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TRANSITION FROM SLOW BURNING TO DETONATION: PRESSURE AND VELOCITY MEASUREMENTS

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NAVORD Report 6104

SENSITIVITY OF EXPLOSIVES VI

TRANSITION FROM SLOW BURNING TO DETONATION: PRESSURE AND VELOCITY MEASUREMENTS

By

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ABSTRACT: Cast confined charges of diethylnitramine dinitrate (DINA) were electrically initiated by Nichrome igniters. As slow burning accelerated toward detonation, pressure in the region around the igniter and propagation velocities over three adjacent intervals along the charge were measured. Preliminary pressure measurements on TNT and pentolite were also made. The pattern of velocity increase in DINA is similar to that previously determined for pentolite. The pressure in the region of initiation is approximately exponential in time. The results are given in tabular and graphic form. Their relevance to the understanding of shock formation is briefly discussed.

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Many explosives are known to ignite and burn before detonating. The transition from deflagration to detonation has not been studied extensively and the purpose of this research was to elucidate the mechanisms involved. It represents part of a program on explosive sensitivity following the recommendations of NavOrd 3906 "Key Problems in Research and Development, Part I". This work was authorized under the New Explosives task, NO 800-667/76004/01.

W. W. WILBOURNE
Capt. USN
Commander

Albert Lightbody
ALBERT LIGHTBODY
By direction

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SENSITIVITY OF EXPLOSIVES VI

TRANSITION FROM SLOW BURNING TO DETONATION: PRESSURE AND VELOCITY MEASUREMENTS

INTRODUCTION

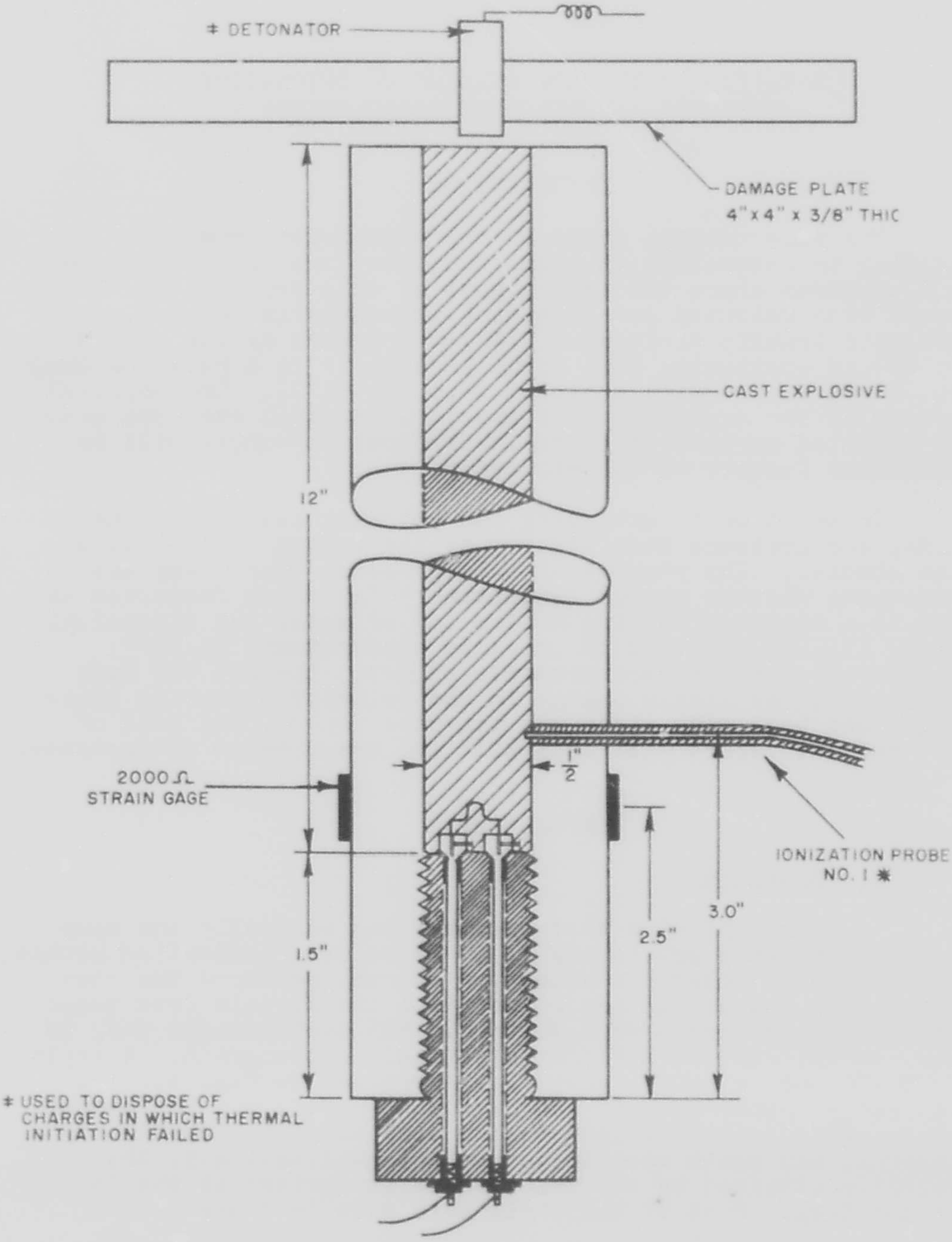
The experimental study of the transition from slow burning to detonation in high explosives has been continued and expanded since the last report of this project (1), which dealt with velocity determination in pentolite charges. Diethylnitramine dinitrate (DINA) was chosen as the explosive to use in continuing this work, because it is a pure compound and it is also easily castable (M.p. 51-54°C). The physical set-up of the explosive test specimen remained much the same as reported earlier (1); the few important changes will be described further on in this report.

In addition to extending the velocity determinations to DINA, the pressure-time history of the region of initiation was studied. The purpose of this pressure-time study was to determine whether or not requirements for shock formation are met in a confined burning medium (2) of specified dimensions (Fig. 1). In addition to pressure measurements in DINA, similar preliminary measurements on pentolite and TNT have been made. As little change in the velocity measuring technique has been made since the previous report, the bulk of the present report will deal with the measurement of pressure.

EXPERIMENTAL

A. Equipment

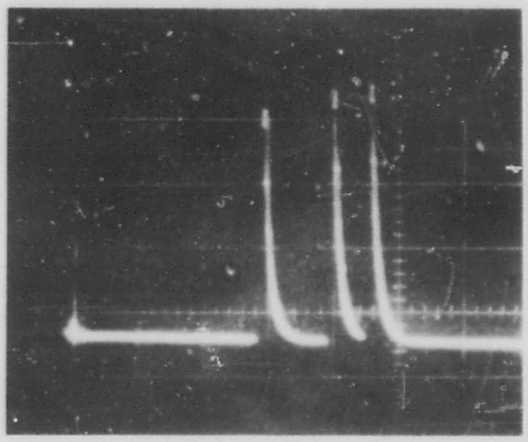
The explosive test specimen was basically the same as that reported previously (1). As before, ionization probes, positioned at intervals along the charge, measured the subdetonation and detonation velocities; the signals from these probes were recorded on a Tektronix 545 oscilloscope and, in some shots, also on a Potter electronic chronograph. A typical oscilloscope velocity record is reproduced in Fig. 2. The ionization probe circuit can be found in Ref. 1. The target plate, with detonator inserted to dispose of malfunctioning charges, was again used to determine, qualitatively, the velocity attained by the reaction as it arrived at the top of the tube. Most of the shots were made in tubes of the



‡ USED TO DISPOSE OF
CHARGES IN WHICH THERMAL
INITIATION FAILED

✱ NOT SHOWN IN FIGURE ARE IONIZATION PROBES 2, 3, AND 4 WHICH WERE LOCATED AT KNOWN DISTANCES UP THE CHARGE FROM PROBE NO. 1

FIG. 1 CROSS SECTION OF THE CHARGE



HORIZONTAL SCALE: 1 CM = 20 μ SEC

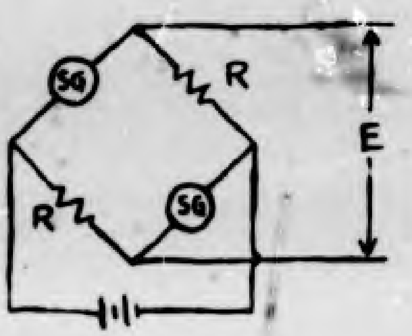
THE FIRST PROBE STARTED THE SWEEP. THE OTHER SIGNALS RECORDED AT 57, 79 AND 90μSEC. STEADY-STATE DETONATION REACHED BETWEEN THE SECOND AND THE THIRD PROBE.

FIG. 2 OSCILLOSCOPE VELOCITY RECORD OF SHOT D12 previously used 0.375 in. wall thickness; however, to facilitate pressure measurements by increasing the strain of the tube wall, several shots in which a wall thickness of 0.250 in. was used were fired. This permitted a comparison of the transition patterns obtained under different degrees of confinement.

One of the changes in the basic charge was the design of an igniter-pressure seal combination (see Fig. 1). The new type igniter gave more efficient ignitions and more reproducible delays, τ . The data obtained from these velocity measurements in DINA are given in Tables I, II, III and IV.

In addition to the instrumentation described thus far, a number of DINA (and a few pentolite and TNT charges) were provided with strain gauges for the purpose of measuring pre-detonation pressure build-ups. It was intended that these gauges should follow the pressure-time history, especially in the region of initiation where it is an important factor in the theory of transition to detonation from slow burning (2).

The pressure measuring instrument was a Wheatstone bridge (Fig. 3), in which two opposite arms were Baldwin SR-4 strain gauges mounted radially on the charge case. The other (compensating) arms were either the same type of gauge, mounted on a dummy steel tube, or two precision resistors of the same resistance. The unbalance of the bridge, due to the strain in the tube under pressure, was recorded on a cathode ray oscilloscope. Several refinements of this basic circuit were used.



SG - Strain gauges

R - Compensating gauges or precision resistors

E - Unbalance of the bridge

Figure 3 - Basic Strain Gauge Circuit

The first arrangement of the pressure recording system was designed by Mr. J. C. Jerome. Baldwin-Lima-Hamilton type A-14 strain gauges (500 ohm) were mounted at three positions along the charge: near the initiation area, at the half-way point up the charge, and near the upper end of the charge (see p. 15, Ref. 3, for exact positions). In addition, an Aberdeen type gauge was designed so as to be mounted on the initiation end of the charge case in the place of the usual bolt-igniter. The signals from these four bridges were fed into four separate channels of a six-channel oscilloscope (6T CRO) and recorded on film by a 35 mm. reel camera with a writing speed of 2.3 mm/msec. The maximum deflection of the oscilloscope and the writing speed of the camera were too low for an accurate analysis, but a record was obtained which showed that, in one shot (PD-3), the pressure in the region of initiation rose several kilobars in less than 100 µsec. The signals from the other two gauges were discontinued abruptly (about 100 µsec. after the gauge near the region of initiation showed deflection) indicating a very rapid pressure increase. The frequency response of the Aberdeen gauge was not sufficiently high to record these rapid phenomena. A more detailed account of this first attempt can be found in the original Laboratory Notebook (3).

Another series of pressure measurements was made on the basis of the information that the pre-detonation pressure in the region of initiation increases to the bursting strength of the steel tube in about 100 µsec. As before, a transducing element was designed using two Baldwin SR A-14 strain gauges (cemented on the outside of the tube at the level of the igniter, as shown in Fig. 1), as two active arms in a bridge. The two passive arms were also strain gauges cemented on a dummy tube. The output of this bridge fed into a 545 Tektronix oscilloscope. With this arrangement, several shots were fired. No readable records were obtained, because both the triggering signal and the noise were in the millivolt region. To obtain results, the signal to noise ratio had to be increased. This was done by improving the system in several ways.

Baldwin SR C-14 gauges were used in the improved system. These gauges have the advantage of possessing a gauge factor of 3.3 as compared to 2 for the SR A-14 gauges. Thus a larger signal voltage could be obtained. The SR C-14 gauges also have a resistance of 2000 ohms as compared to 500 ohms for the SR A-14. Since the output of the bridge is proportional to the supply voltage, and this is limited by the allowable current through the element, the increased resistance helped increase the signal by permitting a supply voltage of 75 - 80 volts, as compared to a maximum of 30 volts for the A-14 gauges. The maximum signal obtained from this bridge was in the 100-millivolt region.

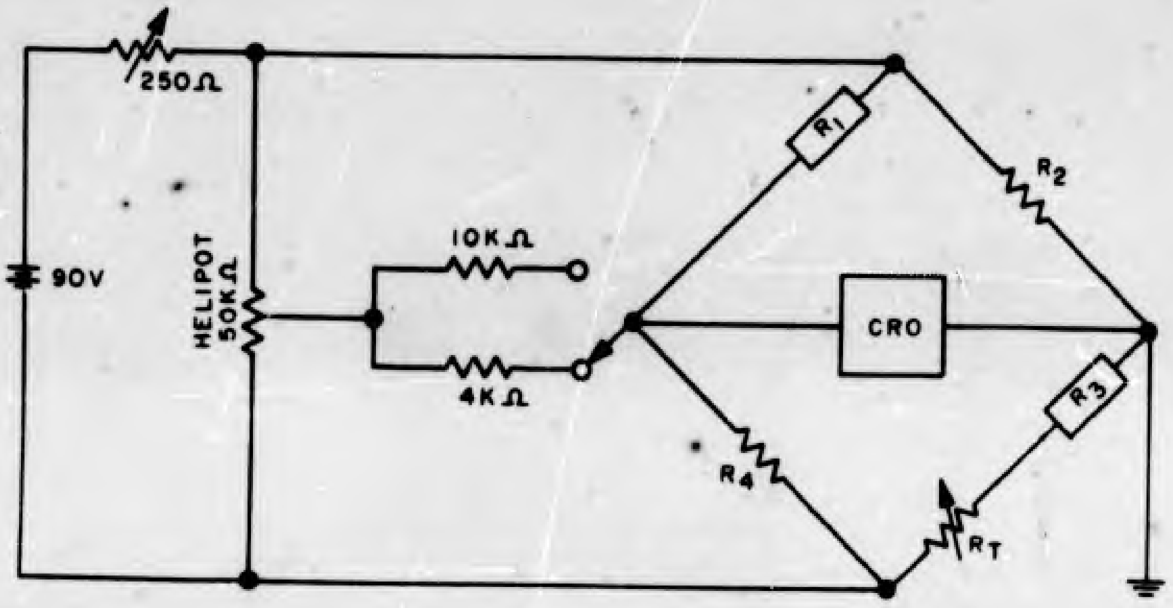
A bridge control circuit, including a 50,000 ohm helipot, was then designed and used to balance the bridge at the zero strain level. It contained the voltage supply for the bridge and a variable resistor which could be used to simulate a signal and thus to ascertain that the circuit was functioning properly. The control also contained two precision 2000 ohm resistors which were used as the passive arms of the bridge. Noise in this circuit was less than one millivolt.

The final circuit (Fig. 4) then consisted of two SR C-14 strain gauges mounted radially on the charge case. These were connected through a shielded cable to the bridge control box, which housed the other bridge components. The output connected to an oscilloscope, upon which a Dumont oscillograph polaroid camera was mounted. Approximately 30 ft. of coaxial cable was used, having a capacitance of 27.65 μμfd/ft. Hence the rise time of the circuit was approximately 2 μsec. Either a Tektronix 545 or a Tektronix 535 oscilloscope was used with a 53/54D plug-in unit. The oscilloscope was used on DC coupling with a positive DC internal trigger, so that the triggering was independent of frequency, and adjusted to trigger on 2 - 4 mm vertical deflection. This triggering level corresponded to 5 - 10 percent of the oscilloscope's maximum deflection for the 545 Tektronix oscilloscope, and to 3 - 6 percent for the 535 instrument. The remainder of the signal was recorded in one rapid sweep of the oscilloscope (200 μsec.). A typical oscilloscope pressure record is reproduced in Fig. 5.

The pressure-time curves obtained in these measurements are given in Fig. 6. (The numbering of the DINA shots in which the pressure was measured is preceded by the letters "PD".)

B. Pressure Calibration of the Steel Tubes

In order to translate the output of the bridge into pressure, the bridge circuit was calibrated by introducing known pressures into empty steel tubes, instrumented with two gauges, as in dynamic firing. The dummy tubes were securely capped at the upper end and had a pressure adaptor replacing the bolt-igniter on the lower end. Through this adaptor, the tubes were pressurized with oil up to 50,000 psi; the corresponding bridge output was read directly off the oscilloscope at various pressure levels indicated on a Bourdon type pressure gauge. The output was a linear function of pressure up to approximately 40,000 psi for the 0.250 in. tube and ca. 45,000 psi for the 0.375 in. wall tube. Beyond these respective pressures, the voltage output increased more steeply. Readings taken with decreasing pressure always



R_1 & R_3 - STRAIN GAGES; 2000 OHM, C-14

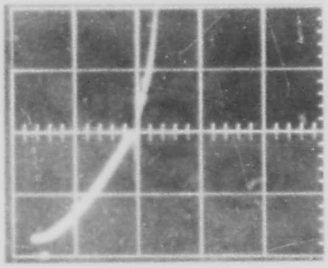
R_2 & R_4 - PRECISION RESISTORS; 2000 OHM, ±1%

R_T - TEST POT; USED TO CHECK POLARITY OF SIGNAL AND TO HELP SET TRIGGERING LEVEL OF THE CRO

CRO - TEKTRONIX 545 CATHODE RAY OSCILLOSCOPE

50K HELIPOT - BRIDGE - BALANCING DEVICE

FIG. 4 CIRCUITRY USED TO OBTAIN DATA IN FIG. 6 AND TABLE 5



HORIZONTAL SCALE: 1 CM = 20 μ SEC
VERTICAL SCALE: 1 CM = 50 MVOLT = 16.8 kpsi
THE INITIAL PRESSURE p_0 = 4.58 kpsi

FIG. 5 PRESSURE-TIME RECORD OF SHOT PD14 remained above those taken for corresponding pressures on the increase, so that, at zero reading of the Bourdon gauge, the voltage output remained finite; after several minutes, however, this value did diminish to zero. Hence the elastic limit was apparently not exceeded; the lack of linearity is possibly due to thermal effects. In translating the voltage output of the gauges into pressure (Fig. 6 and Table V) the slope of the linear portion of the curve was used as a constant conversion factor throughout the pressure range. Fig. 7 is a graph of the calibration data.

The calibration curve, when applied to transcribing the voltage-time oscillograms into pressure-time data, gives only approximate results. Errors are introduced first because the steel caps covering the ends of the calibrated tubes change the strain characteristics of the system; second because no calibration under the experimental rapid loading conditions was attempted, and third because the response of the gauge circuit during the late stages of the pressure rise (large dp/dt) may not be fast enough to follow the rapid strain changes without distortion. Hence the transcribed pressure-time curves, given in Fig. 6, must be considered only an estimate of the pressures which developed in the region of initiation.

RESULTS

A. Velocity Measurement

Six detonator-initiated cast DINA charges gave the average steady detonation velocity of 7.5mm/μsec. The experimental arrangement for these tests was the same as in thermally initiated shots (Fig. 1), but the charge was detonated from the upper (open) end toward the steel plug at the bottom. Another two detonator-initiated shots gave all the evidence of a lower order propagation: measured velocities of 1.2 and 2.2mm/μsec. respectively, large tube fragments, little damage to the steel plug. In still another case, a propagation velocity of 1.2mm/μsec. was measured over a 76.2mm interval starting near the point of initiation, but, judging by tube fragments, the reaction died out after about 21cm of travel. Cast DINA in the confinement used, is thus not reliably detonated by a detonator. (Olin Industries RDX filled Seismo detonators were used.)

Thermal initiation (heat input 5 - 25 cal.) of cast DINA under 0.375 in. steel confinement usually (but not invariably)

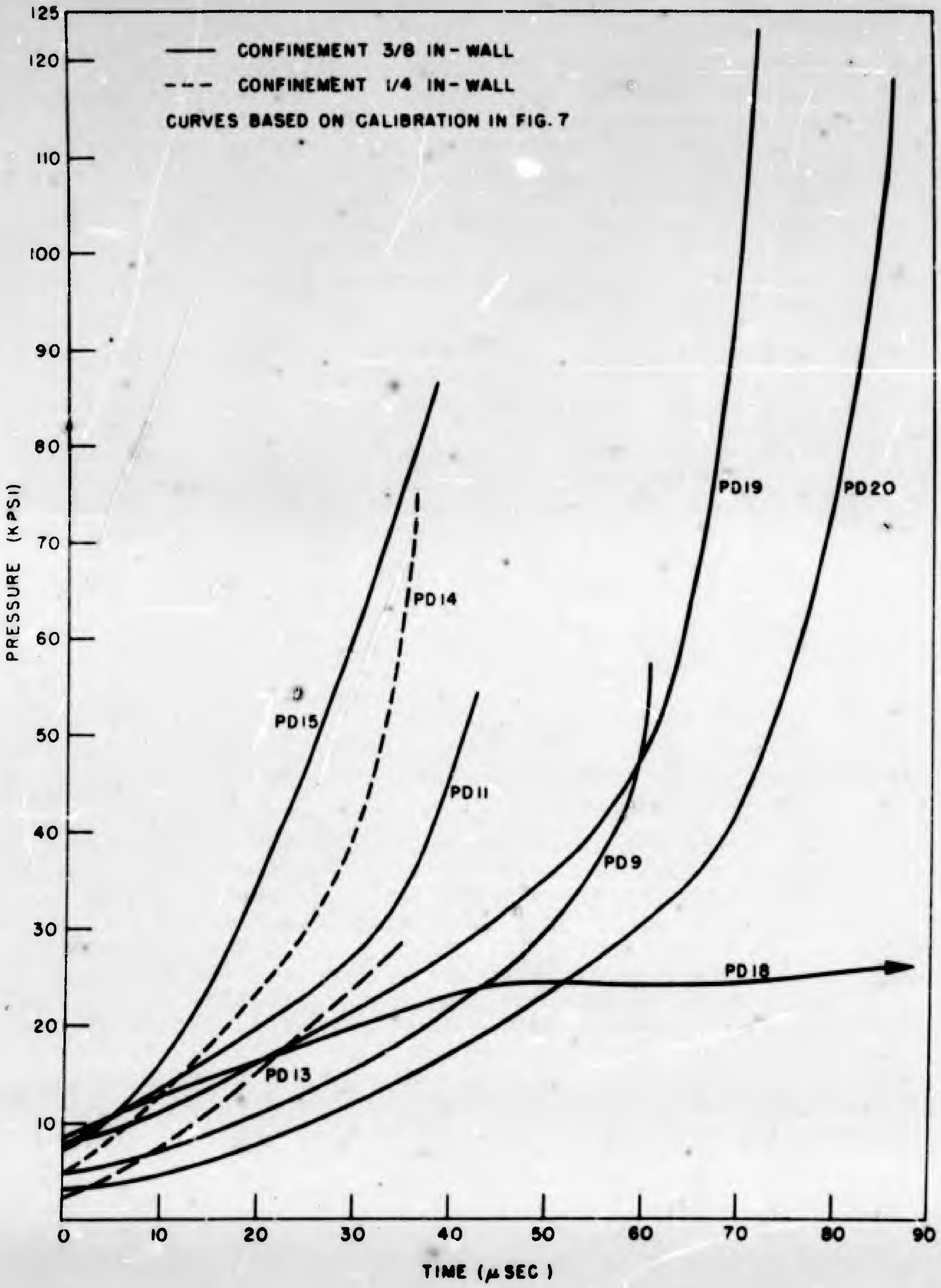


FIG. 6 PRESSURE-TIME MEASUREMENTS

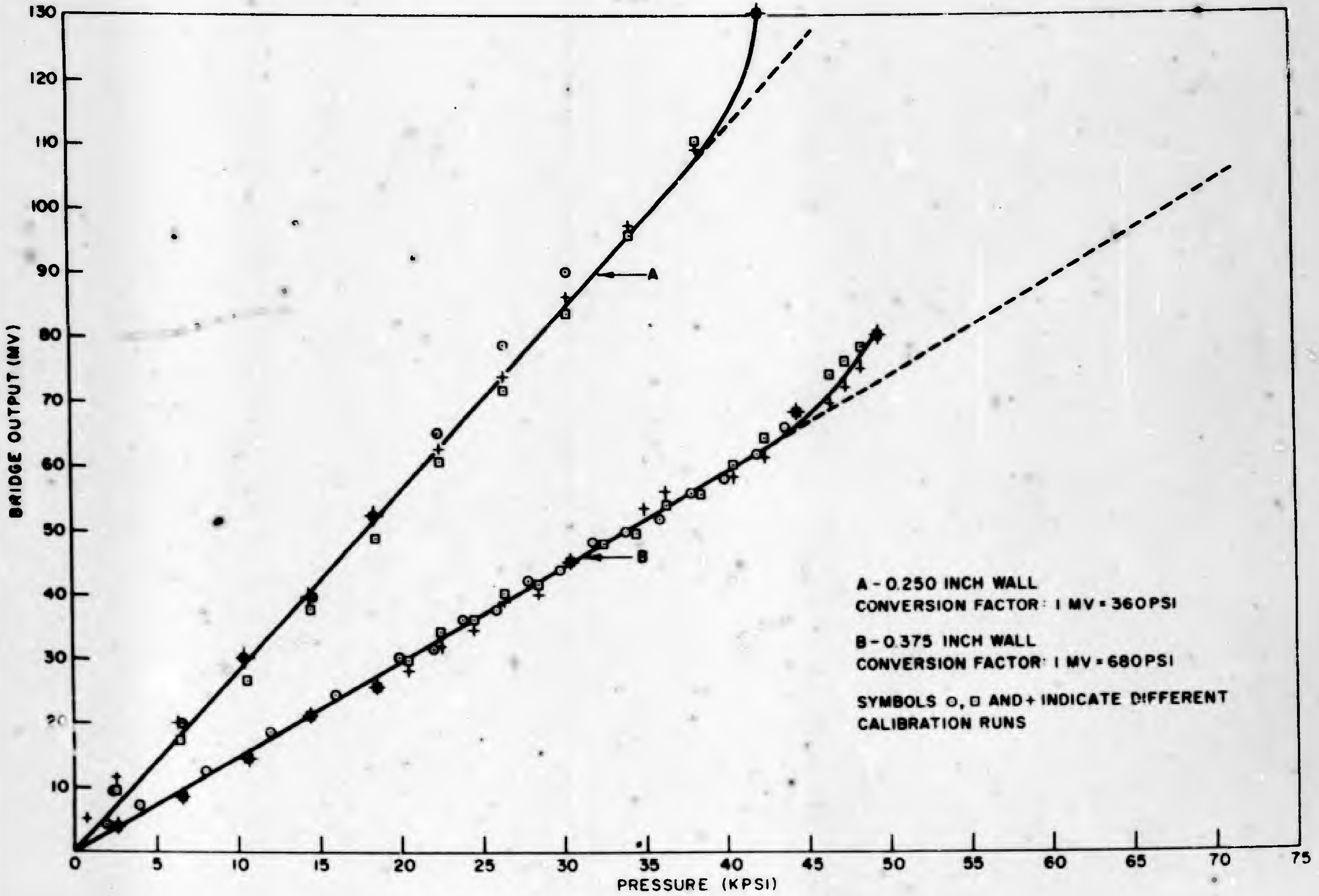


FIG. 7 PRESSURE CALIBRATION OF STEEL TUBES

led to a transition from burning to detonation, as evidenced by the plate damage (for classification of plate damages see Ref. 1) and velocity data presented in Tables I and III. Some discrepancies appear: in shots D 17 and D 31, the 12 in. charge did not develop steady state detonation. Also, some irregularities were noted: in shot D 9 the propagation velocity, after having reached a high value, decreased steadily; in shot D 11 the plate damage was inconsistent with the velocity as measured in the last interval. (In these cases, however, malfunctioning of ionization probes might account for the apparent irregularities.)

Tables II and IV show the results obtained from velocity measurements of charges encased in the thinner (0.250 in. wall thickness) tubes. In three out of five shots large fragments and relatively little damage to the target plate were obtained. This indicates that steady-state detonation did not develop.

B. Pressure Results from DINA Shots

The data taken in measuring the build-up of pressure in the region of initiation are presented in Fig. 6 and Table V. As one could anticipate from the results of shot PD 3 (see Experimental, section A), the pressure generally increases steeply with time and attains several kilobars in less than 100 µsec.; as shown elsewhere (2), the experimental curves can be approximated by the simple exponential $p = p_0 \exp(kt)$. The significance of an exception, shot PD 18, is discussed below. It may be noted that in all the shots, except PD 18, the maximum pressure recorded was determined by the upper limit of deflection of the oscilloscope.

The pressure-time curves do not coincide closely, but this can be accounted for. First, of course, the initial pressure, determined by the triggering level of the oscilloscope, varied from shot to shot and second, the ignition was not reproducible. The possible reasons for the lack of reproducibility are inhomogeneity of the charge in the vicinity of the igniter and irregularities of contact between the igniter and the explosive.

TABLE I

VELOCITY MEASUREMENTS IN DINA (3/8" Steel Confinement)

Shot No.	τ * (Sec)	Dist. from Igniter to 1st Probe ℓ (cm)	Distance between Probes d_{12} (mm)	d_{23} (mm)	d_{34} (mm)	Velocity (mm/μsec) Chronograph D_{12}	Oscilloscope D_{12}	D_{23}	D_{34}	Plate Damage
D7	6.5	~1	88.9	88.9	88.9	1.37	1.3	5.9	6.8	D
D9	9	"	"	"	"	F**	5.2	1.4	0.7	C
D10	7	"	"	"	"	1.55	1.5	2.5	4.7	C-D
D11	15	"	76.2	76.2	76.2	3.85	3.9	3.0	7.4	C
D12	1	"	"	"	"	F	1.3	3.6	6.9	D
D13	4	"	"	"	"	1.33	1.3	1.8	3.2	D
D17	4	"	"	"	"	0.56	0.57	F	F	B
D18	2	"	"	"	"	1.56	1.7	5.4	6.3	D
D19	4	"	"	"	"	1.02	1.0	2.5	2.3	D
D20	1	"	"	"	"	F	1.9	5.9	F	D
D22	3	"	"	"	"	1.42	1.4	5.95	6.9	D
D23	3	"	"	"	"	F	3.5	3.5	7.6	D
D24	3	"	"	"	"	1.37	1.4	2.1	5.9	D
D29	10	"	"	"	"	1.82	1.9	2.2	5.9	D
D31	3	"	"	"	"	1.09	1.1	0.99	1.5	B-C
D36	6	"	88.9	88.9	88.9	2.58	2.7	6.8	7.4	D
D38	2.5	"	50.8	101.6	95.2	1.73	1.7	4.4	7.9	D
D39	8	"	76.2	76.2	76.2	0.45	F	F	F	C-D
D43	6	"	"	"	"	5.08	F	F	F	D
D44	2	"	"	"	"	1.08	1.1	2.2	4.8	D
D45	2	~2	"	"	"	1.16	1.15	2.7	6.9	D
D51	4	~1	38.1	38.1	139.7	not used	F	F	F	D
D52	4	"	"	"	"	"	0.95	1.41	4.9	D
D53	4.5	"	"	"	"	"	0.87	1.81	4.9	D
D54	2.5	"	"	"	"	"	1.15	1.15	3.25	D

---

* Delay from the instant the current is turned on in the ignition circuit to the audible explosion.

** F denotes instrument failure.

VELOCITY MEASUREMENTS IN DINA

TABLE II (1/4" Steel Confinement)

Shot No.	τ (Sec)	Dist. from Igniter to 1st Probe ℓ (cm)	Distance between Probes			Velocity (mm/μsec)				Plate Damage
			d_{12} (mm)	d_{23} (mm)	d_{34} (mm)	Counter D_{12}	Oscilloscope D_{12}	Oscilloscope D_{23}	Oscilloscope D_{34}	
D47	2.1	2	76.2	76.2	76.2	not used	1.2	2.0	2.2	A-B
D48	3	"	"	"	"	" "	1.2	2.1	2.1	A-B
D55	3	"	"	"	"	" "	0.82	1.95	2.54	B

TABLE III (3/8" Steel Confinement)*

Shot No.	τ (Sec)	Dist. from Igniter to 1st Probe ℓ (cm)	Distance between Probes			Velocity (mm/μsec)				Plate Damage
			d_{12} (mm)	d_{23} (mm)	d_{34} (mm)	Counter D_{12}	Oscilloscope D_{12}	Oscilloscope D_{23}	Oscilloscope D_{34}	
PD1	9.3	2	76.2	76.2	76.2	4.51	5.1	7.6	F	not used
PD3	3.9	"	"	"	"	1.52	1.6	7.6	7.6	" "
PD4	6	"	"	"	"	1.24	1.1	2.1	3.5	D
PD6	2.5	"	"	"	"	1.14	0.96	2.2	5.9	D
PD7	4	"	"	"	"	1.96	1.9	5.9	6.4	not used
PD8	2.4	"	"	"	"	1.44	1.9	1.5	4.5	D
PD9	5	"	"	"	"	2.18	F	F	F	D
PD10	1.3	"	"	"	"	1.69	1.8	7.6	7.6	D
PD11	1.4	"	"	"	"	2.0	2.1	7.6	7.6	D
PD15	6	"	"	"	"	not used	2.08	7.5	7.6	D
PD16	6	"	"	"	"	" "	2.3	4.1	7.6	D
PD18	2.5	"	"	"	"	" "	0.85	1.2	1.8	B
PD19	2.3	"	"	"	"	" "	1.4	3.0	F	D
PD20	1.8	"	"	"	"	" "	1.3	2.1	F	D

TABLE IV (1/4" Steel Confinement)*

Shot No.	τ (Sec)	Dist. from Igniter to 1st Probe ℓ (cm)	Distance between Probes			Velocity (mm/μsec)				Plate Damage
			d_{12} (mm)	d_{23} (mm)	d_{34} (mm)	Counter D_{12}	Oscilloscope D_{12}	Oscilloscope D_{23}	Oscilloscope D_{34}	
PD13	1	2	76.2	76.2	76.2	1.5	1.7	5.2	7.9	D
PD14	1	"	"	"	"	1.9	2.0	3.5	7.6	D

---

* Pressure data given in Fig. 6 and Table V

TABLE V

PRESSURE (in kpsi) VS TIME DATA

t(μsec) Shot Number	0	10	20	30	40	50	60	70	80
9	5	7	11	15.5	22	30	53	-	-
11	8	13.5	20	27	47	-	-	-	-
13	2	7.5	15	24	-	-	-	-	-
14*	4.5	13	23	40	-	-	-	-	-
15	7	16	35.5	61	-	-	-	-	-
18	8.5	12.5	16	20	23	24.5	24	24.5	25
19	8	11	16	21.5	28	36.5	48	102	-
20	3	4.5	7.5	12	17	23.5	31	43	110

---

* Data used to calculate the time and the length of travel for shock formation (Ref. 2).

DISCUSSION

The build-up of propagation velocity under 0.375 in. confinement in DINA, on the whole, is similar to that previously established for pentolite (1).* The process of transition from thermally initiated slow burning includes a relatively long (50 μsec. or more) interval of rapid sub-detonation velocities. The length of travel between ignition and detonation often exceeds 10 cm.

Information about the effect on propagation velocity of reducing the confinement from 0.375 in. to 0.250 in. of steel remains inconclusive. While shots D 47, D 48, and D 55 (Table II) definitely point to a difference in propagation acceleration, shots PD 13 and PD 14 (Table IV) followed the general pattern established for 0.375 in. confinement.

Results of the pressure measurements are important. The pressure-time history of the region of thermal initiation is characterized by a long initial delay τ (see Tables I IV). For the entire duration of this delay, except for the last 40-80 μsec, the pressure does not exceed 10,000 psi. During the last 40-80 μsec, however, the pressure increases steeply to above 100,000 psi (and probably to the bursting pressure of the confining tube).

One of the main objects of this study was to find out if there is any correspondence between pressure-time conditions leading to shock formation within the charge and the pattern of transition to detonation. The correspondence in DINA is very good. Seven out of eight shots, for which $p = p(t)$ is given in Figure 6, developed into detonation; these are the shots in which pressure increased very rapidly (approximately exponentially) during the later stages of the build-up. It can be shown that such rapid pressure surges must lead to shock formation within the charge; this is the subject of a separate report (2). On the other hand, the one shot which did not follow the general pattern of rapid pressure increase was PD 18, in which the pressure increased approximately linearly from 8,000 to about 25,000 psi in about 45 μsec with no further increase during subsequent 100 μsec. These conditions are not conducive to shock formation within a short distance, and they were also insufficient to effect a transition from slow burning to detonation in shot PD 18 (see Table III).

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* As mentioned previously, there were several cases, both of thermal initiation and detonator initiation of DINA, in which propagation velocities were decreasing. In the case of pentolite this was not observed, but multiple probe velocity measurements on pentolite were too few to conclude that the growth of detonation is in fact more reliable than in DINA.

MEASUREMENTS IN PENTOLITE AND TNT

Simultaneous pressure and velocity measurements, analogous to those in DINA, were taken on several charges of pentolite and TNT. Preliminary results show that pentolite exhibits a pattern of pressure (and velocity) increase similar to DINA. In TNT, the pressure build-up is slower, so that no shocks can form within the charge; measured velocities were erratic, but always considerably below the stable detonation velocity. A more complete report of these experiments will be written later.

SUMMARY

Multiple probe data reveal that in confined charges of cast DINA the growth toward detonation from thermally initiated slow burning is similar to that previously established for pentolite. The process of transition to steady state detonation includes a relatively long (50 μsec or more) interval of rapid sub-detonation velocities. The length of travel between ignition and detonation often exceeds 10 cm.

The pressure-time history of the region of thermal initiation is characterized by a long (seconds) delay during which the pressure does not exceed 10,000 psi. During the subsequent 40-80 μsec, however, the pressure increases steeply to above 100,000 psi. This information furnished a quantitative basis for a theoretical inquiry of shock formation (Ref. 2).

PLANS FOR FUTURE WORK

Velocity and pressure-time measurements on cast charges of pentolite and TNT will be continued. A more accurate static pressure calibration of the steel tubes will be carried out over a wider pressure range (up to 100,000 psi). Plans are being made to test the effect of a shock on a deflagrating explosive or propellant as an extension of the present work on transition from slow burning to detonation. It is also planned to improve the theoretical calculation of pressure increase behind a burning front of a confined explosive by taking into account the strength of the confining walls.

ACKNOWLEDGMENTS

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