consisted of a tetryl booster (2 inch diameter), a sufficient number of 0.01 inch thick cellulose acetate gap cards to attenuate the shock to a level which would permit a long enough delay to detonation to allow a considerable separation of the two fronts, and an acceptor charge composed of pressed tetryl pellets of thicknesses of 0.25, 0.50, and 1.0 inch, and 2 inches in diameter. The pellets were used in varying arrangements so as to vary the probe station distances from the gap-acceptor interface.* Two of the collapse probes were placed at the interface and served as trigger

---

* Charges composed of thin pellets give slower build-up to detonation and a wider scatter of data, because placement of probes between pellets introduces an air gap at least one millimeter wide.

probes for two oscilloscopes which were used to record the signals from the ionization probes on one and the pressure-sensing probes on the other. Between each pair of pellets in the acceptor an ionization probe-pressure probe pair was placed to record times of arrival of the respective fronts. From these data it was found that, in tetryl, at a gap thickness of 1.50 inches the pressure front precedes the ionization front for several centimeters while propagation velocities are below the steady state detonation rate; thereafter the ionization front accelerates and catches up with the pressure front and the two proceed at the steady-state detonation velocity as anticipated (Table IIIA). Several shots were fired at a gap thickness which did not permit a build-up to detonation; in these cases, a pressure front of decreasing velocity was measured; no flame front was recorded (Table IIIB). The results of this series of shots indicate that the instrumentation is applicable to studying the two fronts in the transition experiments.

In subsequent thermally initiated charges the arrangement was as shown in the cross-sectional drawing in Figure 3a. As in preliminary gap test shots, two oscilloscopes were used to record ionization and pressure fronts respectively. One of the collapse probes was placed near the igniter(approximately one inch from it)and was used as the trigger probe for both instruments. A number of probe pair stations were placed at varying intervals up the charge. As shown in Figures 3b, 3c and 3d, there is always considerable separation of the two fronts in early stages of growth to detonation. Figure 3b (Shot No. PIN1D7) gives the results of a shot in which probe stations were placed mostly in the lower part of the charge so that the early (low velocity) stage was recorded. Similar measurements over a wider range of times and distances including both the low and the high velocity stages are plotted in Fig. 3c. Here it appears as if the collapse probes were activated by a weak decaying pressure pulse, or possibly by one of a series of weak pulses, which is overtaken by a stronger compression wave (or shock wave) near the region of onset of steady-state detonation. Somewhat different results were obtained by a sturdier collapse probe designed to ignore weak pulses (nominal yielding pressure of 30,000 psi and found not to respond to a static pressure of 20,000 psi; see Ref. 9). With the modified probe*, pressure waves were recorded which start out at lower speeds but

---

* Both the original (12,000 psi) collapse probe and the modified one presented considerable practical difficulties. Quite a few were shorted during casting operations; some failed in actual tests. Hence the entries in Tables IVA and IVB represent only a part of all pressure probe attempts. All entries in Table I denoted by PIN1 are shots in which, in addition to ionization probes, pressure probes were used but without success.

TABLE IIIA - GAP TESTS IN TETRYL (Detonations)

Shot No.	Gap (inch)	$(D_{01})_p$ (mm/µsec)	$(D_{01})_i$ (mm/µsec)	d_1 (mm)	$(D_{12})_p$ (mm/µsec)	$(D_{12})_i$ (mm/µsec)	d_2 (mm)	$(D_{23})_p$ (mm/µsec)	$(D_{23})_i$ (mm/µsec)	d_3 (mm)
PIGTe 1	1.50	5.2	5.0	25.4	6.9	6.5	50.8	-	-	-
" 10	1.50	5.1	4.9	25.4	F*	6.4	50.8	>6.4	6.5	76.2
" 2	1.50	4.4	4.1	12.7	6.5	5.9	38.1	-	-	-
" 3	1.50	4.7	4.2	12.7	F	6.0	25.4	>6.4	6.4	38.1
" 4	1.50	4.7	~4	12.7	6.0	~6	25.4	6.0	~6	38.1
" 6	1.50	3.4	~3	6.4	6.4	~6	19.1	6.0	~6.5	31.8
" 7	1.50	2.6	2.5	6.4	7.0	6.0	19.1	6.4	7.5	31.8
" 8	1.50	2.9	2.6	6.4	6.7	6.4	19.1	6.4	6.4	31.8

TABLE IIIB - GAP TESTS IN TETRYL (Failures)

PIGTe 9	1.85	1.8	-	12.7	1.2	-	25.4	F	-	38.1
" 5	2.00	1.8	-	12.7	F	-	25.4	F	-	38.1
" 13	2.20	1.1	-	25.4	0.62	-	50.8	0.53	-	76.2
" 11	2.50	0.73	-	25.4	0.49	-	50.8	F	-	76.2
" 12	2.50	0.78	-	25.4	0.50	-	50.8	F	-	76.2

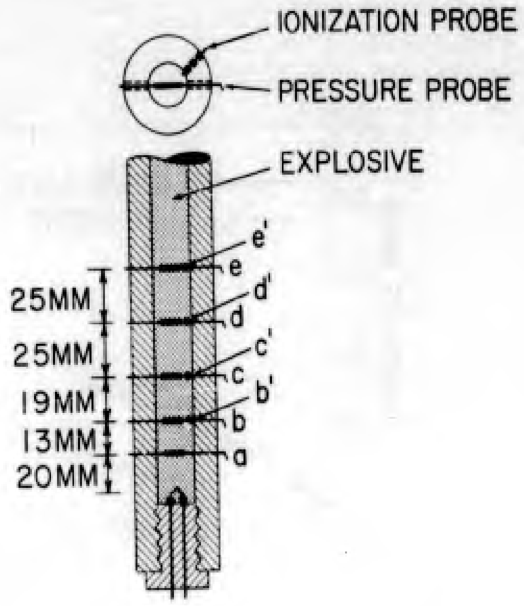
---

d_i - distance from gap to ith station

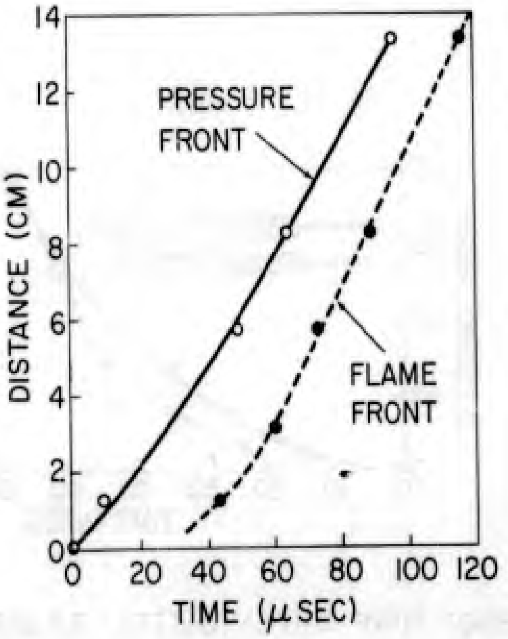
$(D_{ij})_p$ - average velocity of shock wave between ith and jth station

$(D_{ij})_i$ - average velocity of ionization wave between ith and jth station

*F - denotes recording failure

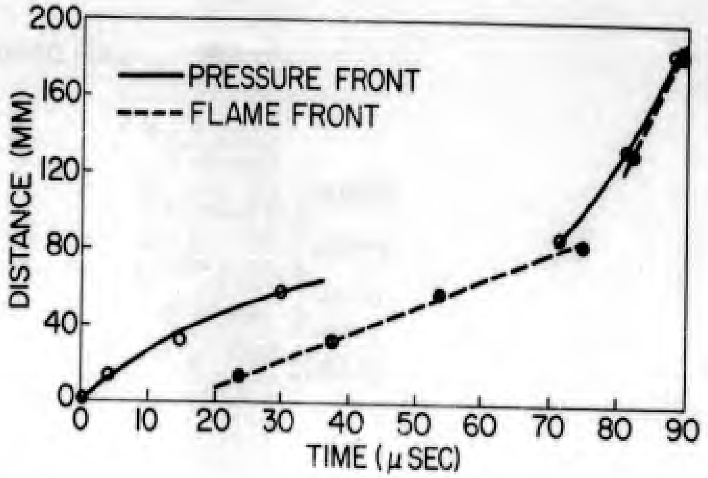


A. CROSS-SECTION OF CHARGE

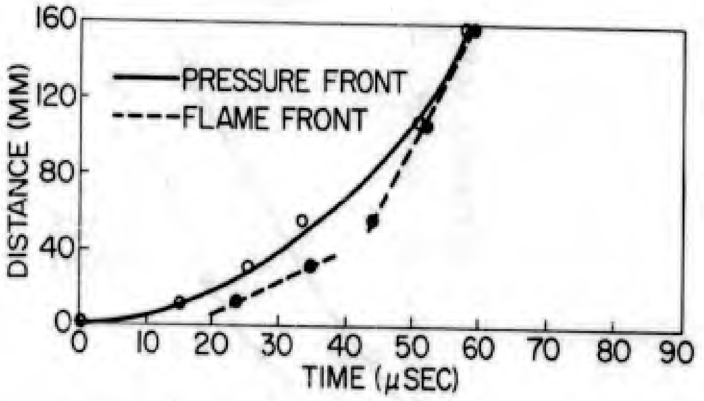


B. SHOT PiNiD-7 (DINA) - 0.8 KBAR COLLAPSE PROBES

FIG. 3A & 3B SIMULTANEOUS RECORDING OF PRESSURE AND IONIZATION FRONTS



C. SHOT PiNiD-10 (DINA) - 0.8 KBAR COLLAPSE PROBES



D. SHOT PiNiP-8 (PENTOLITE) - 2 KBAR COLLAPSE PROBES

FIG. 3C & 3D SIMULTANEOUS RECORDING OF PRESSURE AND IONIZATION FRONTS then accelerate more smoothly into steady state detonation (Fig. 3d). In all shots the ionization fronts, of course, follow the previously established pattern of two distinct velocity stages. Simultaneous pressure and ionization probe data are collected in Tables IVA and IVB.

As is obvious from Tables I, IVA and IVB, distances and times to detonation are not quantitatively reproducible; hence no experimental range of error can be assigned. An approximate a priori precision analysis follows: Both ionization and pressure probe intervals can be measured within 1 mm or better, so that possible error due to the placement of probes seldom exceeds 4 percent and, as a rule, is appreciably less. The oscilloscope records of Table IIIA and IIIB can be read within 0.2 μsec; most of the others within 1 μsec. Thus the precision in the low velocity range is rather good, but steady state detonation velocities which are measured over short time intervals can be in error as much as 10 percent. In view of the fact that for the purposes of this project no exact detonation velocities are needed, the precision is satisfactory. When two oscilloscopes are used in parallel, there is some uncertainty as to assignment of the common time reference; the resulting error is probably not much more than the error of reading the oscilloscope records, so that the ionization and pressure probe pulses are synchronized within 0.2 μsec in Table IIIA and IIIB and within about 1 μsec in Tables IVA and IVB.

III. DISCUSSION

A conspicuous feature of the flame propagation during growth of detonation is the clear-cut division into "low" and "high" velocity regimes. The high velocity regime, of course, is the well known steady state detonation. Information about the low velocity range is still fragmentary, but a few aspects of the phenomenon are becoming apparent:

(1) The average low propagation velocity is usually between 1 and 2 mm/μsec, although it varies appreciably from shot to shot; velocities as low as 0.6 mm/μsec have been recorded. Also, there is often appreciable velocity variation within a single shot. Usually, this appears as an up and down fluctuation (an extreme example is PIN1D6 of Table IVA), but upon occasion there is evidence of a gradual increase of velocity as the front travels through the charge (e.g. CWIN12 of Table I); the acceleration, however, is seldom sufficiently pronounced to give the appearance of a smooth transition into steady state detonation.

(2) The recorded ionization front prior to detonation must evidently have a relatively high temperature, since ordinary

TABLE IV

SIMULTANEOUS RECORDING OF PRESSURE AND IONIZATION WAVES

Shot No.	$(D_{01})_p$ (mm/ µsec)	d_1 (mm)	$(D_{12})_p$ (mm/ µsec)	$(D_{12})_i$ (mm/ µsec)	d_2 (mm)	$(D_{23})_p$ (mm/ µsec)	$(D_{23})_i$ (mm/ µsec)	d_3 (mm)	$(D_{34})_p$ (mm/ µsec)	$(D_{34})_i$ (mm/ µsec)	d_4 (mm)	$(D_{45})_p$ (mm/ µsec)	$(D_{45})_i$ (mm/ µsec)	d_5 (mm)	$(D_{56})_p$ (mm/ µsec)	$(D_{56})_i$ (mm/ µsec)	d_6 (mm)
							(A) WEAK COLLAPSE PROBES										
PIN1D 1	1.3	12.7	1.1	0.64	31.8	0.88	0.98	57.2	F	1.8	82.6						
PIN1D 2	1.2	12.7	1.0	1.0	31.8	0.64	0.94	57.2	F	2.4	82.6						
PIN1D 6	0.63	12.7	1.1	0.73	31.8	1.3	2.5	57.2	1.8	0.91	82.6	0.85	1.6	133.3			
PIN1D 7	1.4	12.7	~1	1.1	31.8	~1	1.9	57.2	1.7	1.6	82.6	1.6	1.9	133.3			
PIN1D 10	2.6	12.7	1.8	1.4	31.8	1.4	1.6	57.2	1.1	1.6	82.6	2.4	4.1	133.3	F	7.1	184.2
PIN1D 11	F**	12.7	0.63	0.57	31.8	0.81	1.1	57.2	0.71	1.8	82.6	~5	3.5	133.3	~5	7.5	184.2
							(B) STRONG COLLAPSE PROBES										
PIN1D 15	F	12.7	F	-	31.8	4.4	5.4	57.2	5.6	5.6	108.0	12.3 ?	12.3?	158.8			
PIN1D 16	(0.53)	12.7	1.8	1.8	31.8	3.0	4.5	57.2	6.8	7.3	108.0	7.8	7.3	158.8			
PIN1D 17	1.7	12.7	F	2.4	31.8	F	7.3	57.2	F	7.8	108.0	F	7.8	158.8			
PIN1P 7*	1.3	12.7	1.9	2.0	31.8	2.1	3.3	57.2	3.0	3.0	108.0	6.6	6.8	158.8			
PIN1P 8*	0.82	12.7	1.9	1.7	31.8	3.1	2.9	57.2	2.9	6.1	108.0	7.3	7.8	158.8			
PIN1P 10*	F	12.7	1.3	1.5	31.8	1.9	2.3	57.2	2.2	2.4	108.0	3.5	4.3	158.8			

---

* Pentolite; the rest is DINA

d_i - distance from trigger probe to ith station

$(D_{ij})_p$ - average velocity of compression (or shock) wave between ith and jth station

$(D_{ij})_i$ - average velocity of ionization wave between ith and jth station

**F denotes recording failure

deflagration does not actuate ionization probes in the above experiments. Moreover, it has been seen from the continuous wire measurements (Fig. 2b) that the resistance of the low velocity ionization front is of the order of magnitude of 10^2 ohm. Berger et. al. (10) found the same order of magnitude in shock pretest experiments, but they ascribed it to the inert shock preceding the development of detonation rather than to chemical reaction. The quantitative similarity of the two results is interesting, but in the thermally initiated transition experiment the intermediate conductivity can hardly be due to a pure shock, first because the ionization probe does not respond until considerably after the pressure probe has been triggered (Fig. 3), and second because the propagation velocities so registered are too slow for any kind of a shock in a condensed medium.

(3) It also appears that the low velocity burning front is associated with a relatively low pressure, because it does not do violent damage to the confining tube. In fact, when in the above experiments DINA and pentolite were replaced by the less sensitive explosives TNT or Composition B (TNT/RDX/Wax, 59.4/39.6/1), velocities of the order of 1 mm/μsec were again observed but no detonations developed; in some cases the confining steel tube remained intact.

Velocities of pressure fronts are somewhat more reproducible than those of ionization fronts. The values obtained are always lower than most reported sonic speeds. This can perhaps be accounted for by ascribing the response of the pressure probes prior to shock formation to plastic deformation waves in which the propagation velocity depends on amplitude.

A pattern of growth of detonation similar to the one reported herein has been obtained photographically by Griffiths and Groocock (11) with loosely packed granular explosives. Photographic records of Griffiths and Groocock do not reveal either shocks or compression waves, but they have the advantage of permitting continuous observation. For instance, a shot in which granular PETN (1.2 gm/cc) was burned to detonation reveals propagation of burning at a velocity of 0.8 mm/μsec for about 100 μsec, whereupon steady state detonation starts at a point about 15 mm ahead of the burning front. While the ionization probe data reported in this paper do not give any evidence of a jump-ahead, something of the kind could be expected, because the onset of detonation must be ascribed to the action of the precursor shock, as detailed below, rather than to the low velocity burning front.

A space-time scheme of the transition process consistent with experimental evidence is given in Fig. 4. The sequence of events is started by a compression wave C_o which emerges from

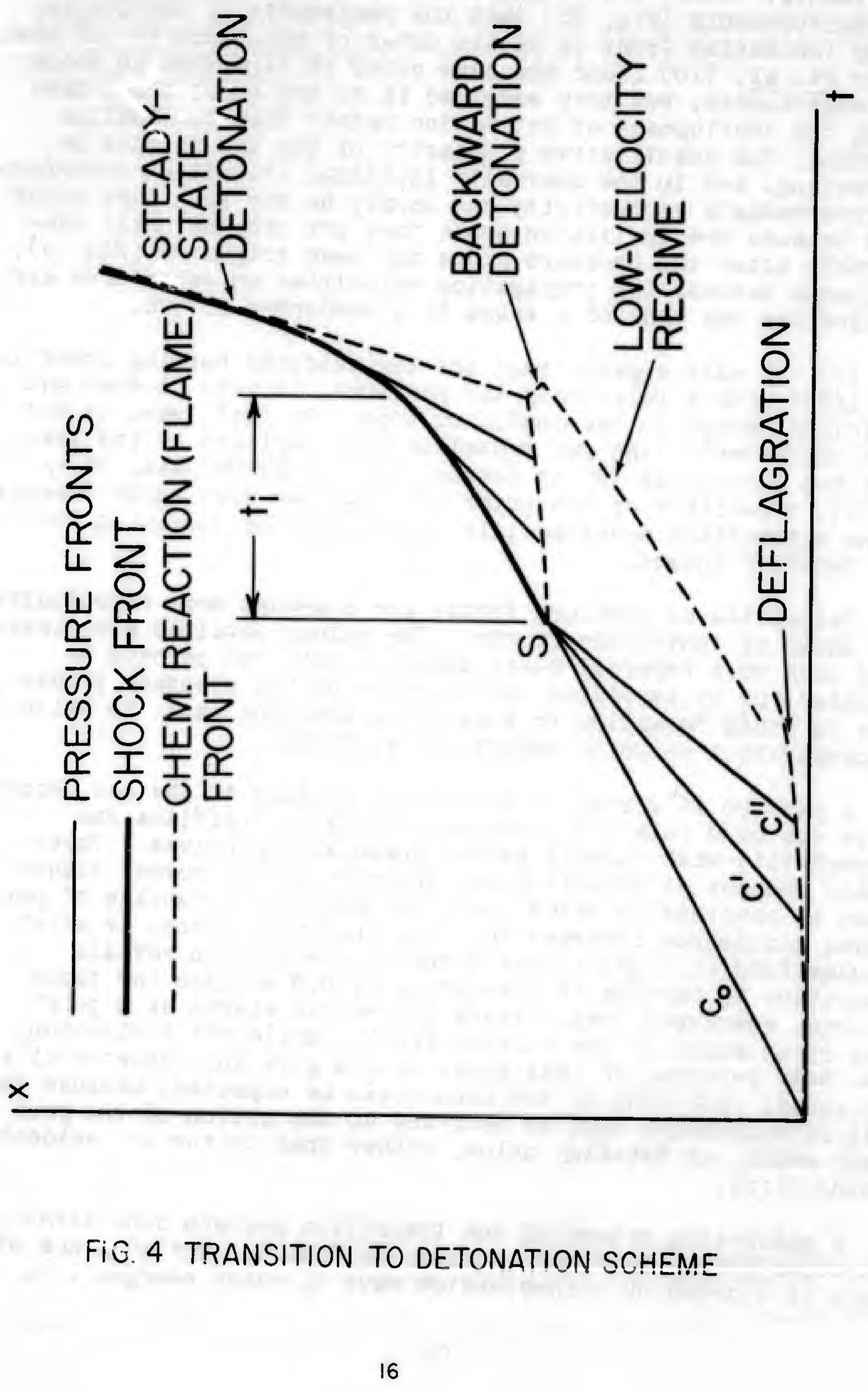


FIG. 4 TRANSITION TO DETONATION SCHEME

the deflagration front and propagates through the intact explosive. Because of confinement of the deflagration, additional compression waves of higher amplitudes (two representative examples C' and C" are drawn in the figure) arise at later times and converge into a shock at point S.* The main assumption in the explanation proposed here is that this is the shock that starts detonation in a manner analogous to initiation in the shock sensitivity test (gap test) in which the explosive charge is subjected to the action of an externally imposed strong shock wave. During the early stages following shocking of the explosive the chemical reaction is slow and the reaction front starting at S is initially carried at the shock particle velocity, but after a delay period t_i it accelerates rapidly thus resulting in steady state detonation. Meanwhile the shock front has also been reinforced and accelerated until it attains detonation velocity. As it emerges from the transition region the steady state detonation travels both forwards and backwards as shown in the figure. The scheme, among other things, accounts both for the reported discontinuous change of the luminous front (11) and a smooth acceleration of the shock front (4).

While shock initiation in the gap test and in a spontaneous transition experiment is thus essentially similar, there is an important quantitative difference. In a gap test the imparted shock, typically, has relatively high pressure and short duration (order of magnitude of a microsecond though often difficult to determine with any precision). On the other hand, a shock arising from confined deflagration is a sustained one, indeed, it is of steadily increasing amplitude. The theoretical limit of its amplitude is the constant volume explosion pressure, but since such pressures usually exceed the ultimate strength of materials by a wide margin, the practical limit in any concrete case is the strength of confinement; the pressure within the container will decrease soon after the walls rupture. Under experimental conditions described in the previous section compression waves and shock waves of the order of magnitude of 10 kbar can be maintained for perhaps 10 microseconds.

In the transition experiment as well as in the gap test, initiation of detonation or failure to detonate depends on the balance between chemical reaction engendered by the shock and side rarefactions so that initiating capability of a shock is always defined by effective confinement; while in shock sensitivity tests this is essentially a diameter effect modified by

---

* The locus of shock formation, in general, is not a point but a region in the x-t plane; the matter has been discussed in some detail in Ref. 3. The assumption of a point S simplifies the argument presented here without detracting from its validity. The generalization is straightforward, at least in principle.

by the nature of the casing, transition experiments can be designed so that the strength of the casing plays a decisive role. The fundamental dependence on two physical parameters, shock pressure p_s and the time t_s during which the explosive is maintained in the compressed state (closely related to t_1 of Fig. 4) should be the same in both cases; the effect of the shock, presumably, is an increase of temperature which, in turn initiates the chemical reaction leading to detonation. Hence it is possible to construct a p_s vs. t_s diagram which divides the continuum into a detonation region and a failure region. For the case of shock initiation of explosives this has been done theoretically by Hubbard and Johnson (6). Although their results diverge widely from experimental data of Majowicz and Jacobs (4), in view of the present uncertainties about chemical kinetics of combustion and detonation of solids, this is neither surprising, nor should it be discouraging. In principle it should be possible to extrapolate such diagrams to thermally initiated transition conditions and vice versa; at the present time this cannot be done, because in transition experiments, such as those described herein the variation of p_s is not known. Evidently, reliable simultaneous data of shock pressures and shock durations are much needed.

ACKNOWLEDGMENTS

The authors wish to thank Dr. D. Price for valuable advice and a critical review of the manuscript, to Mr. B. Harrell for help with instrumentation, and to Mr. G. E. Roberson for competent handling of explosive charges and related equipment.

REFERENCES

(1) A. Maček and R. W. Gipson, *Transition from Slow Burning to Detonation in Cast Pentolite*, NavOrd Report 5758, 1 November 1957.

(2) A. Maček, R. W. Gipson and P. F. Donovan, *Transition from Slow Burning to Detonation: Pressure and Velocity Measurements*, NavOrd Report 6104, 12 May 1958.

(3) A. Maček, *Transition from Deflagration to Detonation in Cast Explosives*, *J. Chem. Phys.*, *31*, 162 (1959).

(4) J. M. Majowicz and S. J. Jacobs, 10th Annual Meeting of Div. of Fluid Dynamics, *Am. Phys. Soc.*, November 1957.

(5) G. P. Cachia and E. G. Whitbread, *The Initiation of Explosives by Shock*, *Proc. Roy. Soc.*, *A246,* 268 (1958).

(6) H. W. Hubbard and H. M. Johnson, *Initiation of Detonation*, *J. Appl. Phys.*, *30*, 765 (1959).

(7) A. B. Amster, P. A. Kendall, L. J. Veillette and B. Harrell, *Continuous Oscillographic Method for Measuring the Velocity and Conductivity of Stable and Transient Shocks in Solid Cast Explosives*; *Rev. Sci. Instruments* (in press).

(8) A. B. Amster, and R. L. Beauregard, *Pressure Sensing Probes for Detecting Shock Waves*, *Rev. Sci. Instruments*, *30*, 942 (1959).

(9) NOL Lab. Notebook 96-5272, p. 84.

(10) J. Berger, J. Favier, J. Fauquignon, *C.R.*, *247*, 1305 (1958).

(11) N. Griffiths and J. M. Groocock, *The Burning to Detonation of Solid Explosives*, ARDE Rep (MX) 6/59, March 1959.

DISTRIBUTION LIST

	No. of Copies
Chief, Bureau of Naval Weapons, Washington 25, D.C.	
Attn: DLI-3	1
Attn: RRRE-5	2
Attn: RUUO-3	2
Attn: RMMP-3	1
Chief of Naval Research, Washington 25, D.C.	
Attn: Code 425	1
Attn: Code 426	1
Chief of Ordnance, Department of the Army, Washington 25, D.C.	1
Attn: Research and Development Division	1
Superintendent, Naval Weapons Plant Washington 25, D.C.	
Attn: Dr. J. M. Majowicz	1
Commanding Officer, Naval Propellant Plant Indian Head, Maryland	
Attn: Research and Development	1
Commander, Naval Ordnance Test Station China Lake, California	2
Commanding Officer, Naval Mine Depot Yorktown, Virginia	1
Commanding Officer, Picatinny Arsenal, Dover, N. J.	
Attn: Chemistry Research Section	1
Attn: Mr. F. J. Masuelli	1
Los Alamos Scientific Laboratory, P.O. Box 1663	
Attn: Reports Librarian for Dr. L. C. Smith	1
Attn: Mr. H. C. Hoyt	1
Director, Naval Research Laboratory, Washington 25, D.C.	
Attn: Chemistry Division	1
Armed Services Technical Information Agency Arlington Hall Station, Arlington 12, Virginia	
Attn: TIPDR	10
Commanding General, Redstone Arsenal Huntsville, Alabama	1
University of California Lawrence Radiation Laboratory P. O. Box 808, Livermore, California	
Attn: Information Division	1
Attn: Dr. J. S. Foster	3
Attn: Dr. M. Martin	1
Commanding General, Aberdeen Proving Ground, Md.	
Attn: Technical Library, Bldg. 313	1
Attn: Mr. M. Sultanoff	1
Director, U. S. Bureau of Mines Division of Explosives Technology 4800 Forbes Street, Pittsburgh 13, Pennsylvania	
Attn: Technical Librarian	2

UNCLASSIFIE

AD 234 290

Reproduced

Armed Services Technical Information Agency

ARLINGTON HALL STATION; ARLINGTON 12 VIRGINIA

UNCLASSIFIE