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INITIATION OF EXPLOSIVES BY
EXPLODING WIRES

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INITIATION OF EXPLOSIVES BY EXPLODING WIRES

I. Effect of Circuit Inductance on the
Initiation of PETN by Exploding Wires

Prepared by:
Howard S. Leopold

ABSTRACT: The effects of circuit inductance and bridgewire length on the initiation of PETN by exploding platinum wires were investigated. A capacitor discharge was used as the energy source. Oscillograms of current and voltage coincident with smear camera records were used to interpret the wire explosion and initiation processes. Increasing circuit inductance lowers the probability of producing detonation in PETN by an exploding wire. Secondary current pulses have little effect on whether or not detonation results. For effective initiation the bridge-wire length should be chosen to eliminate current dwell.

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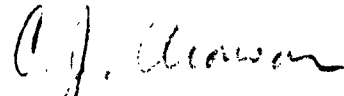
INITIATION OF EXPLOSIVES BY EXPLODING WIRES

This report is Part I of an investigation concerning the initiation of explosives by exploding wires. The work was performed under Task RUME-4E000/212-1/F008-10-04 problem no. 019, Analysis of Explosive Initiation.

The results should be of interest to personnel engaged in initiation research and to those interested in the design of exploding bridgewire ordnance systems. The data and conclusions are for information only and are not intended as a basis for action.

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R. E. ODENING
Captain, USN
Commander


C. U. ARONSON
By direction

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INTRODUCTION

A fine wire can be exploded by a high current surge. Since the publication in 1774 of an article by E. Nairne⁽¹⁾ describing experiments conducted with exploding wires, the literature on the subject has become quite extensive. Numerous papers have appeared within the past ten years. The investigations cover a wide range of experimental conditions governed by diverse motivations. Experimenters have employed exploding wires for their light output, as fuses, in fundamental electrical studies, for shock wave formation, and for production of high temperature plasmas among other uses.⁽²⁾

The exploding wire phenomenon has quite naturally proved to be of interest to workers in the explosive field. One of the early references on the interaction between exploding wires and explosive materials is by A. F. Belajev⁽³⁾ in 1938. He used exploding wires to produce detonation in nitrogen chloride and nitroglycerin. In recent years reports have appeared showing that direct detonation of PETN and RDX can be achieved by exploding wires.^(4,5)

The direct initiation of secondary explosives by high energy inputs has been of increasing interest because it might reduce the growing problem of inadvertent initiation of weapons by electromagnetic radiation and stray voltages. Another possible advantage of a higher energy system such as an exploding bridgewire (EBW) is the elimination of sensitive primary explosives, and consequently the need for safety and arming devices. One can readily see then why there is increasing interest in the use of EBW's in ordnance.

With the increased interest in EBW systems has come a demand for more basic information about the interaction between

- 1/ Nairne, E., "VII Electrical Experiments", Philosophical Transactions of the Royal Society, 64, 79-89, 1774
- 2/ Chace, W. G. and Moore, H. K., "Exploding Wires", Plenum Press, New York, 1959
- 3/ Belajev, A. F., "The Production of Detonation in Explosives under the action of a Thermal Pulse", Comptes Rendus (Doklody), XVIII, No. 4-5, 267-269, 1938
- 4/ DiPersio, R., "Exploding Wire and Spark Gap Central Initiator for High Explosives", BRL Memo No. 851, 1954
- 5/ Muller, G. M., Moore, D. B., and Bernstein, D., "Growth of Explosion in Electrically Initiated RDX", Journal of Applied Physics, 32, No. 6, 1961

the EBW and the explosive, and the factors which affect the process. Published information about the fundamental parameters governing EBW's is lacking. This information is needed by ordnance designers. Most EBW firing systems are based on but few known parameters. This investigation was undertaken to systematically study the initiation process occurring in EBW/explosive systems. This report, one of an anticipated series, deals with the effect of circuit inductance on the initiation and growth to detonation of PETN. The data obtained could not be analyzed to the extent desired. Useful information concerning such factors as peak current, peak voltage, peak power, integrated energy etc. could not be calculated during the time period of interest because of the poor quality (noise*) of the oscillographic traces during the early portion of the discharge.

BASIC CONSIDERATIONS

Initiation of explosive materials by an exploding wire is difficult to analyze. A large number of variables is involved. It seems that initiation can be effected by many combinations of these variables. The apparent variables can be grouped under three main headings:

A. Circuit Characteristics

- (1) Voltage
- (2) Capacitance
- (3) Switching device
- (4) Inductance
- (5) Resistance
- (6) Wire material
- (7) Wire length
- (8) Wire diameter

B. Explosive

- (9) Material
- (10) Density
- (11) Crystal form
- (12) Crystal size and size distribution

C. Environment

- (13) Wire placement
- (14) Volume of explosive cavity
- (15) Geometry of explosive cavity
- (16) Density of confinement
- (17) Thickness of confinement

* See Appendix B

- (18) Ambient gas
- (19) Ambient pressure

In order to drop the number of variables to a reasonable working level in the exploratory stages of this investigation, the following conditions were fixed. The environment was that of a test fixture (described later) which permitted camera observation of the explosive build-up from an exploding wire at atmospheric conditions. This stabilized group C. The first explosive material investigated was PETN, probably the most widely used explosive in EBW devices at this time. A density of 1.0 g/cm^3 and the crystal form and size as shown in Figure 1 was used. The density value and crystal form and size are typical of current usage. These conditions stabilized group B.

Almost all present EBW firing systems use a 1.0 microfarad capacitor charged to 2000 volts. These values were used to start the investigation. This stabilized the two variables which determine the available energy ($\frac{1}{2} CV^2$). The initial switching device was a subminiature cold cathode trigger tube which was later replaced by a triggered spark gap.* Both types have been employed in EBW firing systems. This left five variables in group A. The choice of wire material in an EBW depends on both practical and intrinsic factors. Practical considerations are mechanical strength, ease of attachment, and corrosion resistance. Intrinsic considerations are basic properties of the material such as resistance, coefficient of resistivity, density, specific heat, melting point, boiling point, heat of fusion, and heat of vaporization. Platinum wire was used to start the investigation. This material meets the practical requirements but the importance of the intrinsic properties was not known. Nor is it known how close the intrinsic properties are to optimum. The wire diameter chosen was 1 mil. This size wire was known to explode in nominal lengths (50 mils) with the energy available. The circuit resistance exclusive of the bridgewire was that resistance inherent in the firing circuit. The two remaining variables—circuit inductance and wire length were the subjects investigated. They are reported herein. The effects of varying the circuit resistance and wire diameter will be described in future reports.

ELECTRICAL CIRCUITRY

An EBW circuit is essentially a series RLC circuit. See Figure 2. A brief analysis of this type of circuit is given in Appendix A. The actual test circuit used for the majority

*See Appendix B

of the work is shown in Figure 3. Circuit dimensions were kept small to minimize circuit resistance and inductance. However, a transmission line was necessary for firing. Twenty inches of RG-58/U coaxial cable were used as the transmission line from the firing unit to the current and voltage probes in the firing chamber. An additional eight inches of RG-58/U coaxial cable were used to make the connection from the probes to the explosive test fixture. This length was as short as possible to minimize measurement errors but long enough to permit photographic alignment of the test fixture. A brass plate was placed between the probes and explosive test fixture to protect the probes and electrical connections from fragments. The equipment and methods used for measurement of the circuit parameters are given in Appendix B.

WIRE PHENOMENA

Because of the many varied experimental conditions and firing circuits reported in the literature it was difficult to relate reported observations to circuitry that might be employed in ordnance. Therefore, a limited number of exploratory tests were made with the wire alone. It was expected that these would later help in interpreting the interaction with the explosive. The wire reaction can apparently be divided into three main classes:

- A. Wire Remains Intact - In this case the available energy is sufficient only to heat the wire. If the resistance of the wire is sufficiently low compared to the inductance a normal current pulse is observed, while the voltage trace is primarily inductive because of the large $L di/dt$. See Figure 4a. If the wire resistance is sufficiently high compared to the inductance, the current and voltage wave forms are almost in phase. The iR drop across the wire is high enough to mask the inductive voltage. See Figure 4b.
- B. Wire Melts - In this case the energy supplied to the wire is insufficient to completely vaporize it. Wire reaction ranges from a simple break where a small section of the wire fuses away, to a pseudoexplosion⁽⁶⁾ where the wire is converted into macroscopic molten droplets which are ejected with some force. Typical traces show a sharp suppression of the

⁶/Chace, W. G. and Levine, M. A., "Classification of Wire Explosions", Journal of Applied Physics, 31, No. 7, 1960.

current waveform when the wire opens. The voltage remaining across the wire decreases slowly after the wire opens due to current leakage across the voltage divider shunt in parallel with the wire. See Figure 4c.

C. Wire Explodes - The energy supplied to the wire is sufficient to completely vaporize the wire. A highly ionized vapor (plasma) is formed and is usually accompanied by a shock wave due to sudden expansion of the wire. There is an initial current pulse during which the wire explodes, a current dwell which depends upon the circuit parameters, and a restrike current which discharges the capacitor. See Figure 4d.

One of the more interesting features of a wire explosion is the current dwell. This term is used to describe the period of low current flow that occurs between the time of wire burst and before the second current surge commences. If the other circuit parameters are held constant the duration of the current dwell is a function of the length of the wire, providing enough voltage remains across the wire to cause a current restrike. By varying the length of the wire, the duration of the current dwell can be varied. See Figure 5. Platinum wire gives a peculiar hump in the current trace after the first current surge which is not typical of most other metallic materials. Where there is a definite current dwell, two shock waves are emitted. One shock is formed when the wire first expands and the second when the post dwell restrike occurs. The second shock is usually asymmetrical as the restrike does not originate on the axis of the plasma but near the periphery of the expanding plasma. The exploratory shots also showed that the variability of the dwell duration increases with the length of the dwell period.

TEST ARRANGEMENT

The test fixture which provides the environment for the PETN is shown in Figure 6. The fixture was made by drilling two 0."050 holes in a transparent plastic* plate at the desired distance and force fitting two 0."052 diameter brass contact pins in the holes. A 0."001 diameter platinum bridgewire was then soldered across the contact pins flush with the surface of the plastic plate. The platinum wire was obtained commercially, and was labeled 0."001 dia., reference grade, hard, bar 267. A 60/40 lead/tin solder and stainless steel flux were used.

* Acrylate and methacrylate resin

After soldering, the mounted wire was cleaned with denatured alcohol and then immediately washed in a weak detergent solution using an ultrasonic cleaner. A final swirl in tap water was given to remove any traces of detergent. After drying, a steel ring was glued to the plastic plate. The midpoint of the bridge-wire was located in the center of the ring. The PETN was loaded into the ring at a density of 1.0 g/cm^3 . The fixture was completed by gluing a solid plastic plate on top of the ring to contain the explosive.

The loaded fixture was mounted in a firing chamber. The transparent plastic backing was arranged to permit camera observation of the bridgewire between the two contact pins. The slit of a rotating mirror smear camera was aligned perpendicularly to the bridgewire between the contact pins as shown in Figure 7. The smear camera record would thus show the growth to explosion along the surface of the test explosive in contact with the plastic square. The 0."500 I.D. of the ring permitted the build-up to be observed for 0."250 (6.3 mm) on each side of the bridgewire giving a symmetrical pattern as shown in Figure 7.

The effect that circuit inductance has on the initiation of PETN at various wire lengths was determined. Five wire lengths were used - 0."400, 0."200, 0."100, 0."050, and 0."025 giving a 16:1 ratio from the longest to the shortest. Precise measurements of the wire diameter and length were not made and figures given are nominal values. Test shots were first made with the basic circuit previously described. The inductance and resistance of the basic circuit represent fairly closely the minimum values that can be obtained with a firing circuit of practical dimensions. Additional inductance was added to the basic circuit to determine the effect upon the initiation of PETN.

For each shot, oscillograms of the voltage and current waveforms were obtained of the exploding wire. Concurrently, a smear camera record was obtained of the initiation of the PETN. Correlation of the voltage and current waveforms with the smear camera record was obtained by assuming that the initial flash of light from the wire corresponds to the inductive spike on the voltage trace and the downward dip in the current trace. Oscillograms of wire explosions with definite dwells can be aligned chronologically with the smear camera records bearing out the validity of the assumption.

EXPERIMENTAL RESULTS

The first test series was run with the basic circuit:

C = 1.04 microfarads
 L = 0.77 microhenry
 R = 0.60 ohm
 $V_0 = 2000 \text{ volts}$

A KP-130 cold cathode electron tube was employed as the switching device. The bridge resistances for the five wire lengths are given in Table 1. The experimental values tend to be about 0.15 ohm above the calculated values and can be attributed to the additional contact resistance encountered in making the resistance measurement. The circuit is underdamped with the 0."025, 0."050, and 0."100 long wires and is overdamped with the 0."0200 and 0."400 long wires. Results of the first test series are given in Table 2. With wires 0."100 and longer, a definite current dwell occurred. Figure 8 depicts the results with the 0."400 long wire. It is interpreted as follows:

A. The wire bursts at 0.2 microsecond as evidenced by the inductive spike on the voltage trace and the downward trend in the current trace. At this time the PETN appears to be weakly ignited. There is very little propagation during the ensuing current dwell.

B. 3.8 microseconds later the second current surge occurs. A definite impetus is given to the propagation as evidenced by the accelerated burning. The burning, however, failed to develop into detonation.

Wires of 0."200 and 0."100 length gave similar results, varying only in the length of the current dwell. The PETN went into detonation with wires 0."050 and 0."025 long. Figure 9 depicts the results with the 0."050 long wire. It is interpreted as follows:

A. The wire bursts at 0.23 microseconds as evidenced by the inductive spike on the voltage trace and the downward trend on the current trace. Deflagration of the PETN starts with the wire explosion and a detonation wave develops about 1.3 mm from the bridge-wire. Figure 10 shows that the detonation wave accelerates but does not reach a steady velocity over the observed distance of 6.3 mm. Reflected shock waves from the steel containing ring of the test fixture are apparent. They travel inward at a constant velocity until they meet and apparently reflect again.

B. The dwell is suppressed, appearing as a perturbation on the rising half-wave current pulse which is extinguished at approximately the time the detonation wave meets the steel containing ring.

When detonation occurs the test fixture is shattered into very small pieces. With the 0."400 long wire the plastic test fixture only burst scattering the PETN. The other test fixtures

remained intact with voids burned into the PETN.

A second test series was conducted with the circuit inductance increased to 5.61 microhenrys by the addition of an inductance coil with negligible resistance. This circuit before insertion of the platinum bridgewires has a $2\sqrt{\frac{L}{C}}$ value of 4.64 ohms and remains underdamped initially with all five wire lengths. Test results from this series are given in Table 3. With this circuit, the 0."400 long wire gave a definitely weaker initiation than with the basic circuit. Figure 11 depicts the results with the 0."400 long wire and is interpreted as follows:

A. The wire breaks in 1.0 microsecond as indicated by the inductive voltage spike and current shut off. No restrike occurs. Oscillograms taken with a slower sweep speed also failed to show a restrike. Based on previous results with the bridgewire alone, this type of oscillogram indicates only a melting of the wire.

B. A relatively slow propagation results. The PETN burns at an average speed of 70 meters/sec for the first 20 microseconds. The slow propagation eventually burns out leaving a void in the PETN about the bridgewire.

The 0."200 wire gave similar results. A more vigorous burning results with the 0."100 wire. Figure 12 depicts the results with the 0."100 long wire and is interpreted as follows:

A. The wire breaks in 0.5 microsecond as indicated by the inductive voltage spike and dip in the current. The dwell which was very definite in the basic circuit with this length wire is now restrained by the higher circuit inductance.

B. A vigorous burning of the PETN results, but the burning velocity gradually decreases and burning dies out leaving a void in the vicinity of the bridgewire.

Detonation developed with the 0."050 long wire, while the 0."025 wire did not effect detonation indicating the existence of an optimum wire length with the circuit parameters used. The change in such parameters as peak current, peak power, peak voltage, energy/volume, energy/surface etc. occurring across the optimum would be significant to an analysis of the cause for the optimum. However, the poor quality of the early portions of the oscillograms made calculations of these quantities impossible.

A third test series was conducted with the circuit inductance increased to 13.7 microhenrys by the addition of a larger inductance coil of negligible resistance. This circuit before insertion of the bridgewires had a $2\sqrt{\frac{L}{C}}$ value of 7.26 ohms

making the circuit highly underdamped for the shorter length bridgewires. The results for this series are given in Table 4. No detonations were observed with a circuit inductance of 13.7 microhenrys. Oscillograms of the 0."400, 0."200, and 0."100 wire lengths indicated that the wires broke into macroscopic particles and all gave weak initiations similar to the smear camera record shown in Figure 11. The KP-130 tube used as the circuit switch is normally unidirectional. However, with 13.7 microhenrys in the circuit, the circuit is so underdamped that with the shorter wires it does not extinguish and becomes bidirectional similar to a spark gap. Figure 13 depicts the results with the 0."050 wire. It is interpreted as follows:

A. The wire breaks in 1.3 microseconds as indicated by the inductive voltage spike and the perturbation in the current trace. Deflagration of the PETN appears to start in three places in the plane of observation. The burning accelerates rapidly for approximately 10 microseconds, then gradually burns out leaving a large void in the PETN.

B. The light maxima in the smear camera record can be correlated with the current maxima in the oscillogram. The current maxima occurring after the wire explosion appear to have little effect on the burning. The second and third current pulses give no acceleration to the burning. The top oscillogram was taken concurrently with the smear camera record. The lower oscillogram was taken under the same experimental conditions to provide more detail in the initial part of the current and voltage traces.

DISCUSSION

Inductance can be defined as that characteristic of an electric circuit that prevents sudden increases or decreases in current. As the circuit inductance is increased the initial rate of rise of current $\left(\frac{di}{dt}\right)_{t \rightarrow 0}$ in the discharge pulse is

lowered which in turn decreases the rate of energy input. Each increase in inductance also limits the $i_{\max}$ that can be achieved in a circuit as more of the energy will be stored in the

magnetic field of the circuit ($\frac{1}{2} Li^2$) prolonging the duration of the discharge. Figure 14 shows current waveforms obtained with circuits having parameters very similar to the ones employed in this investigation except that a spark gap tube is used as the switching device. The low inductance circuit shuts off after two cycles while the circuits with higher inductance ring for a longer period.

At the outset of the investigation it was not known whether circuit inductance should be minimized or whether there might be an optimum value of inductance for the circuit. It can be assumed a priori that too much inductance would be detrimental as some minimum power is necessary for explosion of the wire. The results show that when the wire explodes on the initial slope of the current pulse, increasing the inductance over a small inherent value is harmful. It results in a lower power and energy input into the wire and also lowers the probability of detonation.

The critical process in the build-up to detonation of PETN is the transition from deflagration to detonation. In all the tests some deflagration of the PETN was observed (i.e. initiation always occurred). A comparison was made of the power and energy delivered the 0.050 length platinum wire using the low inductance basic circuit and the circuit containing 13.7 microhenrys. The former circuit gave detonations while the latter caused deflagrations only. For the computations, the observed current is assumed to be correct and the observed voltage is corrected for the inductive component by subtracting out the inductive voltage $L \frac{di}{dt}$ in the measuring circuit. The remaining

voltage should closely represent the iR drop across the wire. Instantaneous power was calculated by multiplying the observed current and corrected voltage. The energy was obtained by graphical integration of the power-time plot. The error of the calculated power and energy is believed to be less than $\pm 20\%$.

Figure 15 shows the current, voltage (iR), power, and energy plots for the low inductance circuit. The inductive voltage spike signifying the start of the wire explosion appeared in 0.23 microsecond. At that time approximately 42 millijoules of energy had been deposited in the wire.* The peak power was 1460 kilowatts. The peak voltage occurs at the time of peak power (0.26 microsecond) at which time approximately 65 millijoules had been delivered to the wire. The power then rapidly dropped as did the voltage. The current which dropped sharply during the wire explosion increased as the low resistance

*45.3 millijoules required for complete vaporization of wire

restrike arc formed. The restrike permitted the power to increase again. At 1.2 microseconds, the time at which the detonation wave in PETN is observed, roughly 480 millijoules of energy had been delivered.

Figure 16 shows the current, voltage (iR), power, and energy plots of the wire in the high inductance circuit. The inductive voltage spike signifying the start of the wire explosion appeared in 1.0 microsecond at which time approximately 27 millijoules of energy had been deposited in the wire. A peak power of 310 kilowatts occurred concurrently with the peak voltage at 1.22 microseconds. At that time 49 millijoules of energy had been deposited in the wire. The current showed only a slight perturbation during the wire explosion due to the high circuit inductance. The power dropped off rapidly after the wire explosion and at 1 microsecond after the peak voltage roughly 140 millijoules of energy had been delivered.

It is apparent that a minimum power level and a minimum energy value are necessary for a wire to explode. These minima are met by both the low inductance circuit and the high inductance circuit for the 0.050 inch long wire. The relative importance of the power as opposed to the energy on the transition to detonation cannot be determined at this time as both the power and the energy are larger in the low inductance circuit. See Table 5. The relative significance of events up to the time of wire explosion only, as opposed to those up to the time of detonation, about one microsecond later, is not known either. In the comparisons of Table 5, the low inductance circuit had higher values for these quantities. Extensive analysis of other current and voltage waveforms was not made at this time because of the large amount of "noise" on the oscillograms.

When the length of the wire is changed, the resistance and mass are also changed, thus three variables are changed at once. Since the experimental results show that restrike currents occurring after a long dwell have little effect on producing detonation, the wire length should be chosen to eliminate the dwell. Exploratory shots with the wire alone also indicated that long dwells should be avoided because of the asymmetrical output of the second pulse and the variability of the dwell duration. With a 1 microfarad capacitor charged to 2000 volts, wire lengths very close to those presently used in electro-explosive devices appear to be optimum. Increasing circuit inductance tends to eliminate the dwell period, but since it also lowers the probability of detonation there appears to be no advantage in employing this principle to make use of a longer bridgewire. The weaker initiations from the longer wires appear to occur because of the weaker explosions of these wires. The stored capacitor energy is sufficient to supply about six times

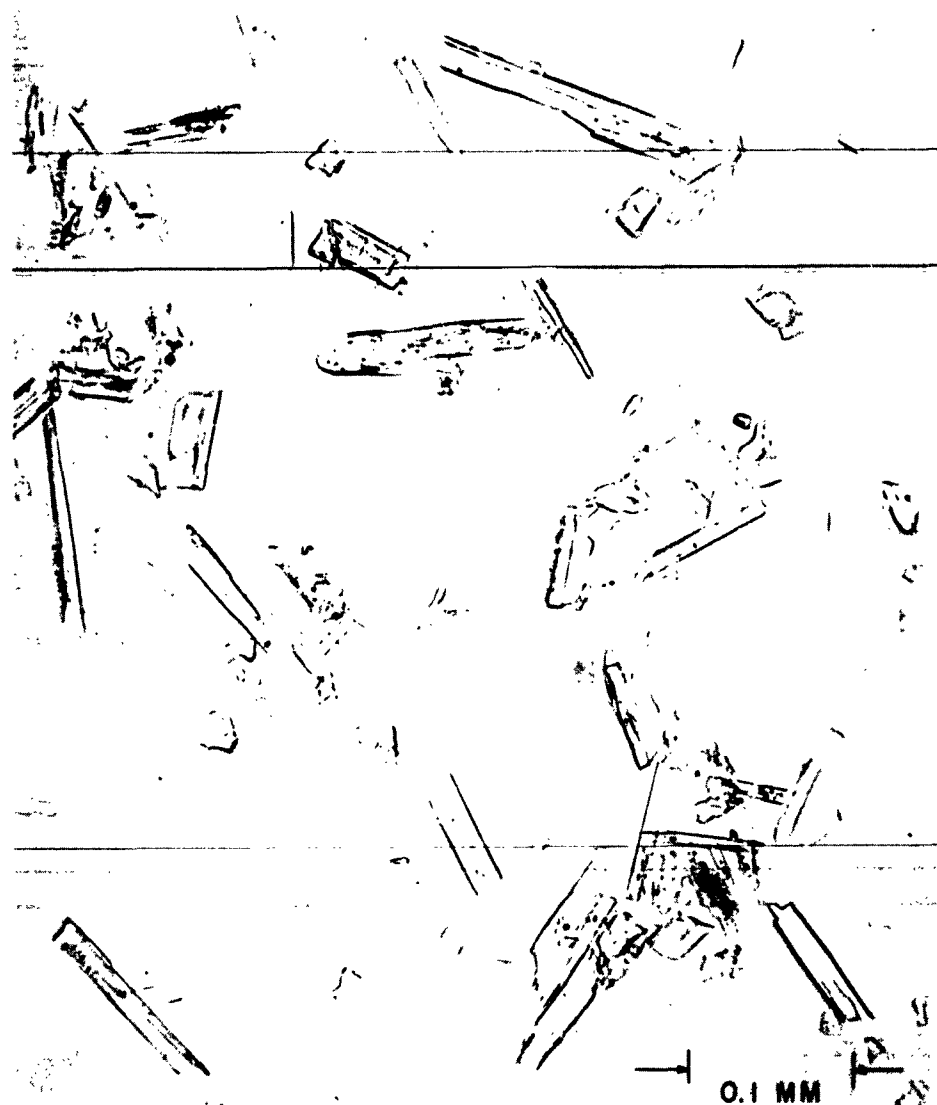
*See Appendix B

the energy necessary to completely vaporize the longest wire used (0.400 inch) making the mass effect relatively minor.

CONCLUSIONS

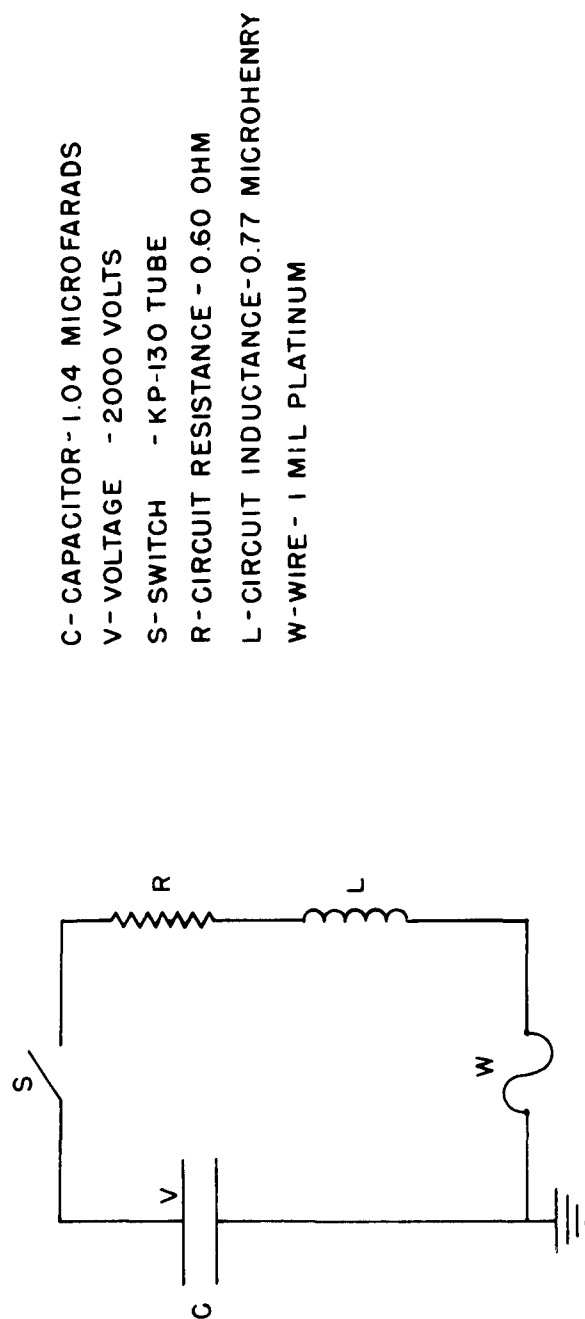
Since our initial experiments cover only a limited range, the following conclusions are drawn subject to the experimental circuit conditions described herein:

- A. PETN can be initiated by very weak exploding (pseudoexploding) wires as well as fast exploding wires.
- B. The build-up to detonation in PETN after initiation is a critical process.
- C. A complete description of the interaction between the wire and the PETN must account for the transition of deflagration to detonation.
- D. Increasing circuit inductance lowers the power and energy input to the exploding wire.
- E. Increasing circuit inductance lowers the probability of producing detonation in PETN by an exploding wire.
- F. Secondary current pulses have little effect on whether or not detonation is produced.
- G. The bridgewire length should be chosen to eliminate current dwell.



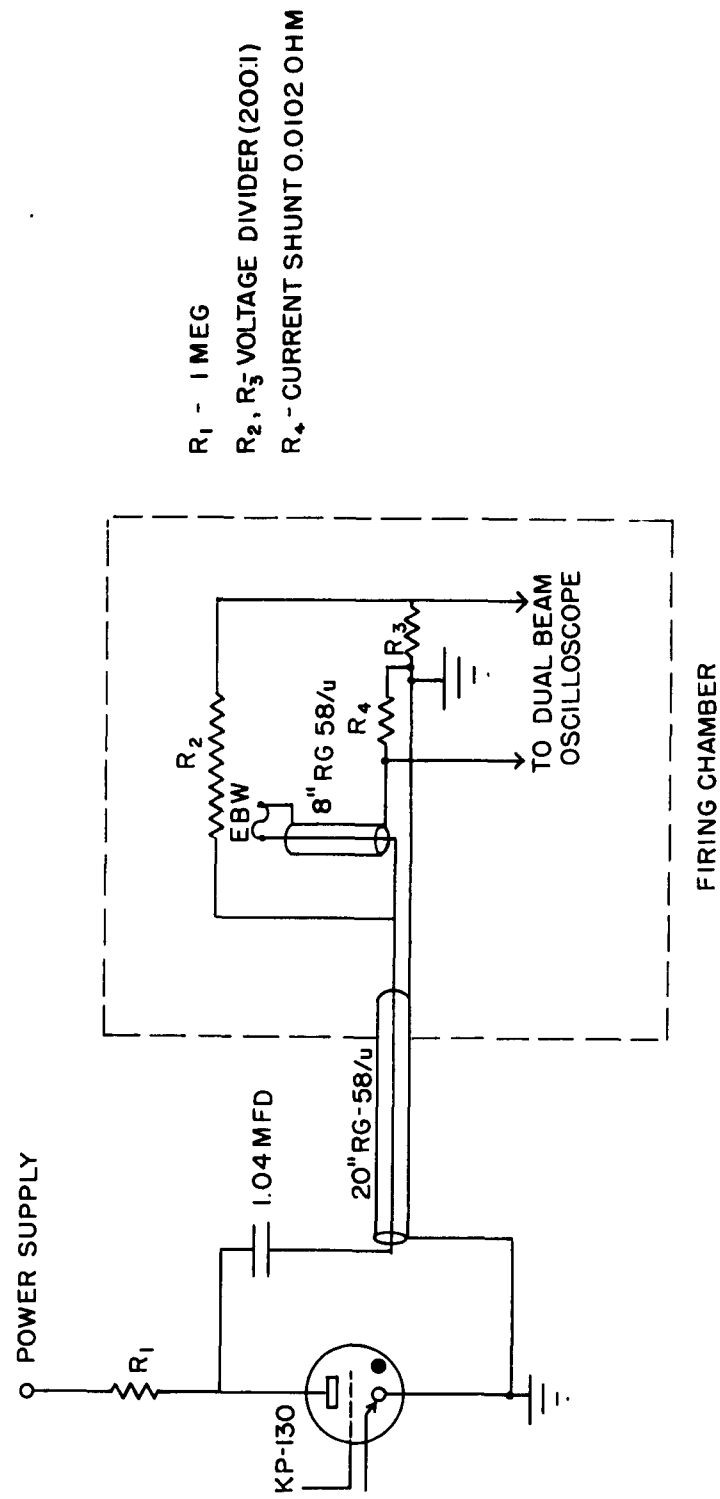
PETN - OMS CODE 5530.21. 557G FROM PICATINNY ARSENAL

FIG. 1 PHOTOMICROGRAPH OF PETN



C - CAPACITOR - 1.04 MICROFARADS
V - VOLTAGE - 2000 VOLTS
S - SWITCH - KP-130 TUBE
R - CIRCUIT RESISTANCE - 0.60 OHM
L - CIRCUIT INDUCTANCE - 0.77 MICROHENRY
W - WIRE - 1 MIL PLATINUM

FIG. 2 EXPLODING BRIDGEWIRE CIRCUIT



R_1 - 1 MEG

R_2, R_5 - VOLTAGE DIVIDER (200:1)

R_4 - CURRENT SHUNT 0.0102 OHM

FIG. 3 TEST CIRCUIT

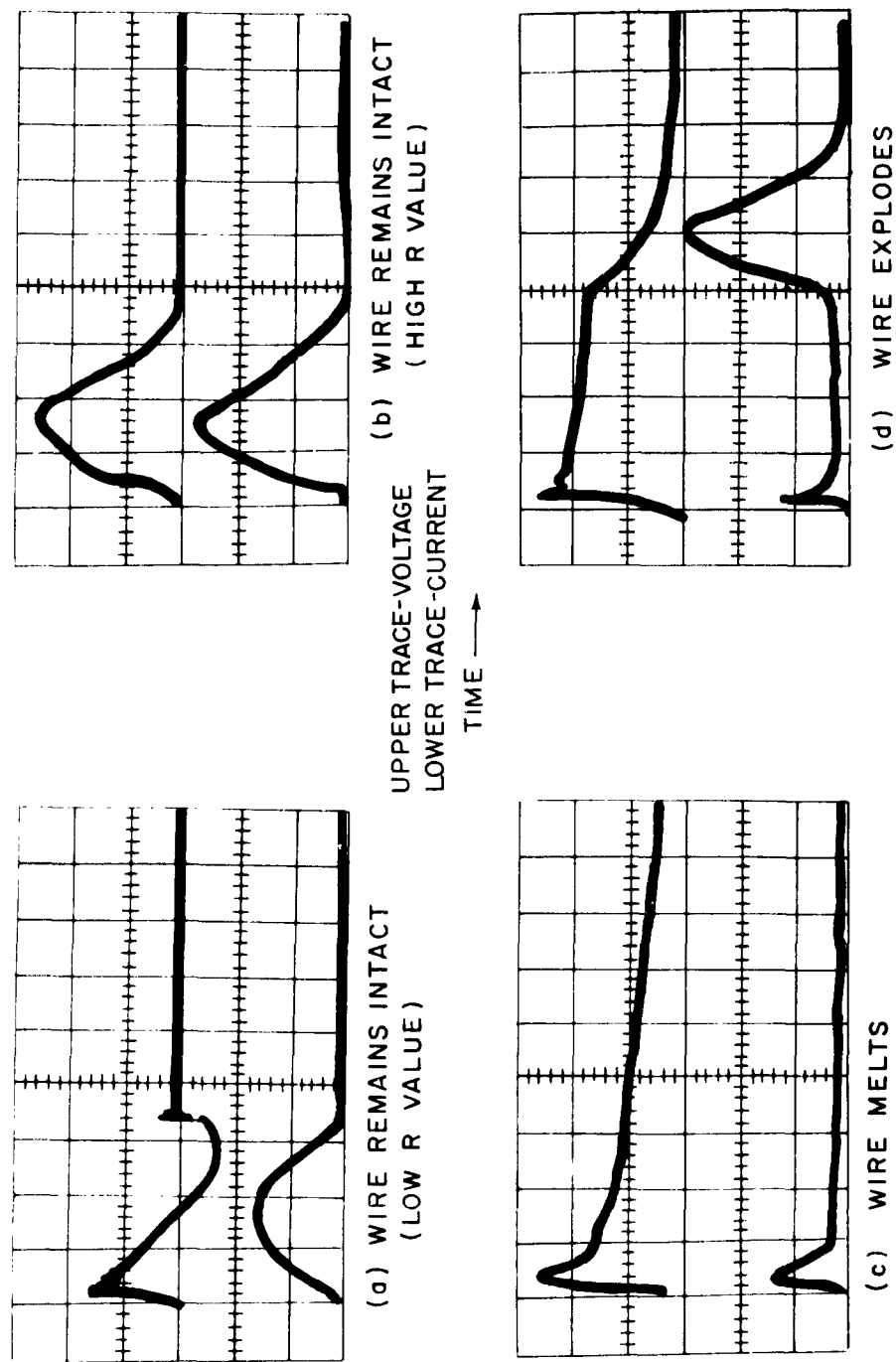


FIG. 4 CURRENT AND VOLTAGE WAVEFORMS
FOR BARE WIRES

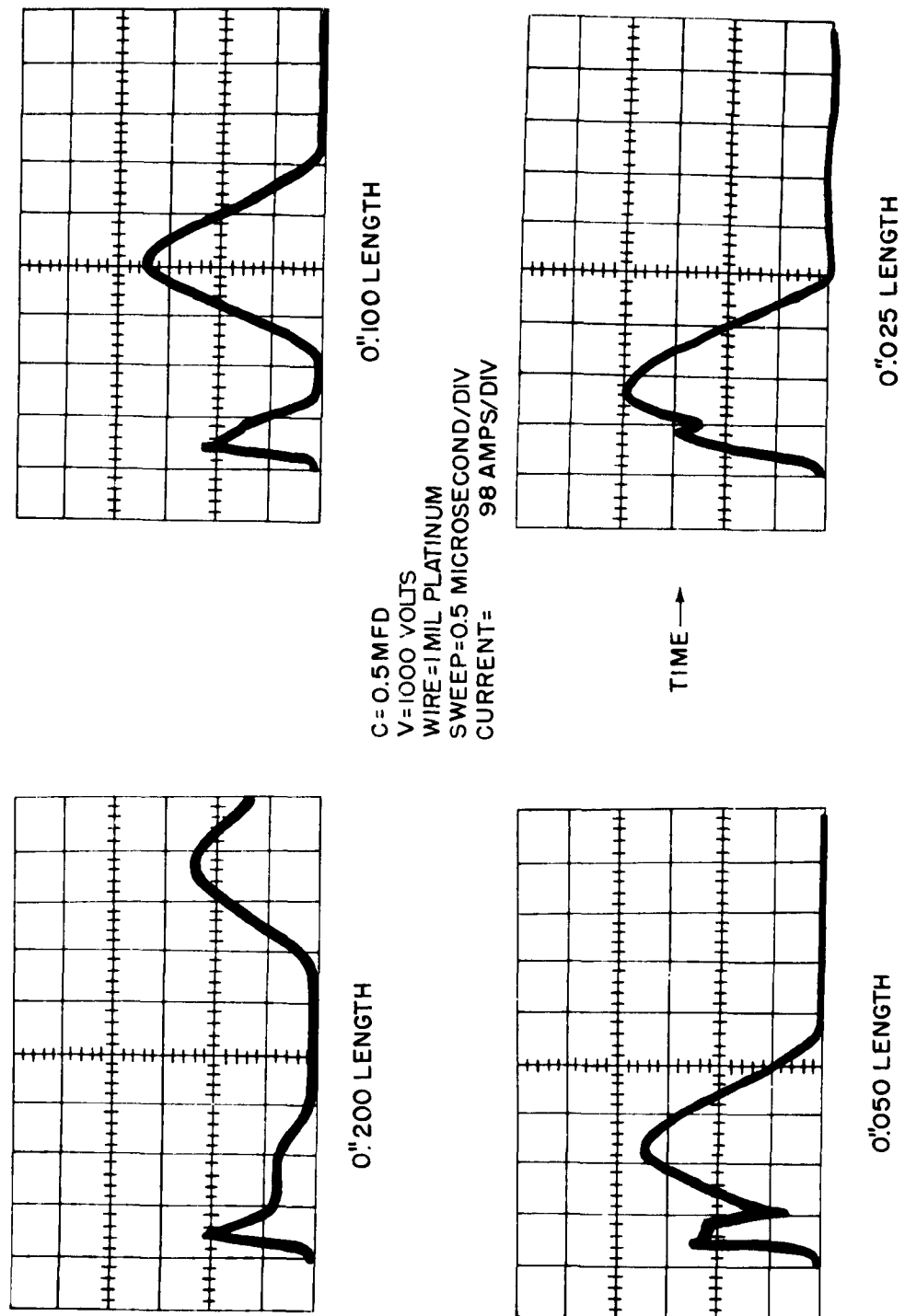


FIG. 5 EFFECT OF BRIDGEWIRE LENGTH ON CURRENT DWELL

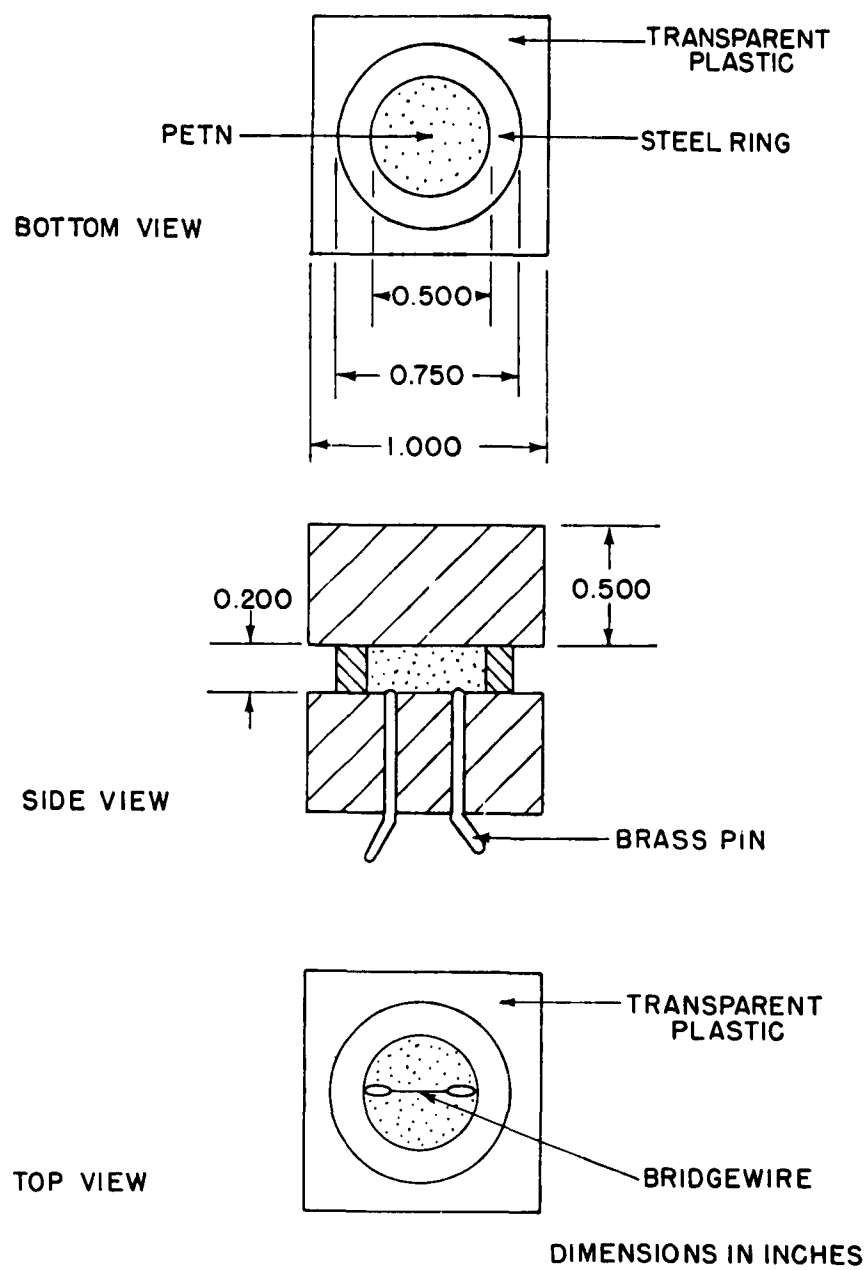


FIG. 6 TEST FIXTURE

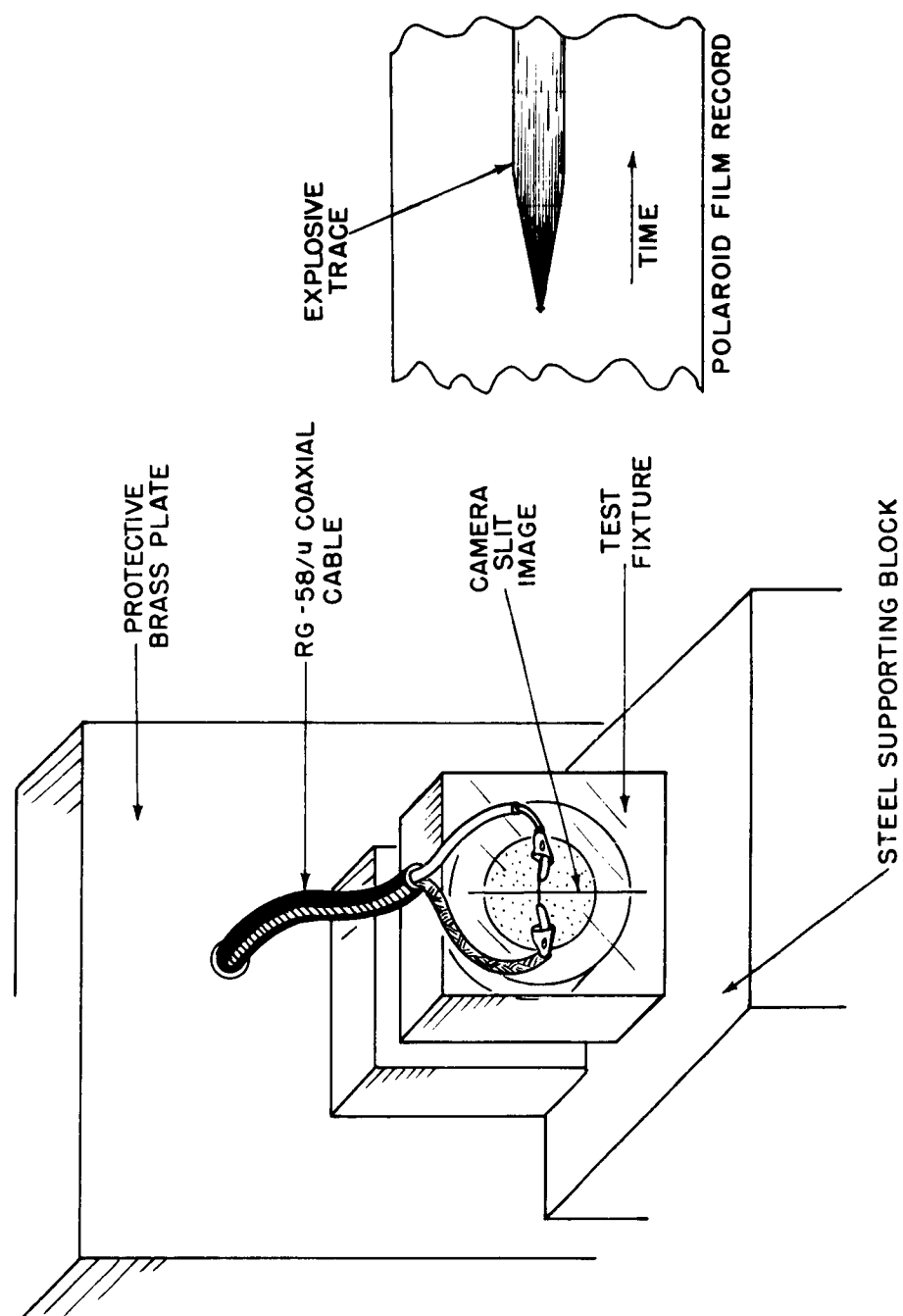


FIG. 7 EXPERIMENTAL ARRANGEMENT AND TYPE OF SMEAR CAMERA RECORD

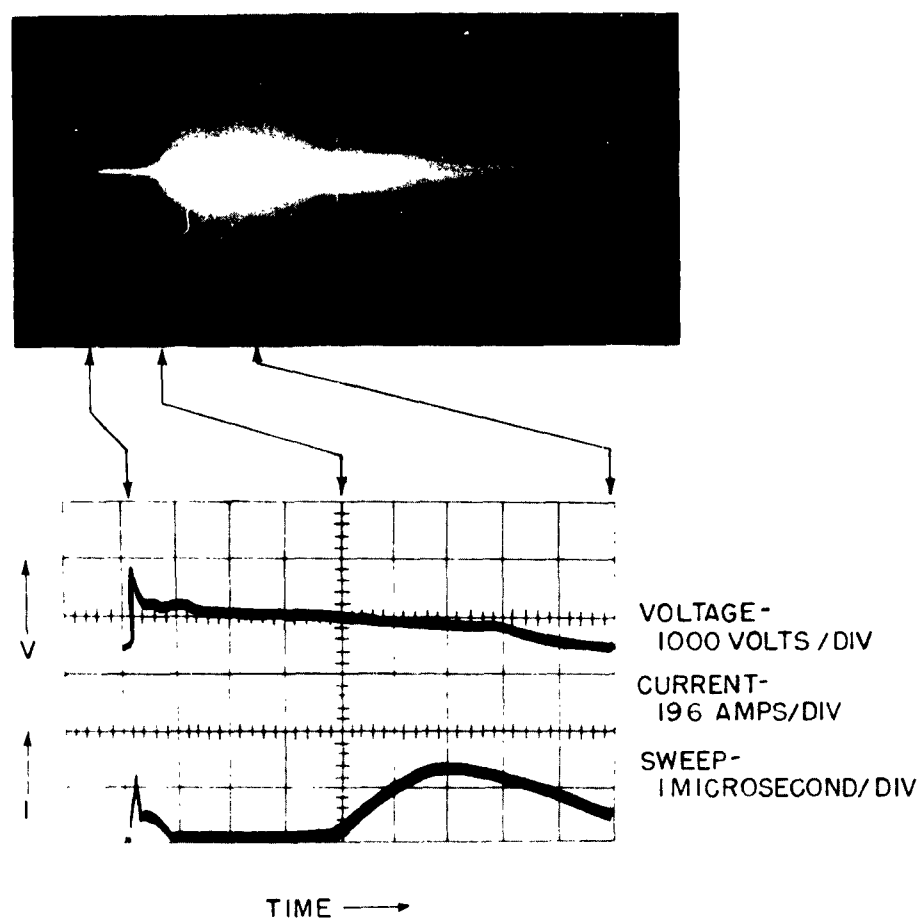


FIG. 8 TEST SHOT NO.1 - 0.400 LENGTH WIRE
IN BASIC CIRCUIT

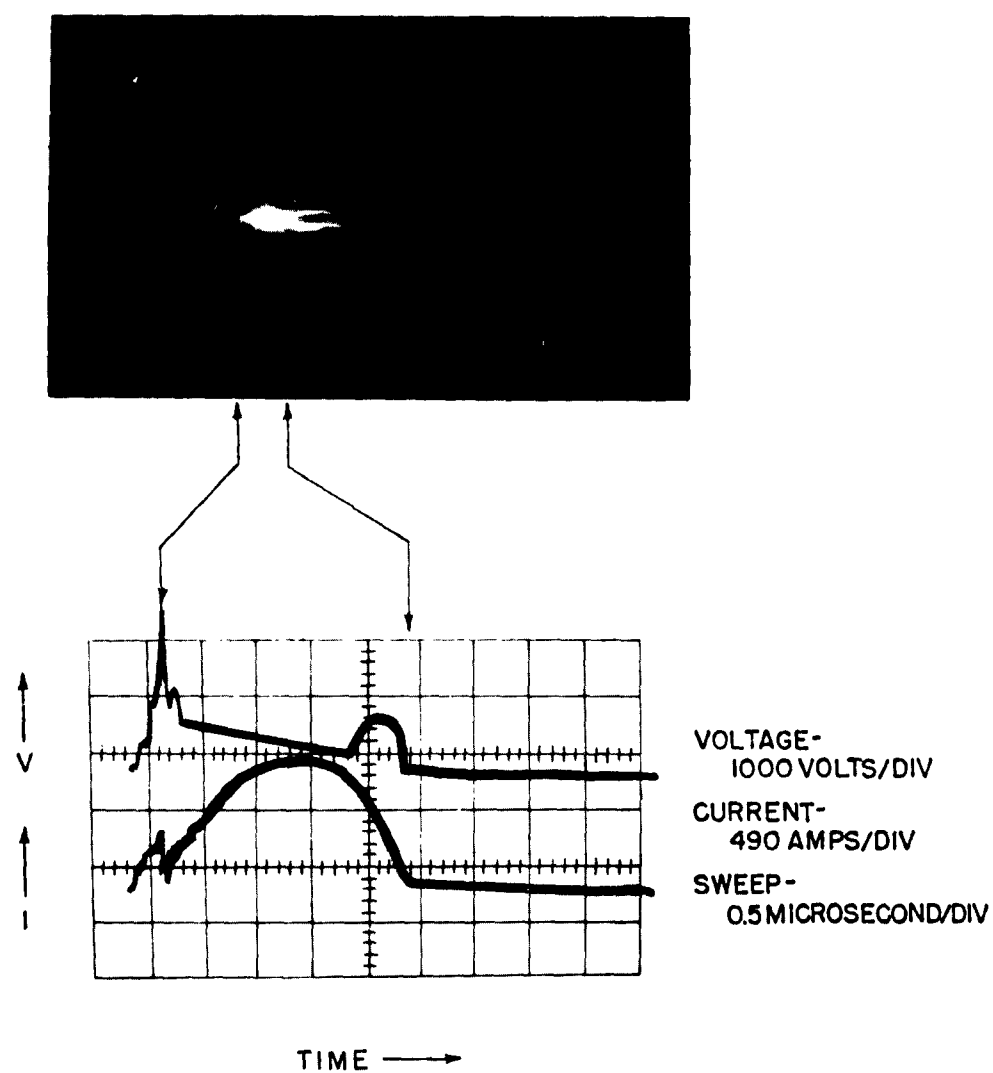
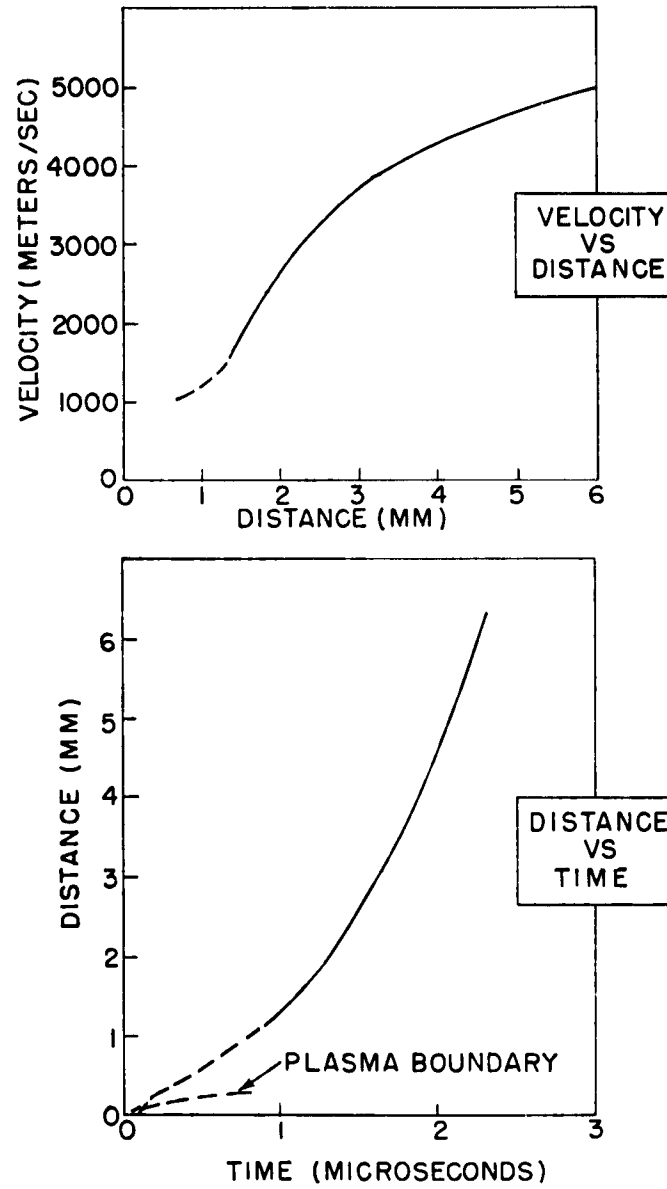


FIG. 9 TEST SHOT NO.5 - 0.050 LENGTH WIRE
IN BASIC CIRCUIT



TEST
SHOT
NO. 5

FIG. 10 GROWTH OF DETONATION IN PETN

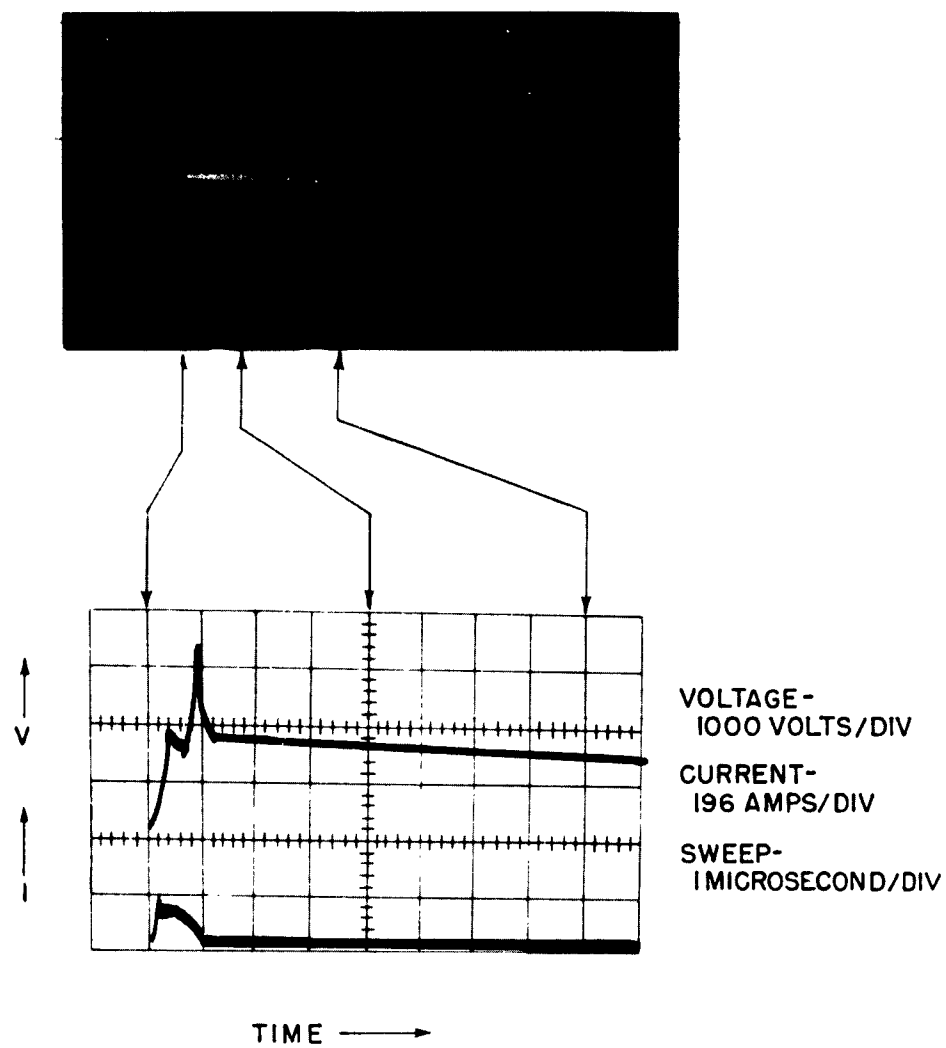


FIG. II TEST SHOT NO.8 - 0.400 LENGTH WIRE WITH 4.84 MICROHENRYS
ADDED TO BASIC CIRCUIT

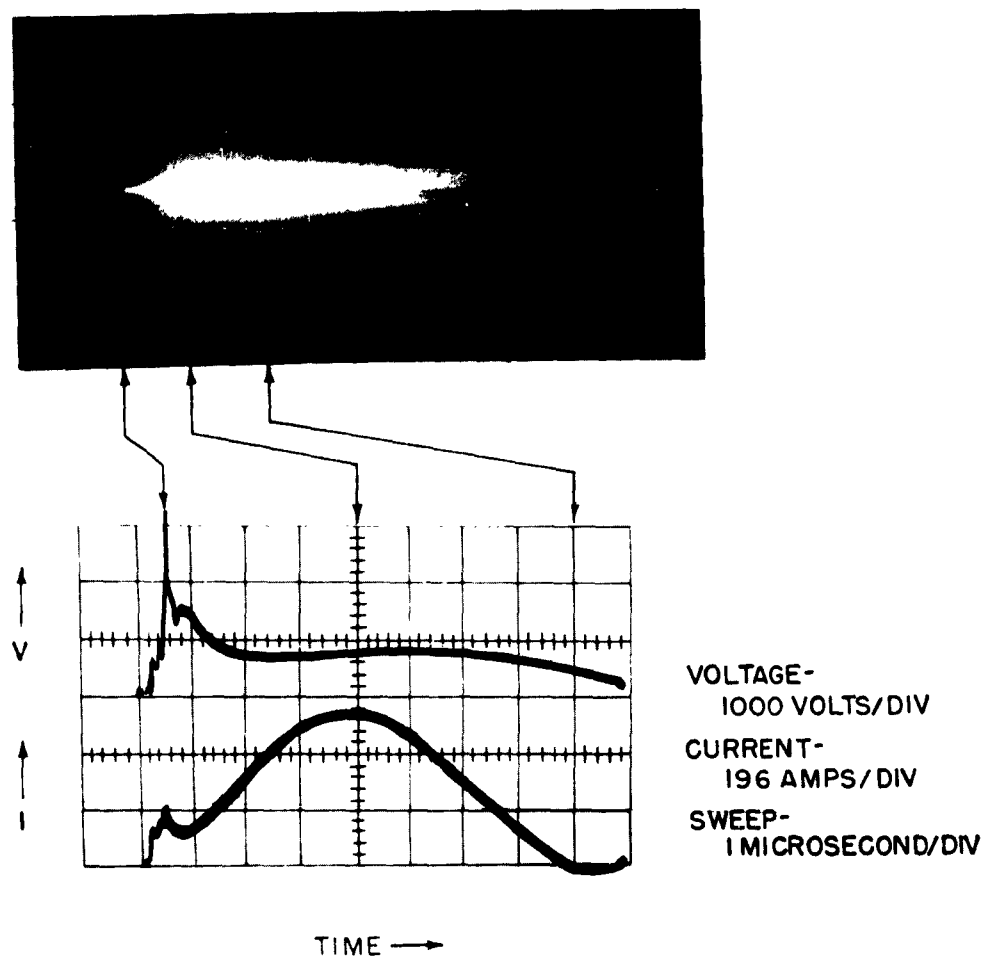


FIG. 12 TEST SHOT NO. 10 - 0.100 LENGTH WIRE WITH 4.84 MICROHENRYS
ADDED TO BASIC CIRCUIT

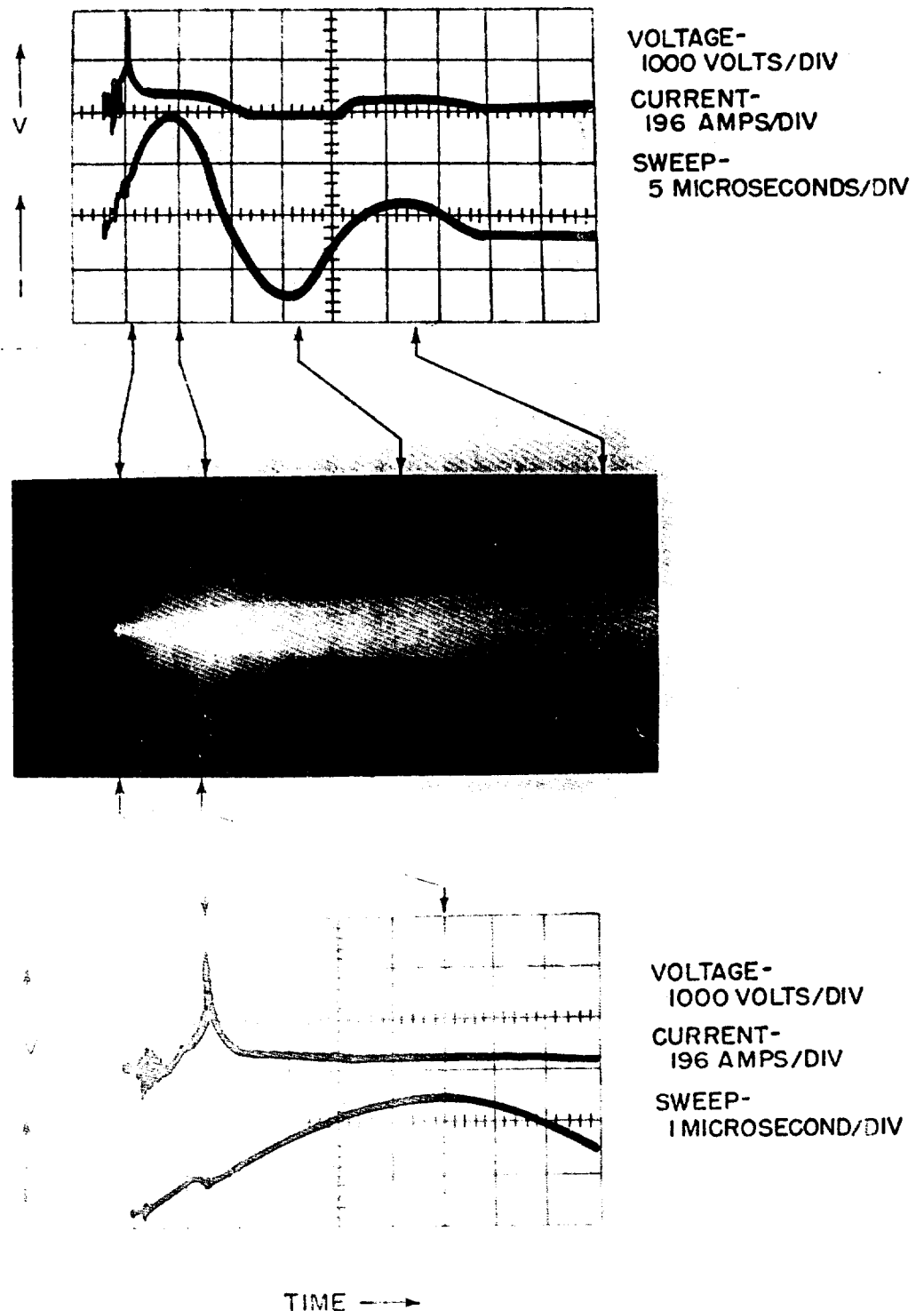


FIG. 13 TEST SHOT NO. 21 - 0.050 LENGTH WIRE WITH 12.9 MICROHENRYS
ADDED TO BASIC CIRCUIT

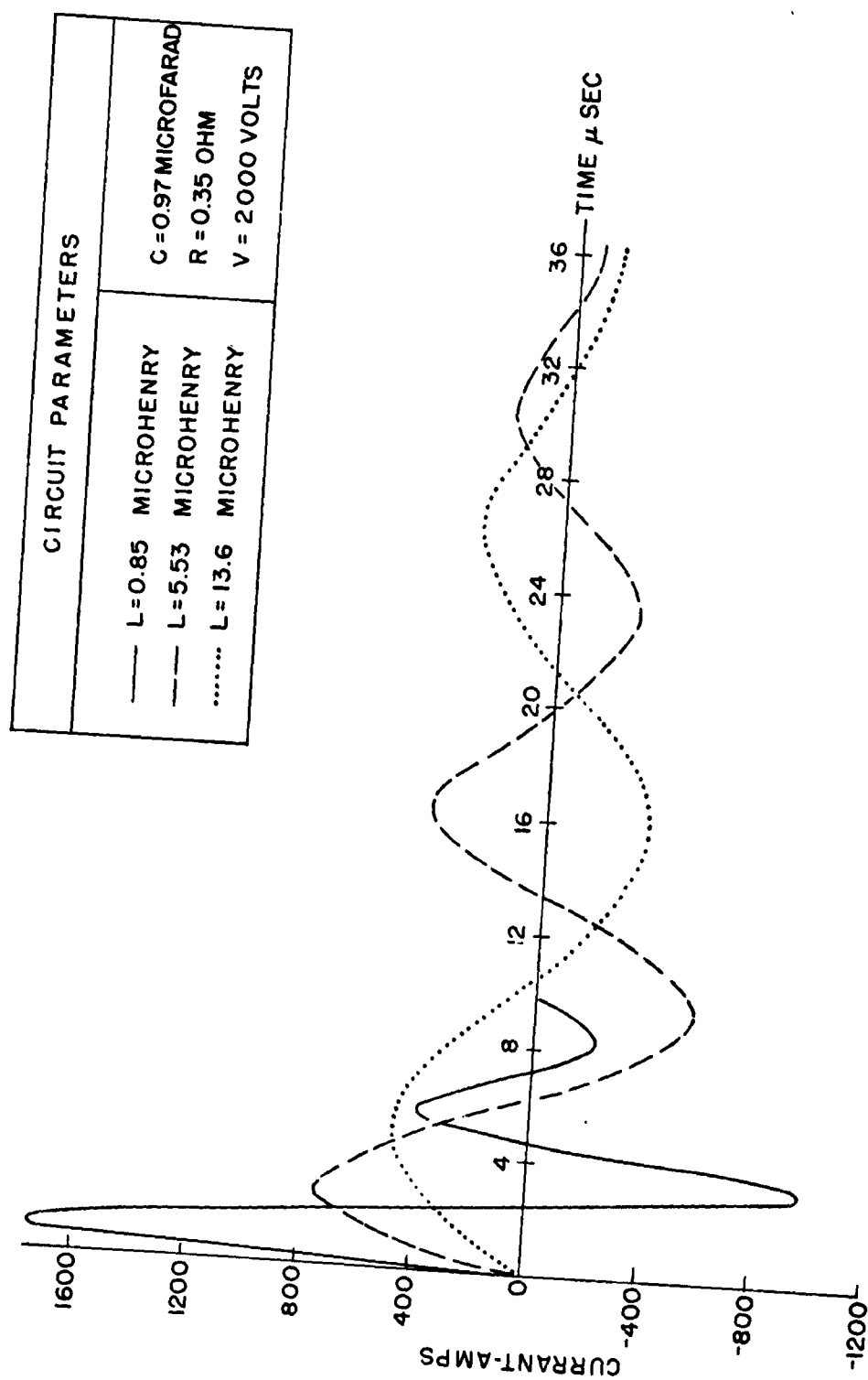


FIG. 14 EFFECT OF CIRCUIT INDUCTANCE ON CURRENT WAVEFORM

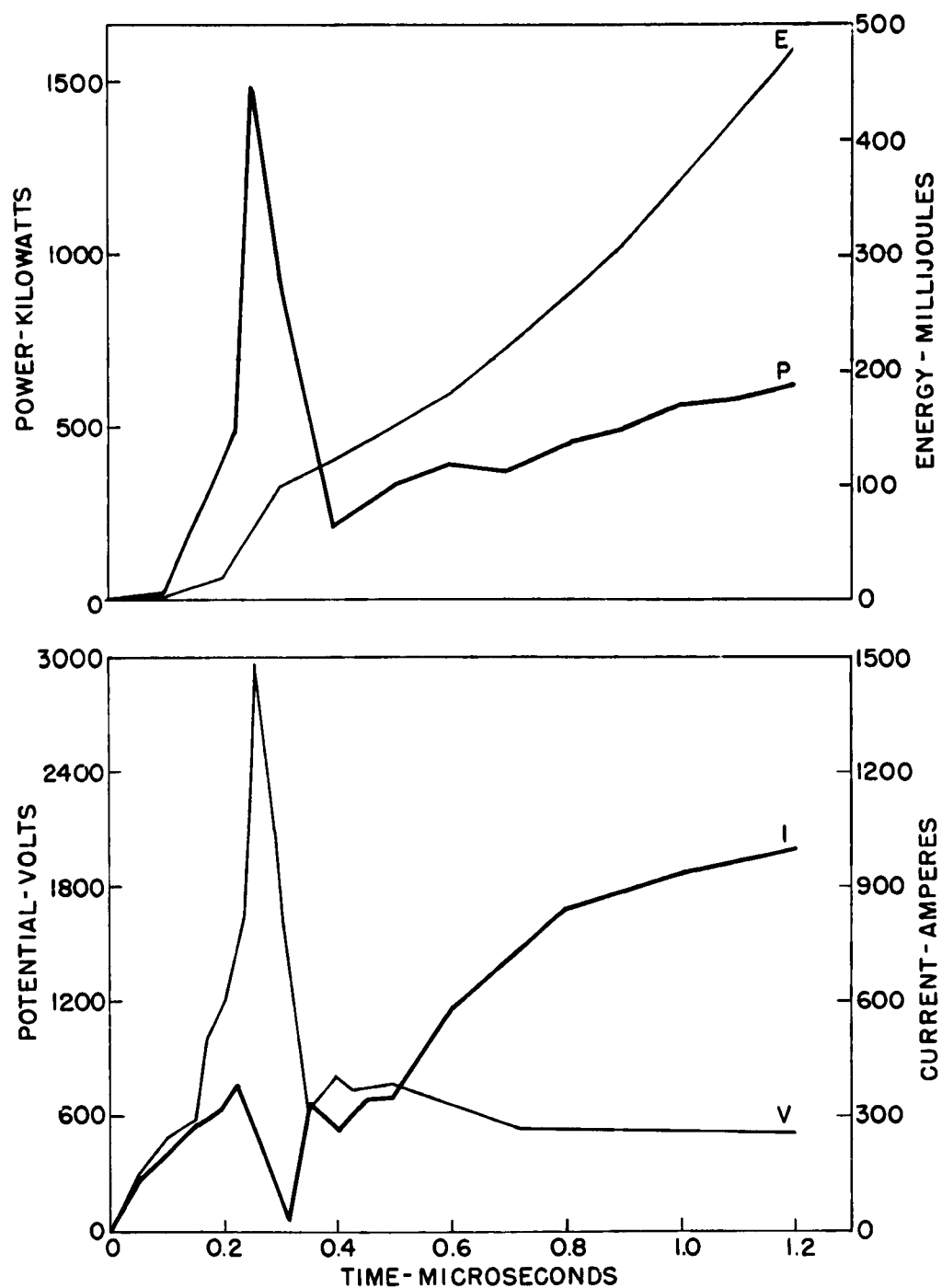


FIG. 15 CURRENT, VOLTAGE, POWER AND ENERGY CURVES FOR TEST SHOT NO.5
- 0.050 LENGTH WIRE IN LOW INDUCTANCE CIRCUIT

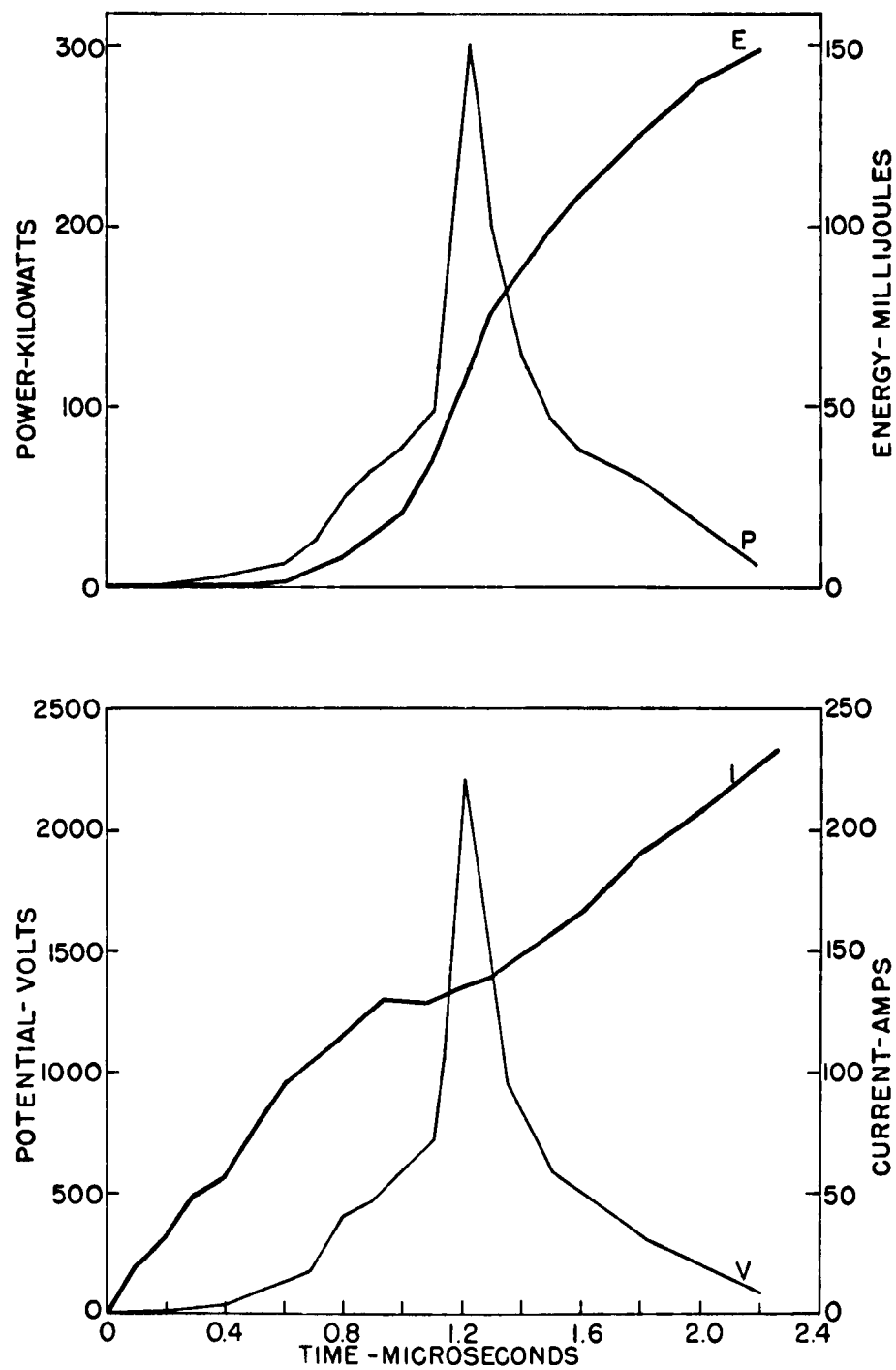


FIG. 16 CURRENT, VOLTAGE, POWER, AND ENERGY CURVES FOR TEST SHOT NO.21
- 0.050 LENGTH WIRE IN HIGH INDUCTANCE CIRCUIT

TABLE 1

Resistance of 0."001 inch Diameter Platinum Wire

Length (inch)	Calculated Resistance (ohms)	Experimental Range (ohms)
0.025	0.125	0.25 - 0.29
0.050	0.250	0.32 - 0.42
0.100	0.500	0.64 - 0.67
0.200	1.00	1.13 - 1.20
0.400	2.01	2.20 - 2.36

TABLE 2

Initiation of PETN with Basic Circuit

Shot No.	Wire Length (inch)	Initial Circuit Condition	Results
1	0.400	Overdamped	PETN initiated, did not grow to detonation
2	0.200	Overdamped	" " "
3	0.100	Underdamped	" " "
4	0.100	Underdamped	" " "
5	0.050	Underdamped	Detonation
6	0.025	Underdamped	"
7	0.025	Underdamped	"

TABLE 3

Initiation of PETN with 4.84 Microhenrys Added to
Basic Circuit

Shot No.	Wire Length (Inch)	Initial Circuit Condition	Results
8	0.400	Underdamped	PETN weakly initiated, did not grow to detonation
9	0.200	Underdamped	" " " " "
10	0.100	Underdamped	PETN initiated, did not grow to detonation
11	0.050	Underdamped	Detonation
12	0.025	Underdamped	PETN initiated, did not grow to detonation
13	0.025	Underdamped	PETN initiated, did not grow to detonation

TABLE 4

Initiation of PETN with 12.9 Microhenrys
Added to the Basic Circuit

Shot No.	Wire Length (inch)	Initial Circuit Condition	Results
14	0.400	Underdamped	PETN weakly initiated, did not grow to detonation
15	0.400	Underdamped	" " " "
16	0.400	Underdamped	" " " "
17	0.200	Underdamped	" " " "
18	0.200	Underdamped	" " " "
19	0.100	Underdamped	" " " "
20	0.100	Underdamped	" " " "
21	0.050	Underdamped	PETN initiated, did not grow to detonation
22	0.050	Underdamped	" " " "
23	0.050	Underdamped	" " " "
24	0.025	Underdamped	" " " "
25	0.025	Underdamped	" " " "

TABLE 5
Comparison of Power and Energy Values

	Energy deposited up to start of wire explosion (millijoules)	Energy deposited up to time of peak voltage (millijoules)	Peak Power (kilowatts)	Energy deposited one microsecond after peak voltage (millijoules)
Low inductance (shot #5)	42	65	1460	480
High inductance (shot #21)	27	49	310	140

33

Calculated wt. of platinum wire (0."001 dia, 0."050 length)
 13.8 micrograms

Total energy necessary to reach M.P.	3.64 millijoules
Total energy necessary to complete melting	5.10 "
Total energy necessary to reach B.P.	10.6 "
Total energy necessary to complete vaporization	45.3 "

APPENDIX A

The series RLC circuit of Figure 2 has for its differential equation

$$L \frac{di}{dt} + Ri + \frac{q}{C} = 0 \quad (1)$$

where i = current, q = charge, and t = time. Differentiating with respect to t gives

$$L \frac{d^2i}{dt^2} + R \frac{di}{dt} + \frac{i}{C} = 0 \quad (2)$$

The solution to this equation gives the equation for the current

$$i = \frac{E}{bL} e^{-at} \left(\frac{e^{bt} - e^{-bt}}{2} \right) \quad (3)$$

where

$$a = \frac{R}{2L} \quad \text{and} \quad b = \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$$

The equation for the current takes three particular forms depending on whether $R^2 = \frac{4L}{C}$, $R^2 < \frac{4L}{C}$, or $R^2 > \frac{4L}{C}$. These forms correspond to a circuit which is critically damped, underdamped, or overdamped.

CASE I. Critically damped, $R^2 = \frac{4L}{C}$

$$i = \frac{E}{L} t e^{-at} \quad (4)$$

and

$$\frac{di}{dt} = \frac{E}{L} e^{-at} (1 - at) \quad (5)$$

CASE II. Underdamped $R^2 < \frac{4L}{C}$

$$i = \frac{E}{LN} e^{-at} \sin NT$$

and

$$\frac{di}{dt} = \frac{E}{LN} e^{-at} (N \cos NT - a \sin Nt)$$

where

$$N = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} = 2\pi f$$

and

f = frequency of discharge oscillation

CASE III. Overdamped $R^2 > \frac{4L}{C}$

$$i = \frac{E}{bL} e^{-at} \sinh bt \quad (8)$$

and

$$\frac{di}{dt} = \frac{E}{bL} e^{-at} (b \cosh bt - \sinh bt) \quad (9)$$

From the foregoing equations it can be seen that the initial rate of rise of current is governed by E and L , for when $t = 0$

$$\frac{di}{dt} = \frac{E}{L}$$

in all three cases.

APPENDIX B

1. Measurement of Firing Circuit Parameters RLC

The value of the capacitor was measured with a Capacitance Test Bridge-Type 740-B, General Radio Co. To determine the value of R and L, a.c. circuit theory was employed. The solution as shown in Appendix A for the underdamped discharge of a capacitor into a resistance and inductance in series is

$$i = \frac{E}{LN} e^{-at} \sin Nt$$

where

$$N = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad \text{and} \quad a = \frac{R}{2L}$$

when

$$t = 0, \quad \frac{di}{dt} = \frac{E}{L}.$$

An oscillogram was taken of the current waveform with a dead short replacing the bridgewire. Since the circuit is underdamped the first half cycle is a slightly distorted half sine wave. See Figure B1. From oscillographic measurements the value of $\frac{di}{dt}$ when $t \rightarrow 0$ was determined, and since the initial voltage E is

known, L can be calculated from

$$L = \frac{E}{\frac{di}{dt}}$$

From the same oscillogram, $i_{\max}$ and $t_{\max}$ can be determined. The current maximum occurs when $\frac{di}{dt} = 0$. Differentiating the expression for current and setting it equal to zero yields.

$$i_{\max} = \frac{\frac{E}{L} e^{-at_{\max}}}{\sqrt{\frac{1}{LC}}}$$

Since all factors are known except a , a may be evaluated and R calculated from $R = 2aL$. These methods were used to obtain the circuit parameter values quoted in the main section of this report.

2. Measurement Techniques

Oscilloscope - A Tektronix type 551 dual beam oscilloscope with two 53/54k plug in units was used to simultaneously obtain the current and voltage waveforms.

Shunts - A resistance type voltage divider consisting of carbon resistors and giving a 200:1 step-down was used. The current shunt employed was a 0.0102 ohm T & M coaxial resistor.

Capacitor Value - The value of the capacitor was measured with a Capacitance Test Bridge-Type 740-B General Radio Co.

Capacitor Voltage - The capacitor voltage was monitored using a Sensitive Research Instrument Co. electrostatic voltmeter.

Wire Resistance - The wire resistance values were obtained with a Keithley Model 502 milliohmmeter.

Smear Camera - The rotating mirror smear camera used was constructed at the NOL and is described in NAVORD Report 6927.

Switching Device - Originally a KP-130 subminiature, cold cathode trigger tube was employed as the switching device. This tube performed well, but was later replaced by a GL 7964 triggered spark gap which was found to generate less "noise" on the current and voltage traces. "Noise" is here defined as spurious signals which are superimposed on the current and voltage waveforms during an instance of importance. The KP-130 tube was used for all the experimental work in this report except the determination of the current waveforms.

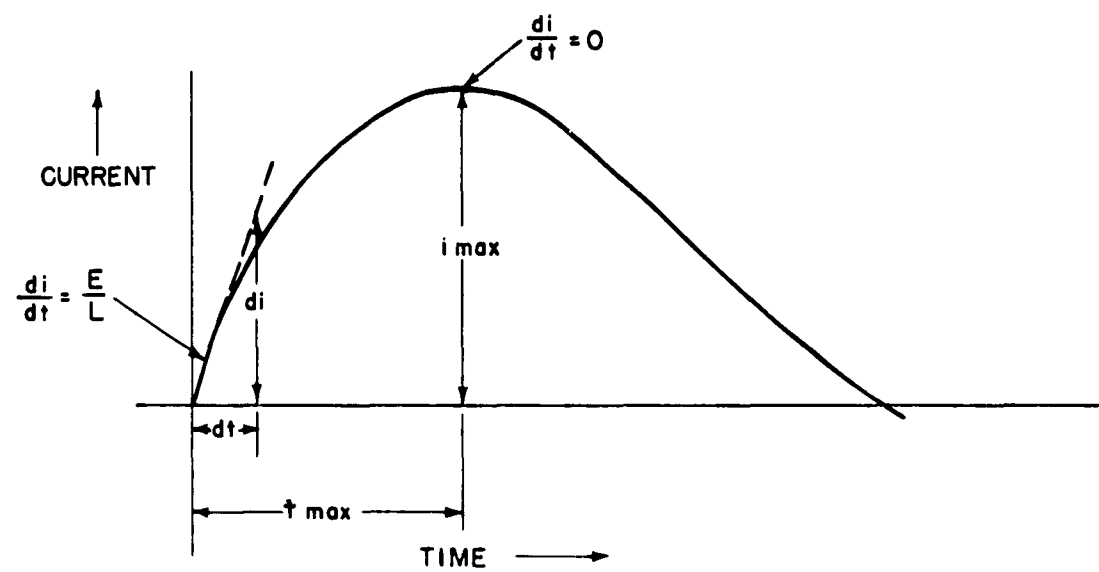


FIG. B-1 ANALYSIS OF CURRENT WAVEFORM FOR DETERMINATION OF CIRCUIT PARAMETERS

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