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Ignition time lag: a measure of explosive energy release

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IGNITION TIME LAG:
A MEASURE OF EXPLOSIVE ENERGY RELEASE

BY

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A

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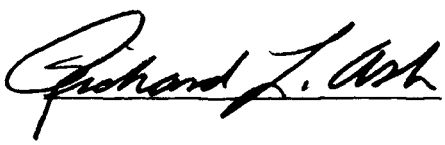

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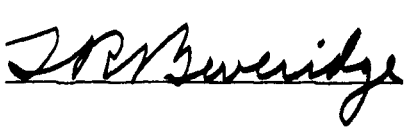

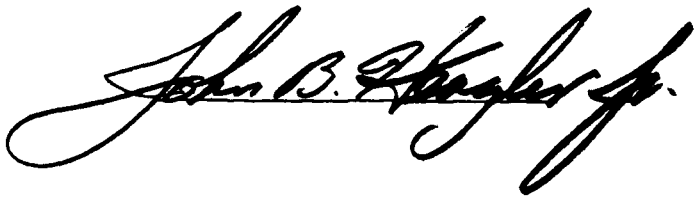

ABSTRACT

By means of the resistance-element, or probe-wire, detonation-velocity measurement technique, explosive reactions from various blasting agents were studied. To reduce the number of variables, only standard AN-FO 94/6 mixtures were used, as are commonly employed today in construction and mining operations. Accuracy of the data obtained was excellent, and the method proved itself not only relatively simple to operate but versatile in providing considerable information under many testing conditions.

Studies of test records revealed the presence of a time-lag frequently occuring after primer detonation. Environmental factors such as confinement, charge diameter, primer size and energy content, and surface coatings on ingredients were then analyzed to determine their influences, if any, on resulting time-lags. The results indicated definite relationships. As was expected, the studies confirmed the fact that primer type and contact surface area had a strong influence on the ignition time lag. With a constant primer-thrust, increases in the time-lag occurred as charge diameter and the degree of confinement were decreased. Furthermore, it was possible to determine from records the transition point between detonation and deflagration, which for the mixtures investigated occurred with a characteristic time lag. For confined charges in 3-inch or smaller diameters, the critical time-lag was near 50 microseconds.

Most significant of all, however, was the fact that the ignition time-lag apparently had a strong influence on the degree of total maximum energy released. If ideal detonation velocities varied linearly with loading density, recorded velocities varied from the ideal values directly with time-lag duration. For a constant chemical composition, it could then be assumed the amount of total potential energy released would similarly vary with the time-lag.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Professor Richard L. Ash of the Department of Mining Engineering, School of Mines and Metallurgy, University of Missouri at Rolla, for his continued advice and guidance throughout the research problem and to Dr. J. J. Yancik of the Explosives Product Group, Monsanto Company, for making available the data needed to conduct the investigation. Appreciation is due also to Professor Robert F. Bruzewski for his assistance in photography and to Mr. James V. Boyle, who aided in the development of many of the figures included in the thesis.

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CHAPTER I

INTRODUCTION.

Investigators (1,2,3,4,5,6,7) have shown that the manner in which rock breaks and the magnitude of dynamic shock transmission through materials from explosions are dependent upon the corresponding stress-strain conditions that are transferred to the medium by the energy released by a detonating explosive. Blast effects require an examination of (1) the manner of stress wave propagation as it traverses through a material, and (2) the energy release mechanism of the explosive producing these stress waves. Because the explosive's ideal energy potential depends only upon its chemical and physical make-up, the maximum energy available is predetermined. The question, then, consists of determining whether or not this full potential is released so as to transmit a maximum effect to the medium.

A search of the available literature on this subject was conducted to see if a method was available to ascertain the degree of maximum potential energy release. Although a wealth of information on energy release and blasting theory was available, it was found that very little had been done to evaluate the actual amount of energy released. All energy release determinations are based on the Thermohydrodynamic Theory, which assumes ideal detonation and infinite confinement of the explosive. Equations expressing the amplitude and direction of energy release advancing through a material from the explosion would be limited by the widely diversified nature of the rock and its surroundings.

Observation of energy release mechanisms and associated parameters have been accomplished to a limited degree by means of highly intricate

devices, such as the streak camera (3), the modified pin oscillograph (8) and resistance-element method (9). These methods are somewhat limited, however, in that they confine their results to a measure of the reaction velocity.

Upon investigation of the various methods, the resistance-element technique, presently used to determine only the velocity propagation along an explosive column, showed the most promise for a detailed examination of detonation phenonema. Research at the University of Missouri at Rolla over the past several years with this method produced considerable photographic data under various conditions. It appeared that valuable information might be gleaned from the data in regard to reactive mechanisms in a detonating explosive. Substantial evidence indicated that many of the blasting agents commonly used today do not detonate ideally but appear to react quite erratically. Therefore, the purpose of this investigation was to determine whether ideal detonation was achieved, and if not, what were the probable causes and the degree of total available energy actually released during the explosive reaction.

CHAPTER II

THE DETONATION PROCESS AND MEASUREMENT OF ITS PARAMETERS.

A. THE CONCEPT OF DETONATION.

The detonation process consists of the creation of a chemical reaction by the propagation of a shock wave traveling through an explosive. The chemical reaction furnishes the necessary energy to sustain the shock wave in a stable manner through the unreacted portion. The reaction leaves in its wake hot compressed gases, which are constantly in motion and exerting high pressures. The products assume a streaming velocity of about 0.75 that of the detonation reaction wave (1) and proceed in the same direction (2). Figure 1 illustrates the distinct regions of a detonating explosive.

The explosion products are known to initiate their lateral motion at a free surface, air expansion being felt at interior points. Because of this, the formation of a release, or rarefaction, wave is allowed to take place, which causes an abrupt pressure drop. The waves are known to travel at about 0.6 of the speed of the detonation wave itself (1).

1. Ideal Detonation.

In order to establish the criteria for the expected performance of an explosive, it is necessary that both the detonation state and explosion state parameters be accurately predicted. Since the only two measurable parameters are the density and detonation velocity, investigators (3,4,5) proposed a theoretical means for computing the various properties of the explosive in its respective states, known as the Thermohydrodynamic Theory. As in the case for most theoretical considerations, certain limitations are placed on the detonation conditions

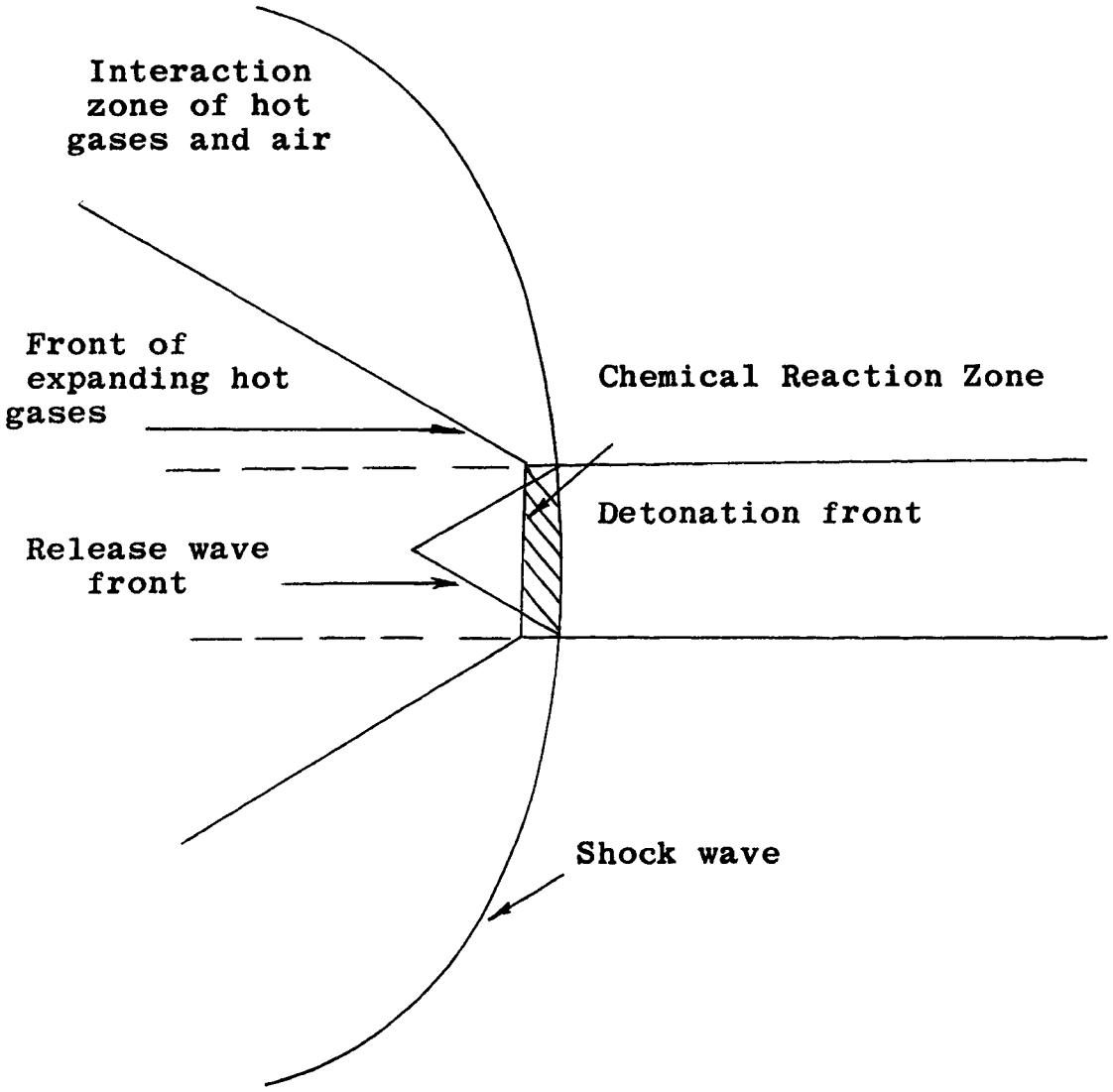


Figure 1. Expansion Patterns of Explosion Products from Finite, Bounded Charges (1).

of the explosive, not only to facilitate computation of the properties, but also to estimate the maximum release of energy available for work on the surrounding medium.

The limitations assume that the explosive possesses (1) infinite volume, or mass, and (2) flow everywhere is one-dimensional (i.e., a laminar-type flow that neglects viscous, thermal, and side losses.) By correlating the assumed limitations with Figure 1, one can see that an explosive of infinite volume will generate a shock wave of such expanse that the arc of the wave passing through the explosive column will approach its own chord. Hence, the wave may be considered a plane wave, and the pressure, composition, and rate of reaction will be uniform across the entire section of the column.

The basic assumptions are utilized in the laws of conservation of mass, momentum, and energy to arrive at a basic hydrodynamic theory. The resulting three relationships are then treated by the following conditions:

(1) an equation of state for gases at high pressures,

(2) the Chapman-Jouget postulate (3),

(3) the Second Law of Thermodynamics, and

(4) the composition of the detonation products as predicted from chemical equilibria.

The combination of all the above conditions constitutes the Thermohydrodynamic Theory. Application of the Theory to a particular formulation of chemical ingredients in an explosive will enable the computation of the values of the detonation-state parameters. The theoretical solution describes that which is considered as ideal detonation.

2. Non-Ideal Detonation.

Theories of non-ideal detonation are based on the assumption that energy is dissipated during lateral expansion of the chemical reaction zone, and that this energy would not be available to maintain a full detonation velocity. The expansion results in a reduction of temperature and pressure within the reaction zone.

a. The Nozzle Theory. H. Jones (6) was the first to consider theoretically non-ideal detonation in a circular cartridge of finite radius. He considered the front portion of the detonation wave as simply a shock wave traveling through the unexploded material, with the compression and temperature of the shock front igniting the material. If an individual were situated on the wave, he would view the products of detonation issuing forth at the end of the reaction zone as material from a nozzle (Figure 2) with a characteristic velocity D-W = C (3). The length of the nozzle corresponded to the reaction zone length. Streamlines of flow within the nozzle were parallel to the axis of the explosive, so that the pressure remained constant across the tube.

Solution of the problem consisted of declaring that the lateral expansion of the reaction zone would affect only the conservation of mass equation in the Thermohydrodynamic Theory, and that the extremities of the nozzle could be determined by the simultaneous solution of Meyer's and Bernoulli's equations. The equations corresponded to the pressures in the outer and inner regions of the nozzle, respectively. Jones applied his solution to three cases:

(1) An unconfined charge in which the rate of lateral expansion of the detonation products was assumed to be determined only

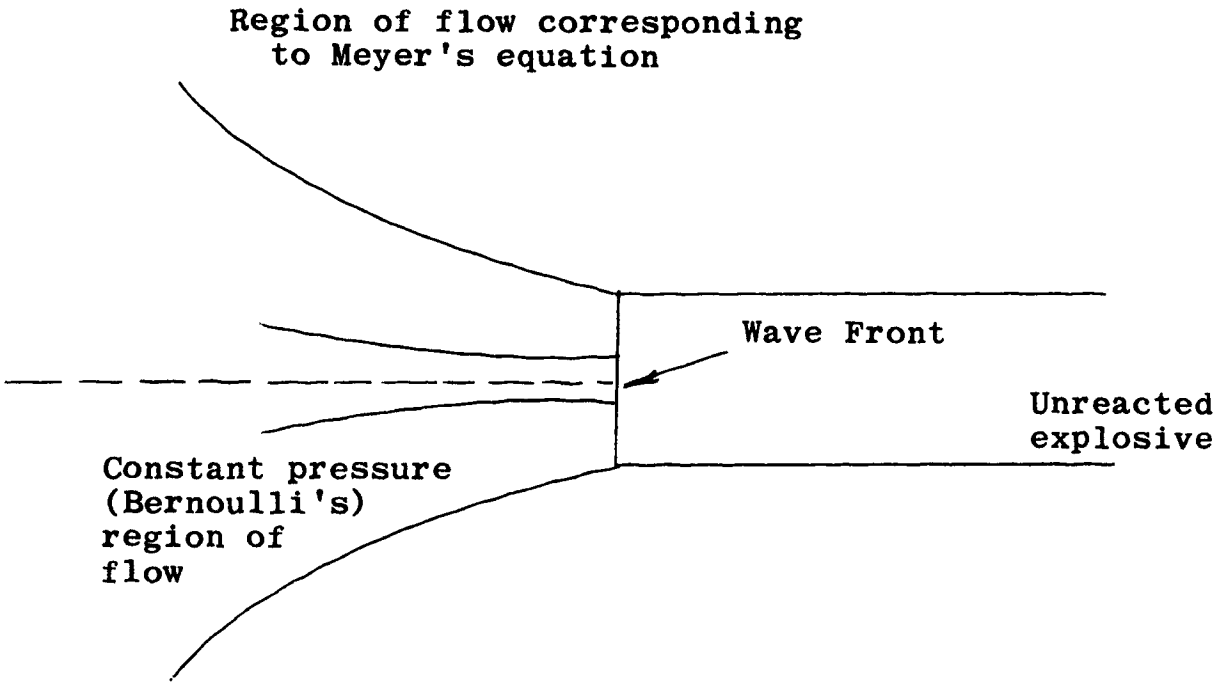


Figure 2. The Nozzle Theory of Detonation (6).

by the movement of the shock wave in the detonation products and in the atmosphere surrounding the charge;

(2) A moderately-cased charge in which the rate of lateral expansion was determined by the rate at which the inertia of the casing was overcome; and

(3) An infinitely-cased charge in which only lateral expansion was permitted by the compression of the inner wall of casing.

b. The Curved-Front Theory. A theory advanced by Eyring (7) was similar to Jones' nozzle theory in that the lateral expansion of the reaction zone affected only the conservation of mass equation. Eyring felt that at the charge's edge a rarefaction wave was sent into the reaction zone. The rarefaction wave, traveling with a velocity C, ate into the detonation wave, thereby reducing the velocity of the wave at the extremities of the explosive. The detonation wave would assume a curved front instead of the hypothetical plane front, and any small portion of the wave was considered to be spherical with a finite radius of curvature. Eyring offered conclusions for three conditions of confinement:

(1) The detonation front of an unconfined charge was considered to be made up of a number of small portions of spherical wave segments;

(2) The detonation front of a moderately-cased charge adjusted to an angle of intersection with the casing, so that elements of the casing moved away from the casing at the same speed that the products of detonation in contact with it departed; and

(3) The confinement of a charge in an infinitely-cased medium was determined by the shock wave in the medium. The wave front

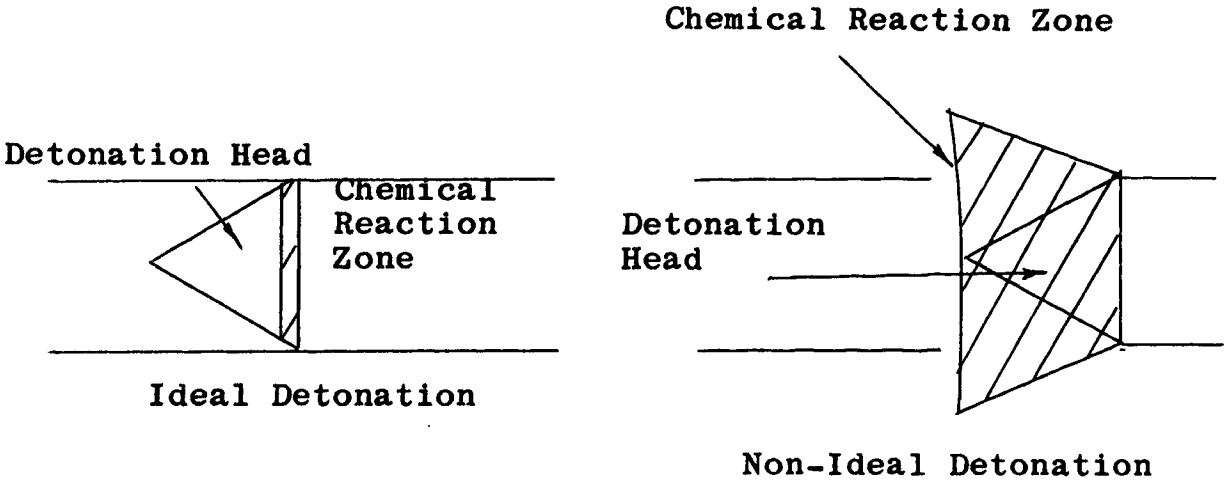
adjusted itself in order that the particle velocity and pressure matched at the boundary of the charge.

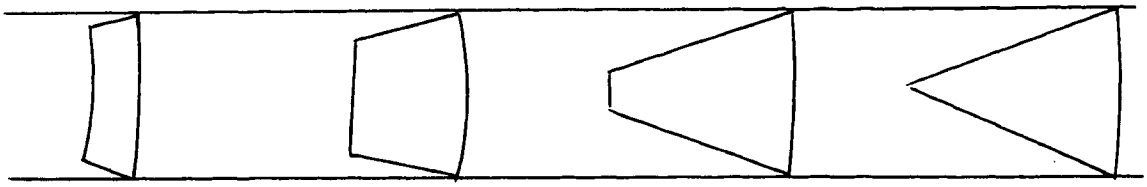
c. The Geometrical Head Theory. A theory proposed by Cook (3) assumed the formation of a detonation head: a region confined by the advancing detonation wave, the rear rarefaction wave, and the lateral rarefaction waves. The so-called head first assumed the shape of a truncated cone, and gradually regressed to a full steady-state cone as the rear rarefaction wave was eliminated by the lateral rarefaction waves. The regression is illustrated in Figure 3. Cook deduced that ideal detonation would end when the reaction zone length encompassed the length of the detonation head. An increase in length of the reaction zone beyond this point would effect non-ideal detonation conditions.

d. The Variable Reaction-Zone Length Theory. Hino (5) suggested that the detonation velocity was directly proportional to the reaction time. He considered the time to be the sum of (1) t_c, the critical time of reaction for any particular explosive, (2) the time increase as a result of the confining action of the medium, and (3) the time increase due to the confining action of the explosive itself about its critical-diameter reaction.

B. MEASUREMENT OF DETONATION VELOCITIES.

Optical and electrical techniques provide the two popular methods for measuring detonation velocities. The ability of the instruments to determine reaction rates under field conditions has been an invaluable aid in securing information for the design and evaluation of explosives. In addition, certain of the instruments permit detailed observations of some of the detonation phenomena that are not yet throughly understood.





Gradual Regression of the truncated detonation head to a full cone shaped head.

Figure 3. The Geometrical Head Theory of Detonation (3).

1. Framing Cameras.

The framing camera provides data for the determination of detonation velocities by accumulating several single-exposure frames during the photographing of the shock wave propagation through an explosive. This is accomplished by focusing the image of the explosive on a rotating mirror or prism. The mirror sweeps the image across several individual sets of apertures and relay lenses, which in turn project their particular received image on a stationary film. Cook (3) and Mauer (11) both provide excellent sketches and discussions of the apparatus.

The cameras can accurately measure detonation rates over a 15 million frames-per-second increment. They are particularly useful in studying detonation wave shapes. If the photographs are taken in color and are reproducible, it is possible to estimate visually the temperature of the various areas within the color record. When explosive reactions are photographed, the cameras must be installed nearby in a suitable shelter to prevent damage from the blast. Since shelter construction requires a great deal of preparation and high cost, the method is limited.

2. Streak Cameras.

This type of camera (3) differs from the framing camera in that the aperture and relay lens are eliminated. The image of the explosive is focused continuously across a film moving at right angles to the direction of propagation of the detonation front. A narrow slit is inserted just in front of the explosive to eliminate lack of definition caused by the luminous expanding gases. The slit serves to restrict the field of view of the camera to a mere line. Correlation of the film speed

with the boundary line, defining the exposed and non-exposed regions of the film, enables one to calculate the propagation rate.

3. Pin Oscillographs.

The pin oscillograph relies principally on the heavy degree of ionization found in a chemical reaction zone. The arrival of the reaction zone at several discrete locations along a charge column, or pin stations, is recorded chronographically. When the arrival times are applied to the measured distances between the pins, finite velocities can be determined. The velocities are usually averaged to find an overall, or effective, detonation velocity.

The equipment consists basically of a modified oscilloscope and a triangular wave generator, which lengthens the straight line sweep of the scope to a zig-zag trace in order to obtain sufficient time resolution, a crystal controlled marker-generator that superimposes time markers on the trace to vacilitate reading of the records, and a pulse-forming circuit that imposes an electrical pulse upon the sweep when the pins indicate the arrival of the reaction zone. A Polaroid camera, attached to the scope, records the zig-zag sweep complete with time markers and pulses for analyzing. The pin oscillograph provides a system that not only is simple and inexpensive but also gives accurate measurements. However, the system is difficult to adapt to large diameter boreholes and is completely unsatisfactory for small diameter boreholes. Because of its intermittent nature in determining the detonation velocity, it must be assumed that the characteristic velocity of the explosive is at a steady-state between pin stations.

4. The Resistance-Element Method.

The resistance-element technique continuously indicates the position of a reaction zone within a charge column in accordance with the remaining resistance of a probe wire of known initial potential. The method is adaptable to test samples and actual blastholes in the field. Chapter III deals exclusively with this method.

CHAPTER III

THE RESISTANCE-ELEMENT TECHNIQUE FOR OBSERVING DETONATION REACTIONS.

Gibson et al (9) and Amster (10) both proposed electrical arrangements for the continuous evaluation of the velocity of an advancing detonation front through an explosive column. The method was later improved by Mauer (11), Breakey (8), and Gibson (12) to measure a wider range of detonation velocities in opaque, confined explosives and propellants. Subsequent modifications to Breakey's work have been made at the School of Mines and Metallurgy, University of Missouri at Rolla.

A. THEORY OF THE TECHNIQUE.

The technique consists simply of placing an element consisting of a single wire loop along the axial diameter of a column loaded with reactive material, and then measuring the change in total resistance as the element is gradually shorted out by the self-ionizing detonation front progressing through the column. A constant current imposed through the wire loop element as it is gradually consumed will allow the change in resistance to relate directly to the change in applied voltage. The decrease in voltage with change of time, when observed on an oscilloscope, will indicate the position and progress of the reaction zone associated with detonation at any instant.

The primary advantage of the system over other electrical methods is that not only can average propagation rates be determined, but incremental velocities, with all associated accelerations and decelerations that may occur during reactions, can be clearly detected. By varying certain parameters with others remaining constant, the performance of

explosives can be evaluated as to the effect of each parameter on the reactions.

Use of the technique is easily adaptable to many conditions, the instrumentation for which is relatively simple to construct. Basic physics states that the resistance of a wire increases proportionally with its length by a constant, r, which is dependent on the physical properties of the material. The relationship can be expressed as follows:

$$R = 2Lr,$$

where

R = total resistance,

L = length of the element, and

r = resistance of the wire per unit length.

When a voltage is applied, the expression becomes

$$E = IR = 2LrI,$$

since the element consists of a single loop of wire. Dividing each side of the equation by time gives

$$(E/t) = 2rI\ (L/t).$$

Because the detonation velocity, D, is equivalent to L/t (the rate at which the wire loop is consumed), the equation may be expressed as

$$D = (E/t) \ / \ 2rI.$$

Since the E/t ratio may be recorded on an oscilloscope continuously, multiplication of this ratio by the 1/(2rI) value will provide incremental and average detonation velocities. If the current and wire

resistivity are kept constant, and the scope is time-calibrated correctly, readings will be comparable in all instances.

B. INSTRUMENTATION.

Although a complete description and appropriate schematic diagrams of the instrumentation used for obtaining data for most of this study had been reported earlier by Breakey (8), certain changes have been made to improve and simplify the original system. The changes were found to provide accurate and consistent results, and in many instances, field operating techniques were greatly improved. Therefore, it would be most appropriate to present brief descriptions of the basic units of the system currently in use.

1. Resistance-Element (Probe).

The probe wire-element consisted of approximately 9 ft. of Driver-Harris No. 36 Nylon-coated Nichrome wire folded into a single loop 4-1/2 ft. long, which was then twisted a minimum of 550 turns. It had been found that consistent contact between the two strands of the loop during ionization was assured with that amount of turns. The probe was then twisted an additional 100 turns around a No. 30 enameled copper wire, which served as a stiffener and electrical ground.

Because all wires were well-insulated, the leads of the Nichrome and copper wires necessarily were carefully scraped, and the bare ends were then soldered to 1-ft. lengths of insulated multistrand wire for connecting to the field leading cables. The soldered connections were carefully coated with waterproofing compound, covered with plastic sleeves, and then taped to insure that the entire assembly was waterproof. The precaution enabled use of the probe element in water without any shorting occurring except at the intended detonation

ionization front. In the event insulation on the probe leads was damaged, shorting to the ground wire resulted. If electrical noise was absent and test conditions were dry, measurement was still assured merely by disconnecting the copper ground from the circuit. Otherwise, the full voltage reading would not be possible, and erroneous test values could be expected.

The resistivity of the Nichrome probe wire was relatively constant, or from 27.5 to 27.7 ohms/ft., while that for the short soldered lead connections was considered negligible. Including lead connections, the total resistance for the 4 1/2-ft. probe element was usually about 257 ohms, with a variation range of only 2 ohms, or a 0.4 per cent variation from the mean.

2. Power Supply.

The system operated from a 60-cycle 115-125 volt AC main power source, the voltage of which was stepped up by a 600-0-600 volt transformer. Conversion to DC was made through a full-wave rectifier, and a 4.5H L-section filter. Constant current was accomplished by use of a dual GL-815 pentode. Two VR-150 cold-cathode tubes were used to supply a screen potential of 300 volts, and a 45-volt B-battery coupled with coarse-and fine-control potentiometers provided a sensitive, controlled gride bias. An 8 K-ohm resistor was placed in parallel with the load to prevent an excessive screen current on the tube in the event an open circuit occurred during field testing. A schematic diagram of the circuitry is shown in Figure 4.

3. Voltmeter.

For all later tests a DigiTec Model #200-B DC voltmeter, manufactured by United Systems Corporation of Dayton, Ohio, was used to measure the current and voltage potential on the probe element prior

to initiation of the explosion. This unit replaced the monitor reported earlier by Breakey (8). Connections were made through a junction-box arrangement (Figure 5) that placed the voltmeter in parallel with the supply current to the probe. The instrument, when calibrated properly and placed in series with the probe, permitted accurate checking of the power supply current, so that fine adjustments were possible to the desired current value. Figure 6 illustrates the field connections with the resistance-element probe attached.

4. Oscilloscope.

A Tektronix Type 533 oscilloscope with a 53/54 D plug-in amplifier unit was used to record the voltage-time relationships during detonation. Traces were photographed with a Polaroid camera to provide permanent records of the measurements.

C. DATA RELIABILITY.

1. Instrumentation Error.

A potential source of instrumentation error for the system would be failure of the power supply to maintain a constant current during a change in load. Since a poor response by the power supply would endanger the validity of any data, it was decided to construct characteristic composite curves (Figure 7) for the 815 pentode to determine if changes in current occurred as the resistance element was consumed. A 250-ohm resistor was used to simulate the resistance element.

Upon completion of the curves, it became necessary to locate the operating points. A plate current of 100 milliamps (the desired current in the field) was found to correspond to the expected plate voltage of

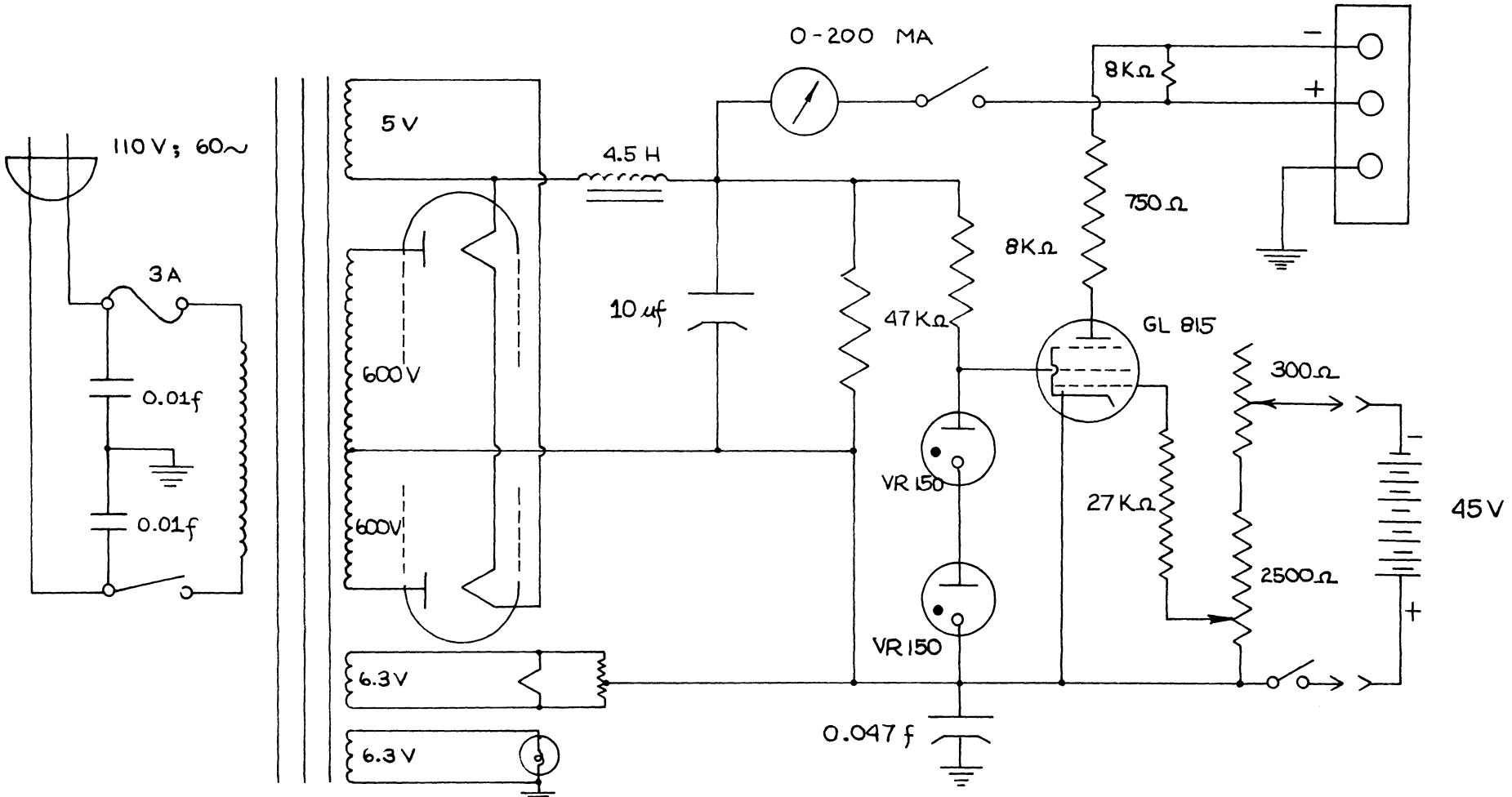


FIGURE 4. CONSTANT CURRENT POWER SUPPLY

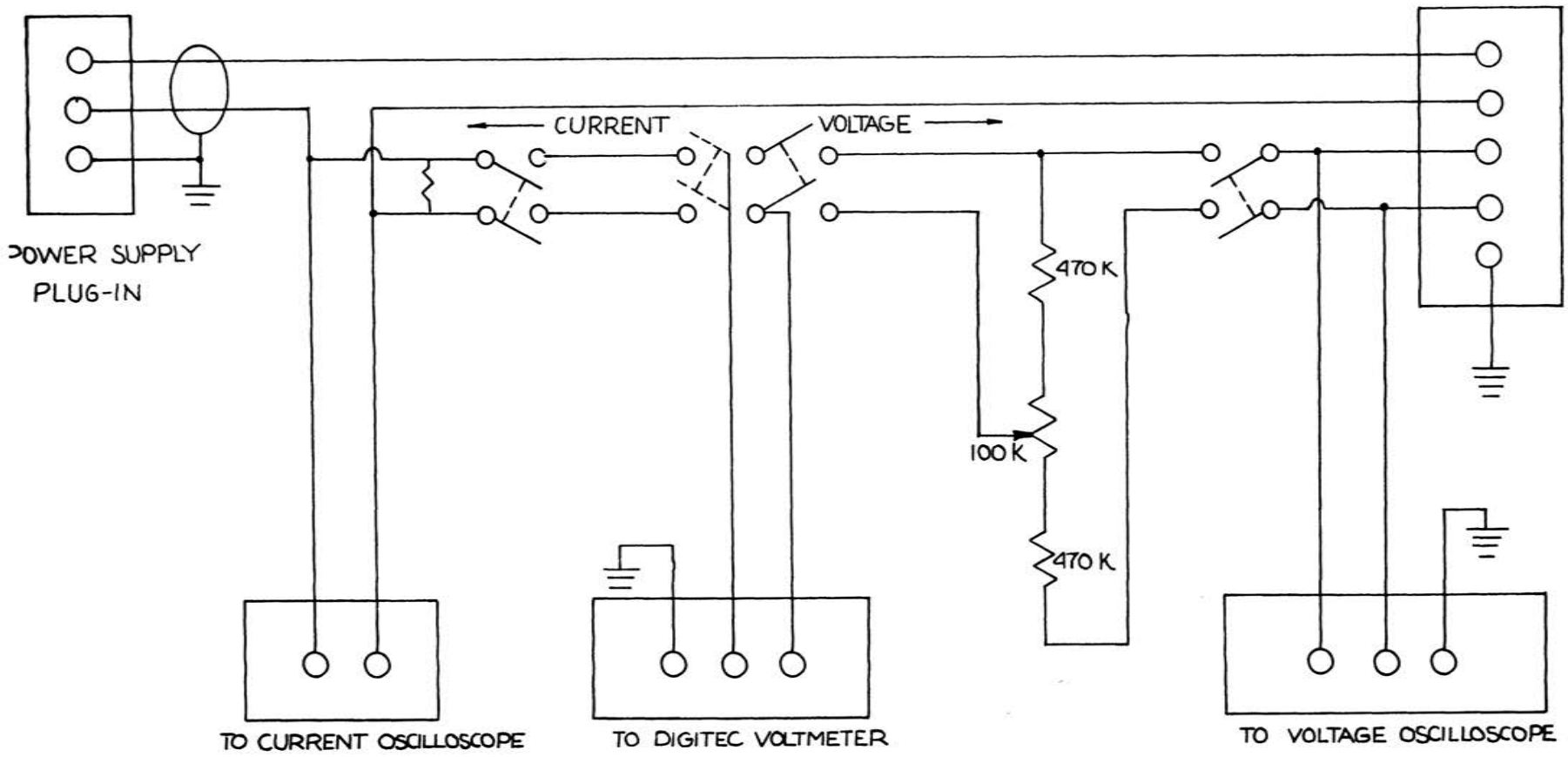


FIGURE 5. JUNCTION BOX SCHEMATIC DRAWING

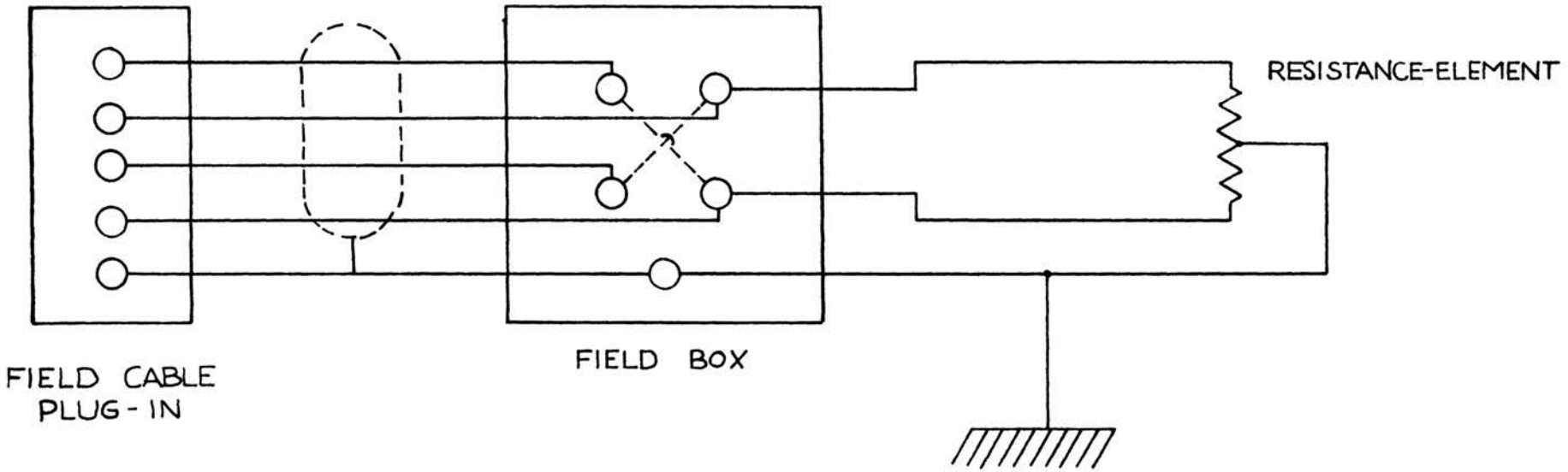


FIGURE 6. RESISTANCE-ELEMENT HOOK UP IN THE FIELD.

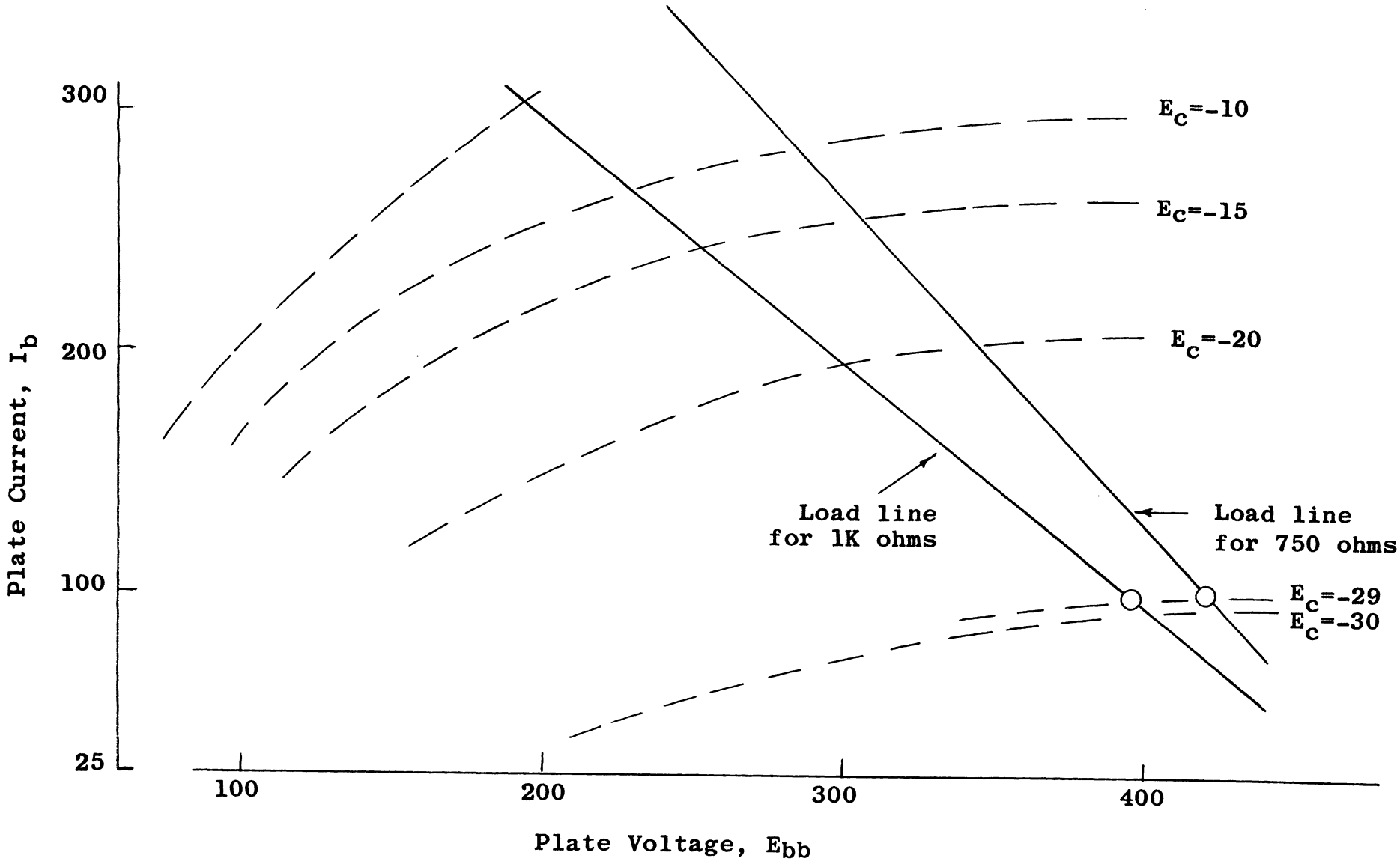


Figure 7. Characteristic Curves for Composite Dual GL-815 Pentode.

400 volts in the region of $E_c = -30$. The grid bias was then adjusted to give exactly 100 milliamps through the tube. Grid bias and plate voltages corresponding to this current were $E_c = -29$ and $E_{bb} = 395$. With the grid voltage held constant, the 250 ohm resistor was removed (i.e., when the element would have been totally consumed in the field), and a plate current and a plate voltage of 100.5 milliamps and 420 volts, respectively, were observed. The points were plotted on the graph of characteristic curves. Load lines of 1 K-ohm (which included the 250 ohms to simulate a field probe) and 750 ohms (to simulate no probe resistance) were originated at a maximum plate voltage (i.e., $E_{max} = E_{bb} - IR_{1k}$). Positioning of the lines on the curves agreed with the previously determined operating points.

Breakey's evaluation of the system indicated that an increase in current of 10 milliamps during the consumption of the wire by the ionization zone would lower the detonation velocity reading by 2000 fps. However, tubes operating at $E_c = -29$ volts indicated an increase in current of only 0.5 milliamps, or a 0.5% deviation, to give a decrease in velocity reading of only 100 fps. If one were to consider a typical blasting agent with a reaction rate of 14,000 fps, the induced error would be expected to be only 0.7 percent of the observed reading.

In the event probe-resistance characteristic data were read or recorded erroneously at the time of manufacture, the fact was detectable by a comparision of the values with those that normally obtained. Probe resistances with excessive deviations from the normal were rechecked. Also, if abnormal resistance differences existed as observed on the oscilloscope by the existence of voltage levels other than those normally seen, circuits were checked prior to test firing. Abnormal

resistances were detectable also by unusual voltage readings on the DigiTec voltmeter, or by the monitor used earlier. Poor connections in circuitry, open and short circuits, probes with damaged insulation, and similar causes for abnormal resistances were generally very easily detected by both the oscilloscope and the voltmeter.

2. Operating Error.

Before introduction of the DigiTec voltmeter as standard equipment, failure to set the current supply at exactly 100-ma could have seriously affected the reliability of test results. To eliminate the possible use of an improper current during test firing, care was exercised to be certain that the supply was steady and the monitor was balanced properly before the voltage was measured. After employment of the DigiTec voltmeter, the exact current value and whether or not its value was constant were readily ascertained. It was relatively simple to adjust the power supply to a steady 100-ma value before reading the voltage. Several checks were made before the actual firing of each test.

3. Initial-Test Reading Error.

Even though every precaution was taken to insure that all possible sources of error in testing were eliminated, confidence that initial data were recorded properly was established by conducting a statistical analysis of initial test readings. It was felt that a check of the E/R ratio served best to indicate the constancy of the supply current, as well as serving to check the recorded voltage and measured initial resistances. After completion of 225 tests, a frequency distributed curve was constructed as shown by Figure 8. The analysis provided the following statistical values for the E/R ratio:

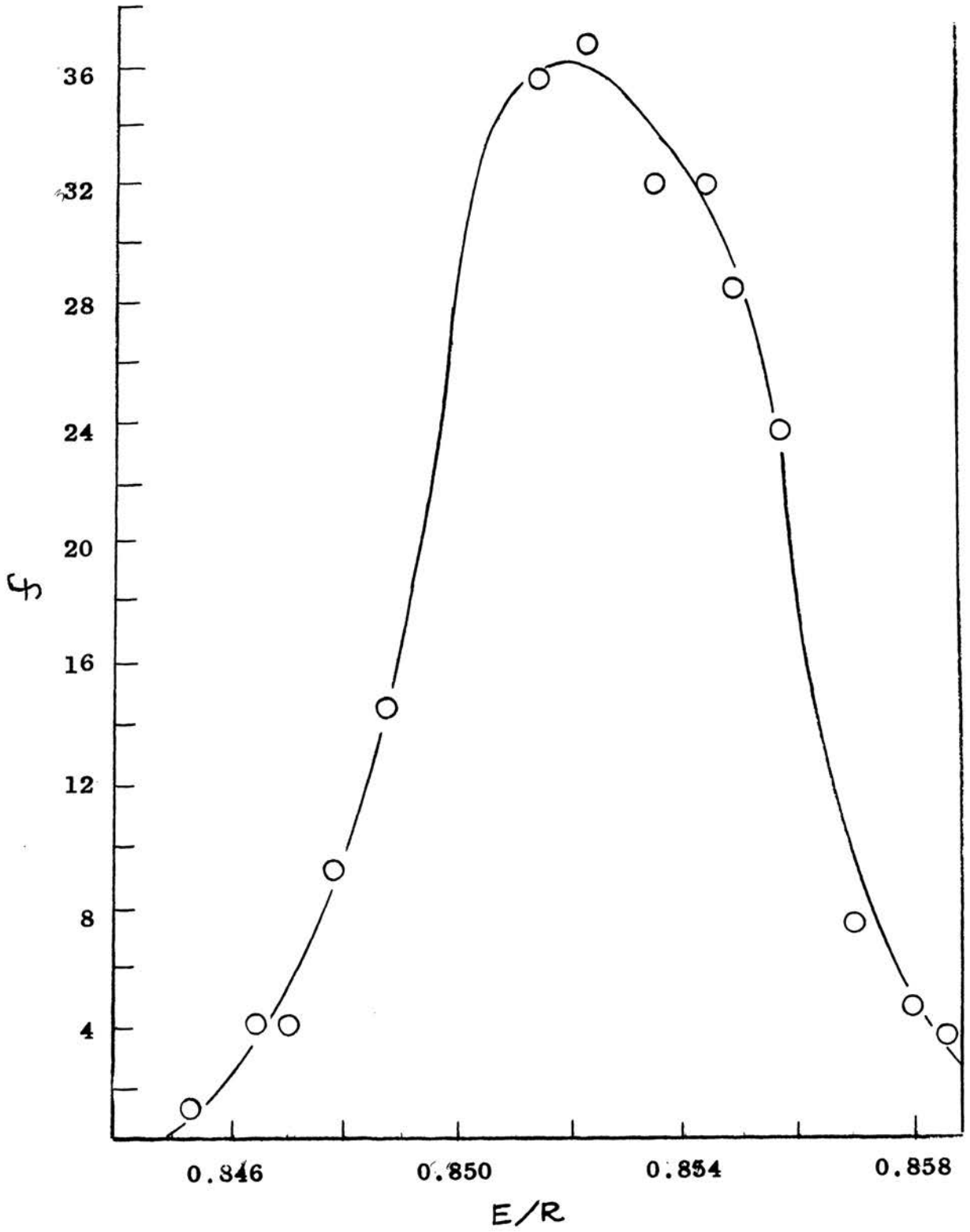


Figure 8. Frequency Distribution Curve for Probe Wire Test Data.

Mean = 0.852,

Mode = 0.850,

Median = 0.852,

Standard Deviation = 0.005, or 0.5 per cent.

For purposes of this study, all data within two times the standard deviation were retained because of the close correlation with the maximum changes in slope.

4. Calculation Error.

In addition to instrumental and operating errors, as well as those incurred in recording, errors in calculation were always possible. A systematic field check was conducted following each test, whereby readings were spot calculated and compared with calibration curve.

Data for the curve consisted of readings made from all previous tests, with additional points being added upon completion of each subsequent test. The curve represented the relationship between calculated velocities and the maximum time elapsed from initiation of a reaction to its completion.

Procedures were modified as experience and conditions dictated. Tests were expanded to a variety of conditions, which included experiments with materials in iron and transite pipes and in boreholes. In addition, tests were made on unconfined cartridged materials, which produced results that were quite satisfactory for the conditions imposed. It was found that for confined tests, iron pipes closely simulated borehole confinement, which confirmed Yancik's observations (2). As most tests were conducted on blasting agents whose major constituents were ammonium nitrate and fuel oil, 1 1/2 to 3-inch diameter charges

were tested as standards. The critical diameters for most of the blasting agents were within that range, and studies of threshold conditions best revealed information on marginal reactions under such conditions. Plates I and II show the instrument layout and the method for placing a probe element in a test pipe.

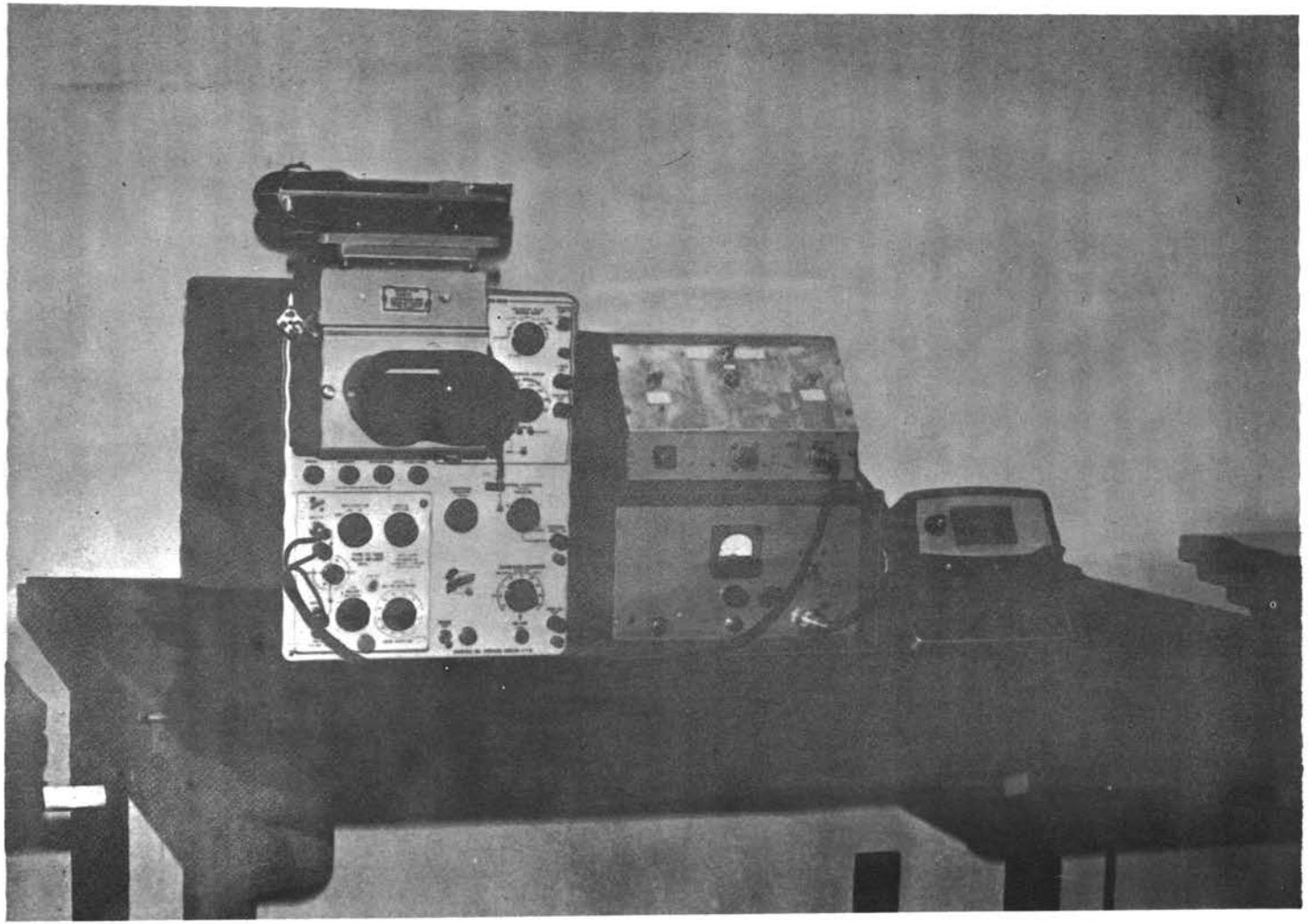


Plate I. Instrument Layout

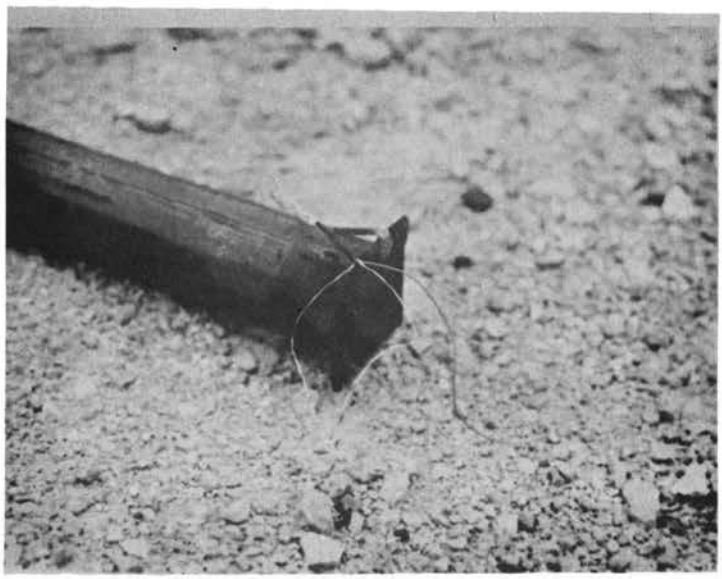


Plate II. Placement of Resistance-Element in Test Pipe.

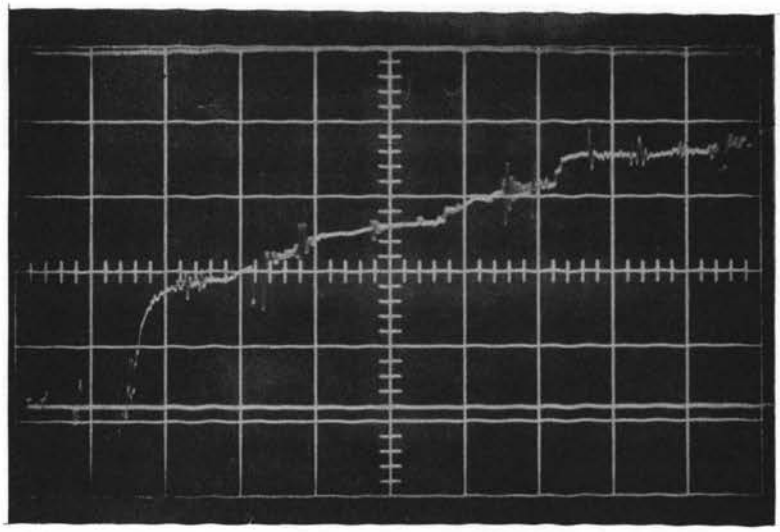
CHAPTER IV

THE IGNITION TIME-LAG.

A. OBSERVATION OF THE LAG ON RESISTANCE-ELEMENT RECORDS.

Close observation of the photographs of tests using probes (Plate III) disclosed that a time gap frequently occurred in the region of initiation. This gap was seen to occur always immediately after the primer detonation and to terminate at a sloping line representing the characteristic velocity of the particular blasting agent (Figure 9). The time increment, or ignition time lag, represented the time difference between completion of primer detonation and the beginning of the normal steady-state detonation of the blasting agent. The lag was a time period of constant probe resistance and often was accompanied by the presence of transient signals. Apparently, ionization from the explosive reaction failed to develop or was too weak to support electrical contact at the time.

Inclusion of the Second Law of Thermodynamics ($ds = dQ/T$) in the Thermohydrodynamic Theory was partly due to the inability to select a terminal-state pressure-volume point using the laws of conservation of mass, momentum, and energy. The application of thermodynamic principles to the Rankine-Hugoniot equation (a product of the mass, momentum and energy equations) produced a family of R-H curves on a pressure-volume graph, where each curve represented a certain degree of the total maximum energy release. Each curve had only one state point (P_1V_1) at which stable detonation would take place (3). The point was called the Chapman-Jouguet stability point, or C-J point, and was found to vary from curve to curve with a change in pressure only.



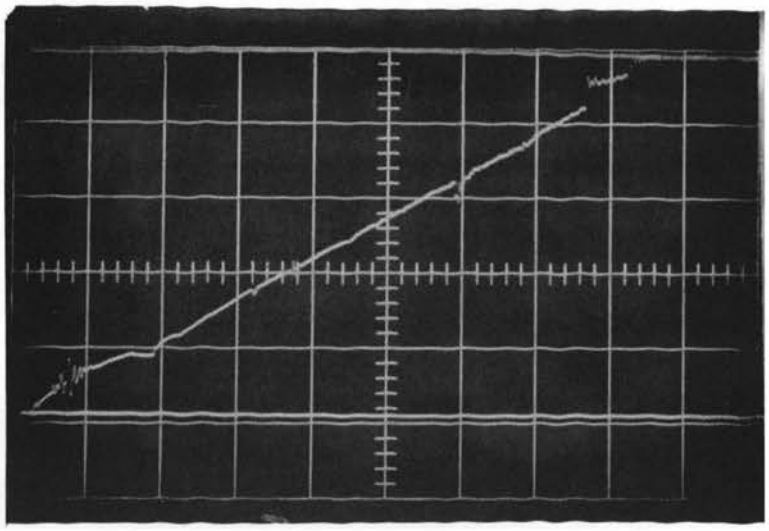


Plate III. Resistance-Element Data for Explosive B in Cartridge Form.

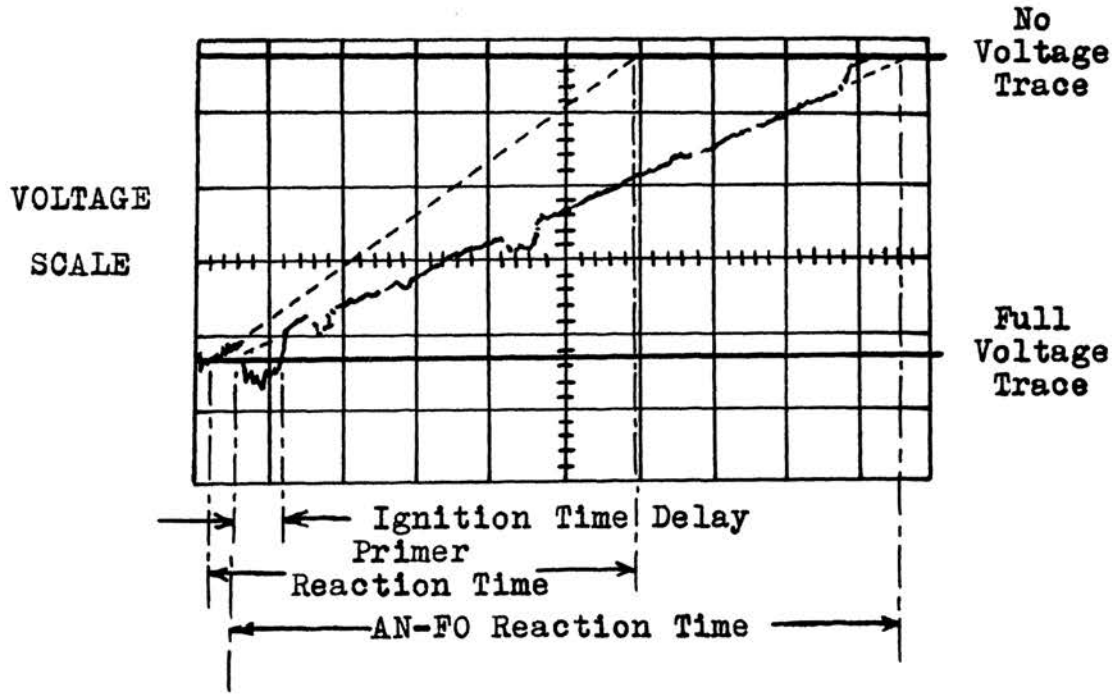


Figure 9. Resistance-Element Photographic Trace.

Figure 10 illustrates several R-H curves for a typical blasting agent. The explosion upon initiation developes a pressure from the original state point A (P_o,V_o) to a higher pressure, P_p, at point B. If the blasting agent reacted ideally, i.e., had ideal detonation, the pressure would then decay linearly along line B-A until it reached the stable C-J point at I. Ideal detonation, however, may not be achieved, in which case the pressure would rise along the non-reactive RH curve only as far as P_p' at point C. At this point, the pressure would begin to drop linearly toward the original state point A until it reached I'. I' would be simply the stable C-J point for an R-H curve at less than ideal detonation. The lag, or gap, that was observed on resistance-element photographs indicated the time delay required for the Chapman-Jouguet stability point to be reached.

B. POSSIBLE FACTORS THAT CONTROL THE AMOUNT OF TIME-LAG.

Graphical analyses were performed on the observed ignition time-lags as related to a number of different blasting parameters. Each parameter selection was made on the likelihood that the time delay was a relative measure of the ease of initiation.

1. Confinement.

Mauer (11) indicated that confinement was a direct aid in controlling the ignition lag. A strong confining medium would not allow extreme dissipation of the initiating energy, thus serving to conserve energy in support of initiation. For this study, two types of confinement were used in the analyses: iron pipe to simulate borehole confinement, and 5 1/2-inch diameter polyburlap-covered cartridges to represent an un-

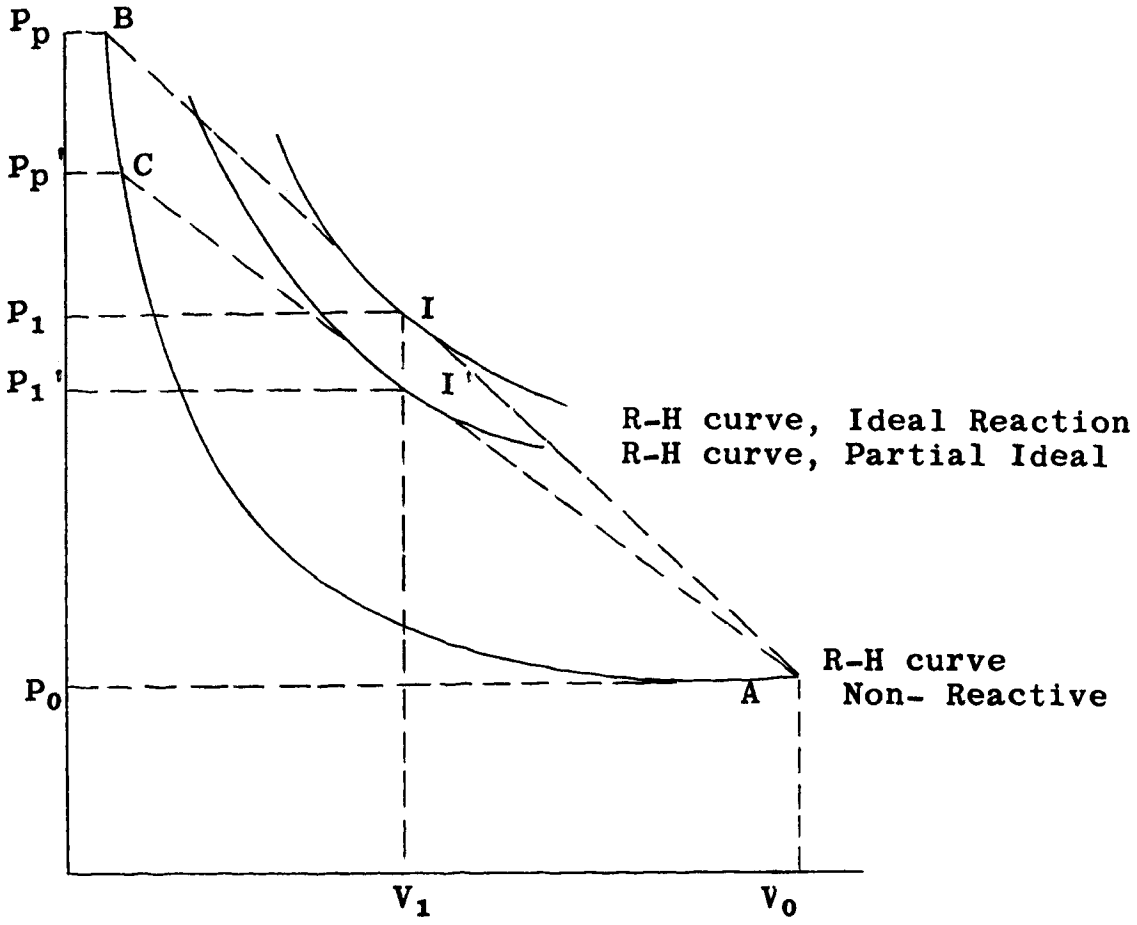


Figure 10. Rankine-Huginot Curves with Corresponding Chapman-Jouguet Stability Points.

confined state.

2. Charge Diameter.

Many investigators have shown that the detonating velocity and sensitivity of an explosive are a function of the charge diameter. It seemed logical that this parameter similarly would influence the time lag.

3. Effective Dynamic Primer Thrust.

The primer used very likely had an important effect not only on the ease with which detonation of a blasting agent was initiated and on possible time-lag occurrence, but also on the order of steady-state velocity that the agent exhibited. Since the mechanism of initiation is basically demonstrated as a dynamic transfer of pressures, the primers were evaluated on a thrust or stress concept. The calculation for the dynamic primer thrust (DPT) was made on a kinetic energy basis, or the product of a primer's mass density and its detonation velocity squared. Table I lists the calculated DPT's for the various primers used.

Because of the large amount of energy dissipated during an unconfined state and because primers are rarely sized to fill a borehole as completely as free-flow blasting agents, the term effective primer thrust (EPT) was chosen to represent the effect of the difference in cross-sectional contact area between the primer and the main explosive column. The reduction in primer thrust quite likely could introduce time lags. The maximum possible DPT was converted to an EPT by multiplying the maximum DPT value by a factor of $(\text{Dia.}_{\text{primer}}/\text{Dia.}_{\text{column}})^2$. Figure 11 illustrates the relationships between the DPT and the EPT for various ratios of cross-sectional areas. For example, if a 3-inch diameter primer with a thrust of 10×10^8 psf was used in a 12-inch

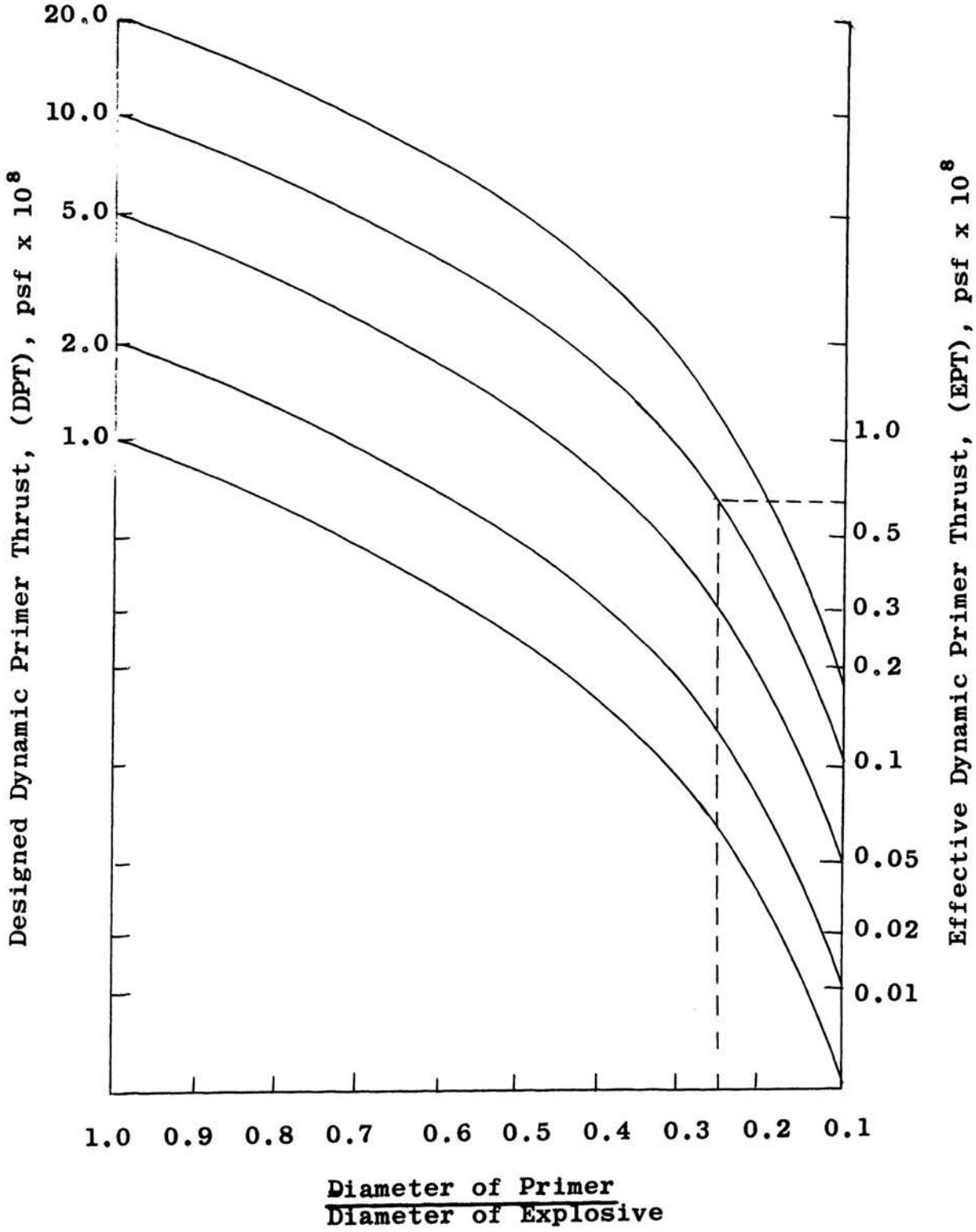


Figure 11. Primer Thrust Calibration Curves.

Table I. Dynamic Primer Thrust Data.

Type	No. of Units, n	Specific Gravity, d	Mass Density (d/g)62.5	Detonation Velocity, v, fps.	D.P.T. $n(d/g)62.5v^2$, psf
Trojan Cast Booster 12 oz.; 2.125-in. x 3.75-in. PETN/TNT - 50/50	1	1.50	2.90	24,500	17.40×10^8
DuPont HDP #1 16 oz. 3.0-in. dia. x 3.5-in.	1	1.22	2.37	24,000	13.60×10^8
DuPont HDP #3 5.33 oz.; 1.75-in. dia. x 3.5-in	1	1.22	2.37	24,000	13.60×10^8
Atlas Gelodyn #3	0.5	1.15	2.23	13,500	2.025×10^8
1.25-in. dia. x 8-in.;	1	1.15	2.23	13,500	4.05×10^8
S.C. = 123	2	1.15	2.23	13,500	10.10×10^8
Atlas 60% Extra	4	1.15	2.23	13,500	20.20×10^8
1.25 in. dia. x 8 in.;	1	1.23	2.48	11,000	3.00×10^8
S.C. = 115	2	1.23	2.48	11,000	6.00×10^8

diameter borehole, the maximum potential thrust would be reduced to an effective value of only 0.63 x 10^8 psf. All primers were evaluated on this concept for the study.

4. Percent of Ideal Detonation.

Using the Thermohydrodynamic Theory, one can predict that the velocity of a specific blasting agent in ideal detonation would vary linearly with a change in bulk density. If an explosive column responded with ideal detonation after initiation, its steady-state velocity would be equivalent to that predicted. Yancik graphically determined the relationship between bulk density and detonation velocity for an ideally-reacted 94/6 AN/FO mixture (Figure 16). If each test pipe is treated as a single cartridge, the bulk density and loading density would be the same. Thus, application of the recorded loading density to Yancik's graph would render the appropriate ideal detonation velocity. The observed steady-state velocity of each blasting agent tested was transformed in this manner to a percent-of-ideal-detonation parameter. It was thought that time-lags might be related to the degree of detonation achieved by an explosive reaction.

5. Surface Coating.

Many blasting agents used inert coatings on the ammonium nitrate particles to prevent caking and insure a free-flowing product. It would be logical to anticipate that such coatings might have an effect on the ignition time-lag.

6. Contact Points.

Ingredient particle sizing and distribution in explosive mixtures had been shown to be important factors controlling detonation (3).

Evidence indicated that the number of contact points between particles was the determining factor rather than their respective surface areas. Although expressions were available for a theoretical determination of contact points for spherical material, based on either the dense or loose-packing concepts, there was no possible way to determine the number of contact points for non-spherical material unless they were counted (Plate IV). For purposes of this study, the difficulties presented by such an evaluation did not seem worthy of further investigation.

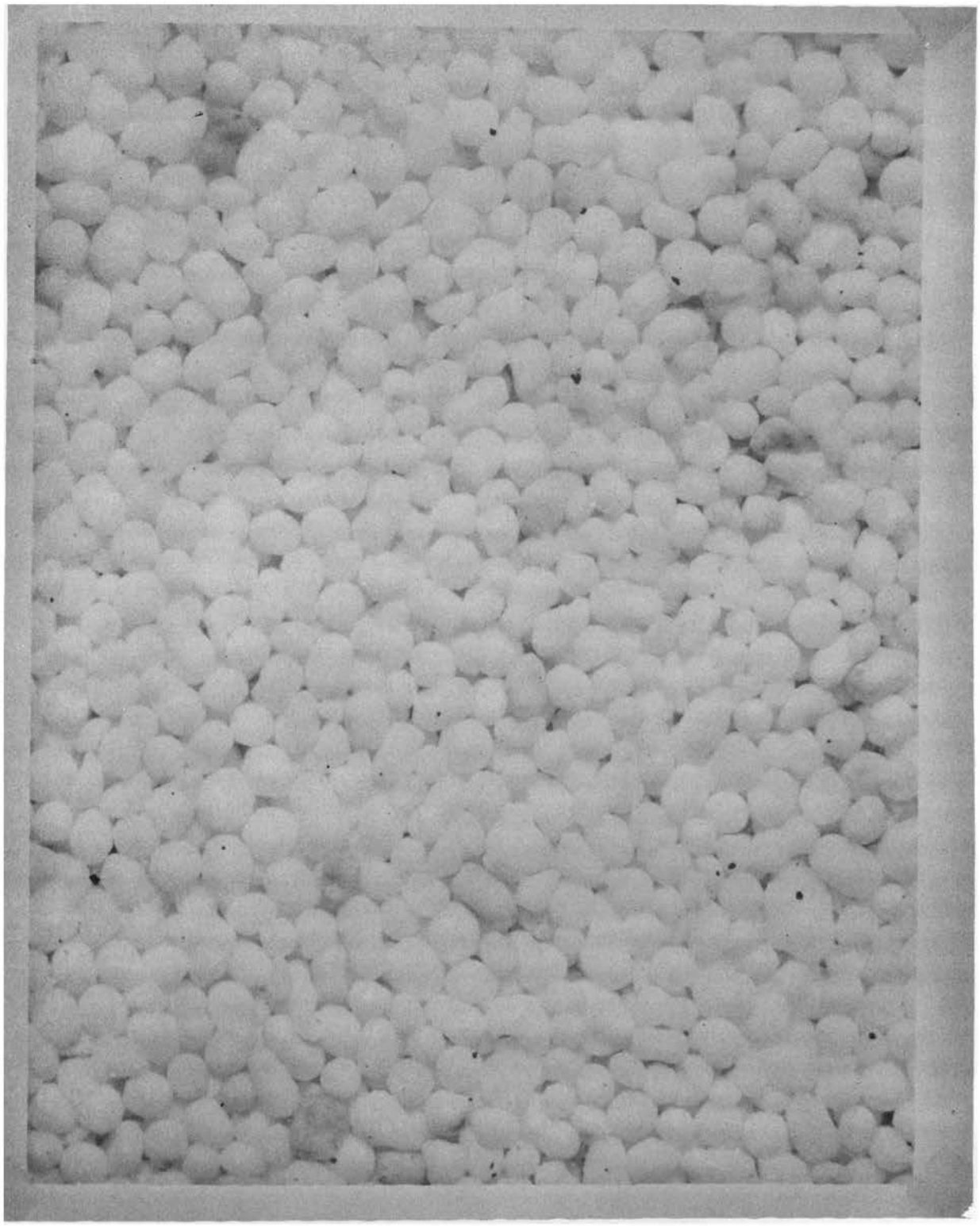


Plate IV. Typical Packing Arrangement for Standard, Coated AN Prills.

CHAPTER V

DATA EVALUATION.

A. DESCRIPTION OF EXPLOSIVES TESTED.

In order to evaluate ignition time lag, knowledge of the various physical and chemical properties of the explosives tested would be required. Data for seven different mixtures appeared to be sufficient for further study. All were blasting agents composed essentially of 94 percent by weight ammonium nitrate (AN) and 6 percent diesel fuel oil (FO), but with different bulk densities.

1. Explosive A.

This blasting agent contained a surfactant-treated clay-coated porous prill. The apparent bulk density of the mixture ranged from 0.87 to 0.89 gm/cc, with a moisture content of 0.15 percent, and an inert coating of 1.75 percent, 0.05 percent of which was a special surfactant. The mixture was considered representative of most AN/FO field-mixed blasting agents commonly used in open-cut blasting with medium-to large-diameter blastholes.

2. Explosive B.

The prilled AN in this mixture was similar to that of Explosive A, except that the moisture content was 0.20 percent and the inert coating was only 0.50 percent. The surfactant was the same as for Explosive A, and represented 0.05 percent of the total weight.

3. Explosive C.

This mixture was similar to Explosive B except that the surfactant used was of a different type. The blasting agent was an experimental compound, designed to study the influence of coatings.

4. Explosive D.

The composition of this experimental blasting agent included AN that was essentially uncoated, like that used for Explosive B. However, the hydrocarbon additives were different and were included to evaluate the effects of hydrocarbon substitutions.

5. Explosive E.

Instead of the usual porous prill included in most of the AN/FO blasting agents studied, this mixture contained a crushed, uncoated, dense AN prill mixed with 6 percent FO. The uncrushed prill was normally considered insensitive, but had a built-in anti-caking property that was ideal for agricultural purposes. The prill was crushed to provide greater sensitivity and increased density, i.e., in excess of 1 gm/cc.

6. Explosive F.

Like Explosive E, this compound was designed to achieve increased loading density. However, it was composed of uncoated AN microprills with 6 percent FO, and had a bulk density in excess of 1.1 gm/cc.

7. Explosive G.

Compounded for use in wet blastholes, this cartridged blasting agent was composed of the AN used for Explosive B, of which 50 percent was the normal-sized prill and 50 percent was crushed by a hammermill.

8. Explosive H.

This blasting agent was composed of the same ingredients as Explosive A except that all AN particles were cursched to achieve a density in excess of 1 gm/cc.

B. INFLUENCE OF THE EFFECTIVE PRIMER THRUST.

Figures 12 and 14 illustrate the relationships between effective primer thrust and ignition time-lag. In all cases, the trend seemed to indicate an increase of time-lag as the thrust was reduced. Three points of interest are shown in the graphs: (1) time-lag readings assumed a wide, scattered range in low primer thrust regions, (2) small differences in coating amounts appeared to have little effect on the time-lag, and (3) there was a considerable increase in time-lag with reduced confinement.

The occurrence of a wide scattering of ignition time-lag data indicated a critical region of ionization. Low primer thrusts often failed to produce detonation.

C. THE INFLUENCE OF CHARGE DIAMETER IN THE IGNITION TIME-LAG.

Data for investigating a charge-diameter, ignition time-lag relationship were limited because of the relatively narrow choice of primer diameters available. Therefore, to determine a meaningful relationship, time-lags for Explosive B from Figure 14 were adjusted to a constant thrust of 3×10^8 psf by the use of the curves in Figure 11. Conversion of the lags gave the relationship illustrated by Figure 15, which indicated that an increasing time-lag results from decreasing charge diameters. In the case of the primer thrust curves, the wide range of readings on the 1-inch pipe seemed to indicate proximity to the critical detonation-deflagration state.

D. THE INFLUENCE OF DEGREE OF CONFINEMENT UPON IGNITION TIME-LAG.

Mauer, in his discussion of ignition time-lag causes, proposed that the controlling factor which determined the amount of time-lag

was the degree of confinement to which the explosive was subjected. The basis of this suggestion was that the rate at which the inertia of the casing was overcome was a direct measure of the time-lag. Figures 12 and 13 confirmed the expected results. The confined state represented use of a free-flow loading density, whereas the slightly tamped and unconfined conditions existed when 1.125-inch diameter cartridges were loosely loaded in a pipe.

E. IDEAL DETONATION AND THE IGNITION TIME-LAG.

Bruzewski, Clark, Mauer, and Yancik investigated various design parameters such as confinement, charge diameter, particle size, etc. for different AN/FO blasting agents as to their influence on the velocity of reaction. Their findings showed that an increase in charge diameter tended to increase the detonation velocity up to a certain diameter beyond which no velocity increase results. This study indicated that an increase in charge diameter tended to decrease time-lag. Since the percent ideal detonation parameter was the ratio of the observed to the theoretically calculated detonation velocities, an inverse relationship between percent ideal detonation and ignition time-lag should exist. Figures 17 and 18 confirmed the relationship. Figure 19, however, revealed that when material was unconfined, the amount of time-lag was considerably increased, even though a relatively high percent of ideal detonation was achieved. Apparently, the influence of confinement on the ignition time-lag was much greater than the influence of the other factors considered.

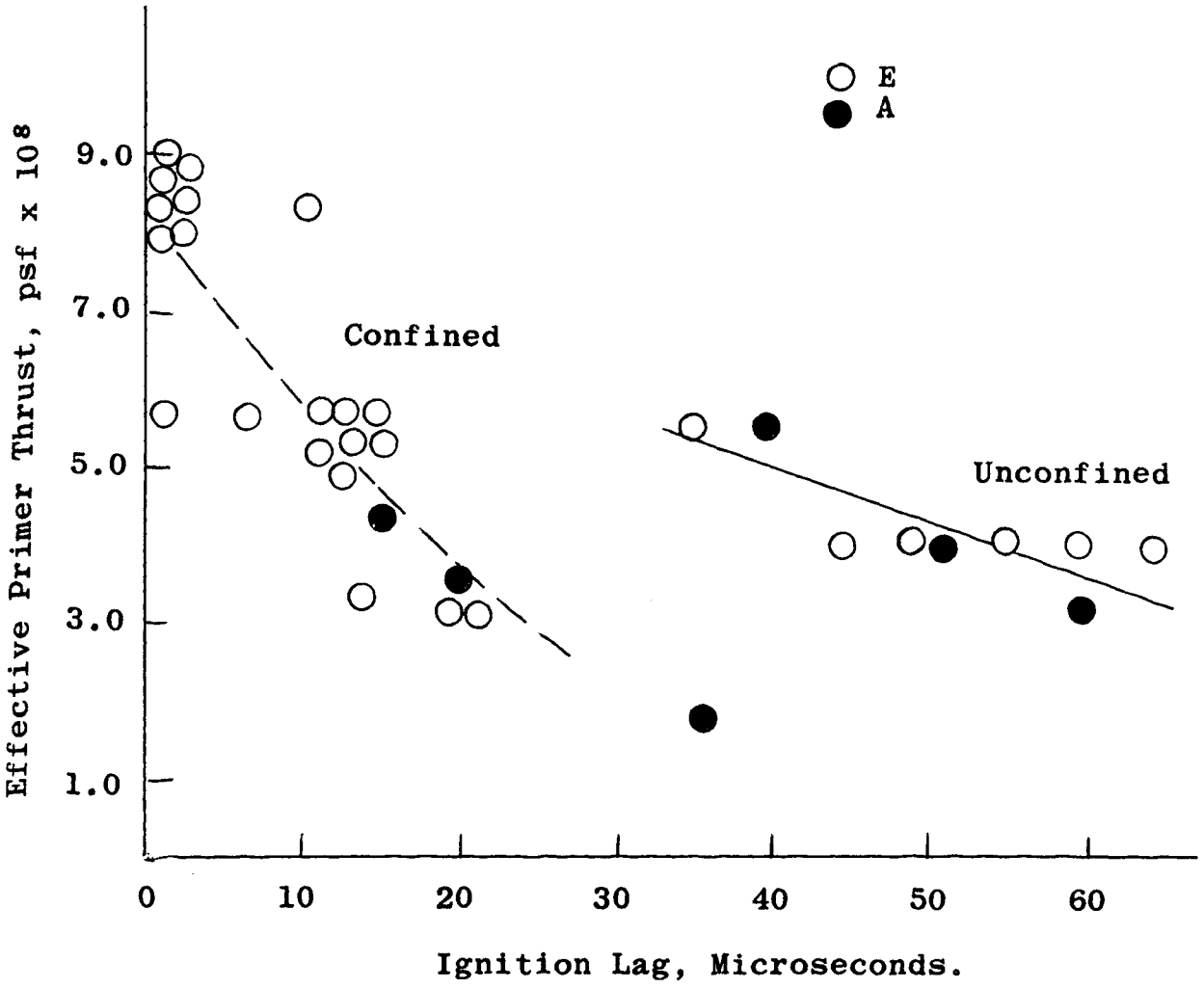


Figure 12. Influence of Confinement on the Time-Lag as a Function of Primer Thrust.

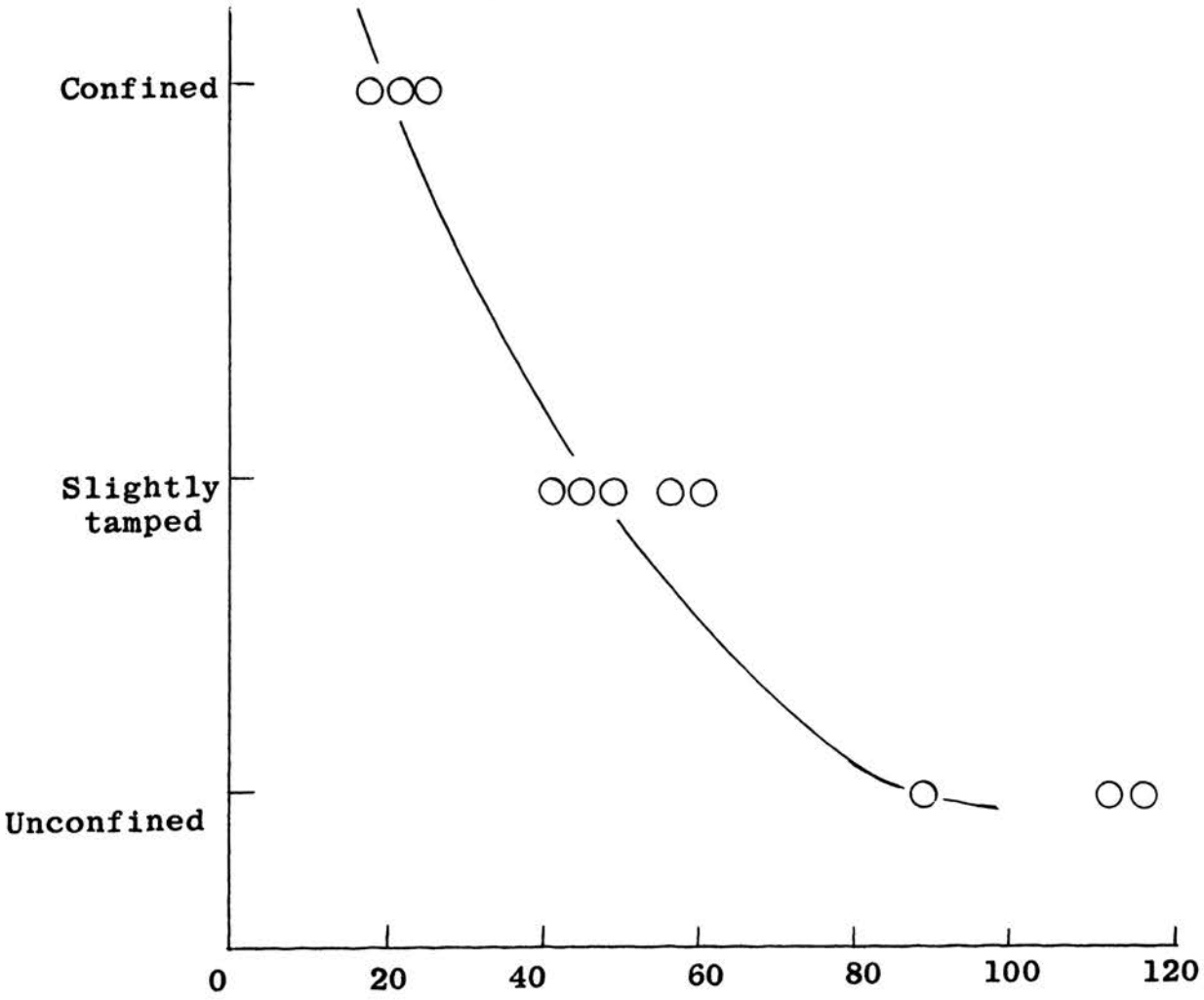


Figure 13. Influence of Confinement on Time-Lag with Constant Primer Thrust (1.60-inch Diameter, Explosive B).

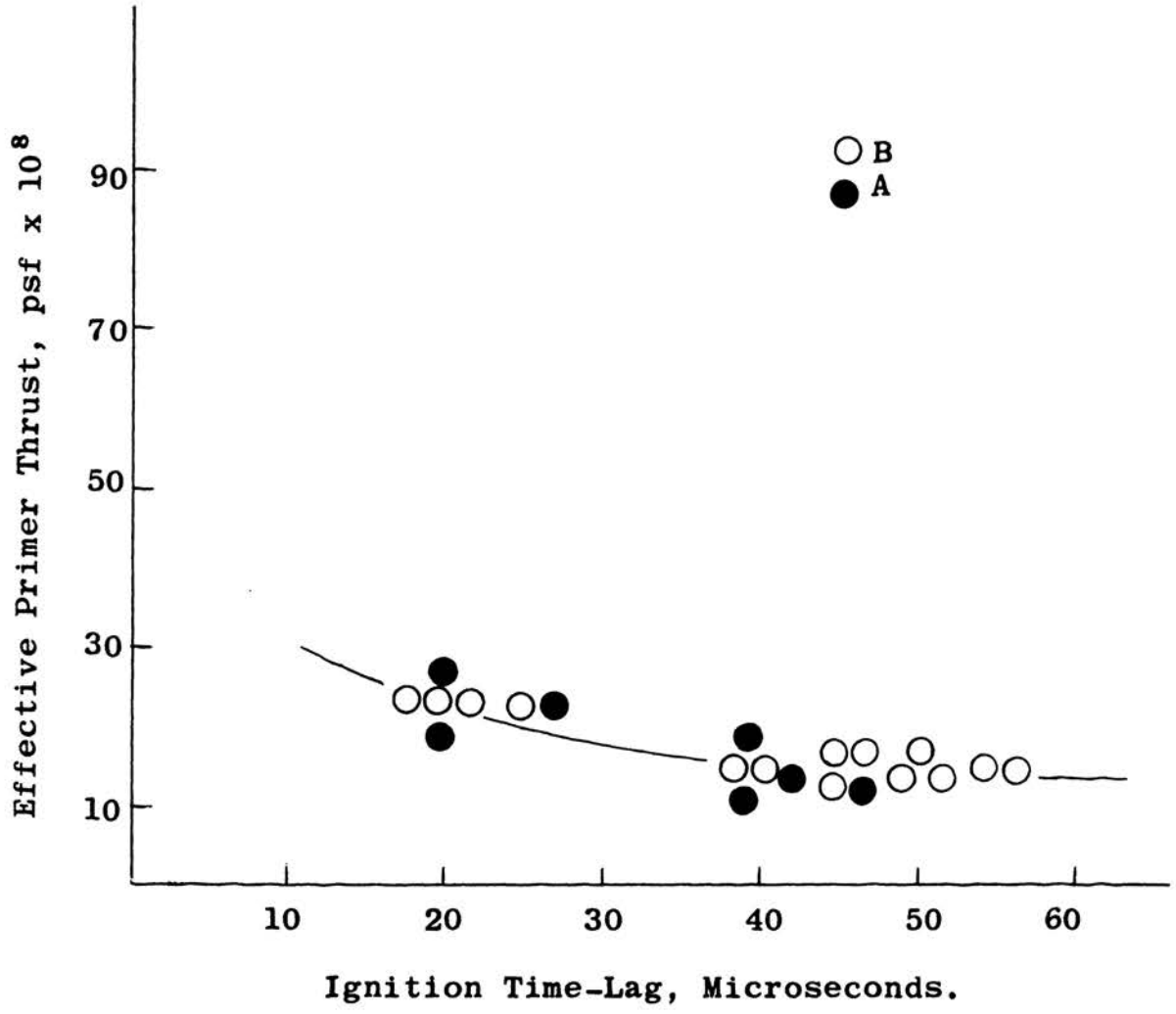


Figure 14. Influence of Coating on Time-Lag as a Function of Primer Thrust (1.60-inch Diameter, Confined).

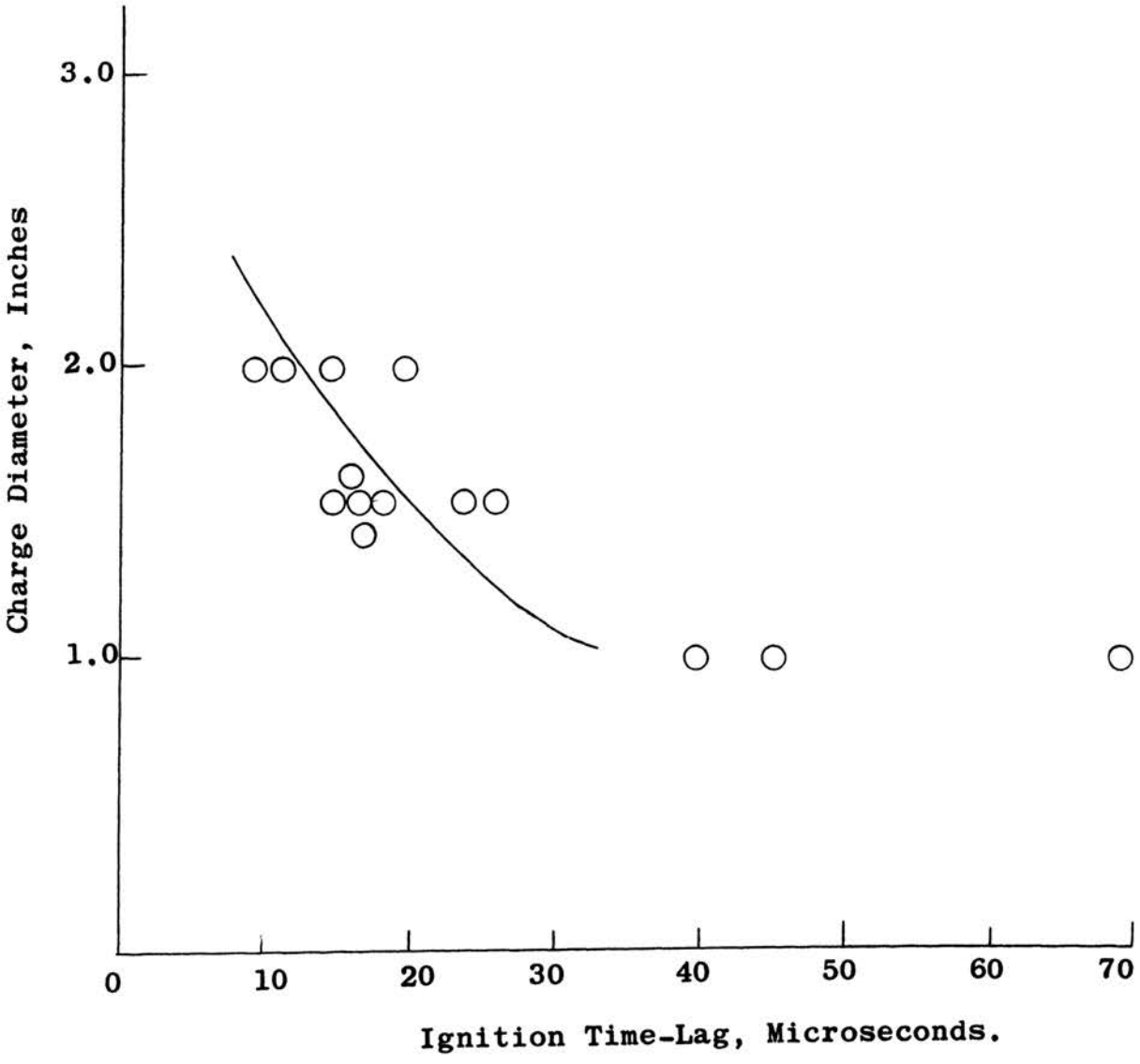


Figure 15. Influence on Time-Lag as a Function of Charge Diameter with Constant Primer Thrust (Explosive B).

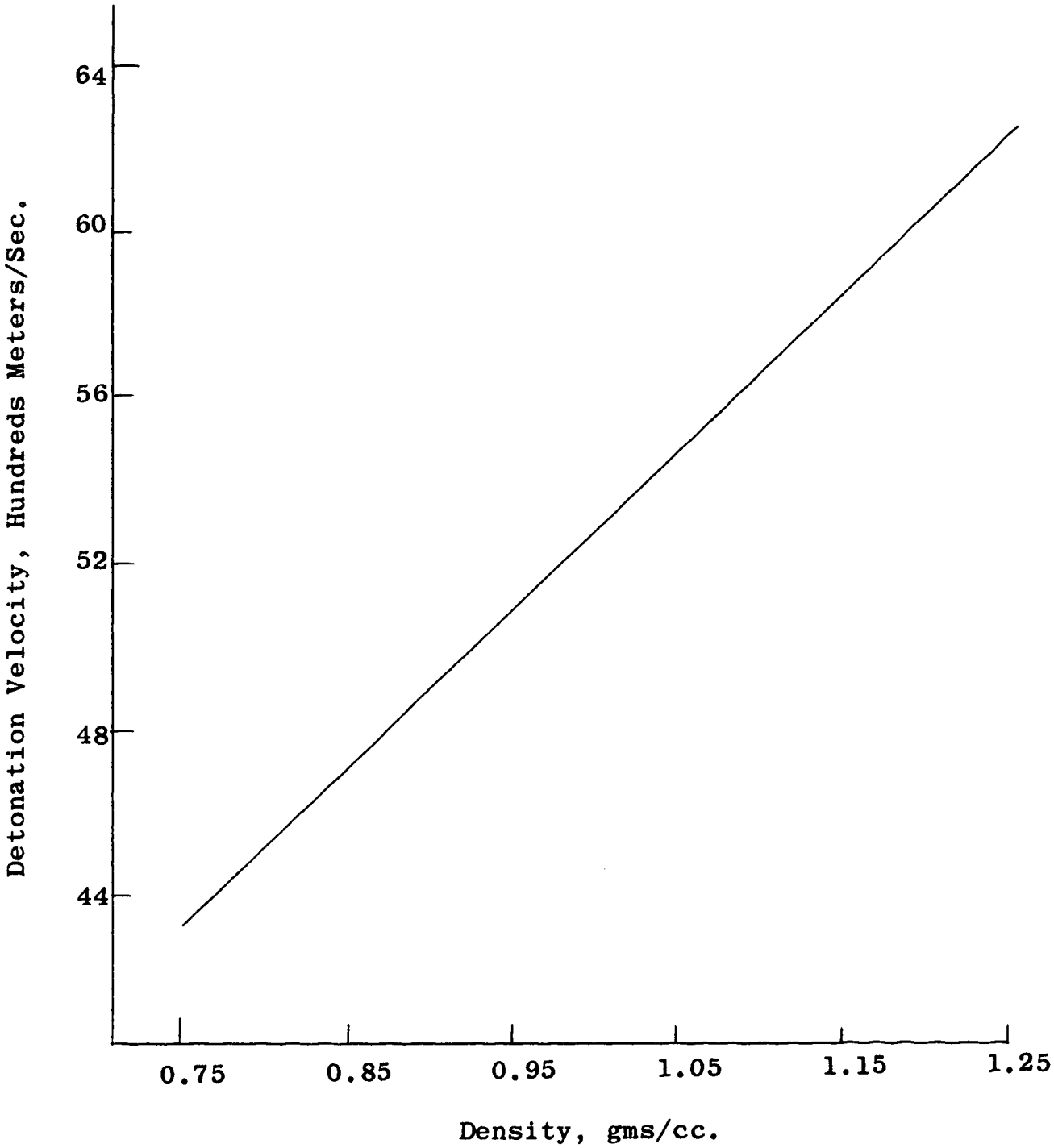


Figure 16. Variation in Ideal Detonation Velocity with Density (2).

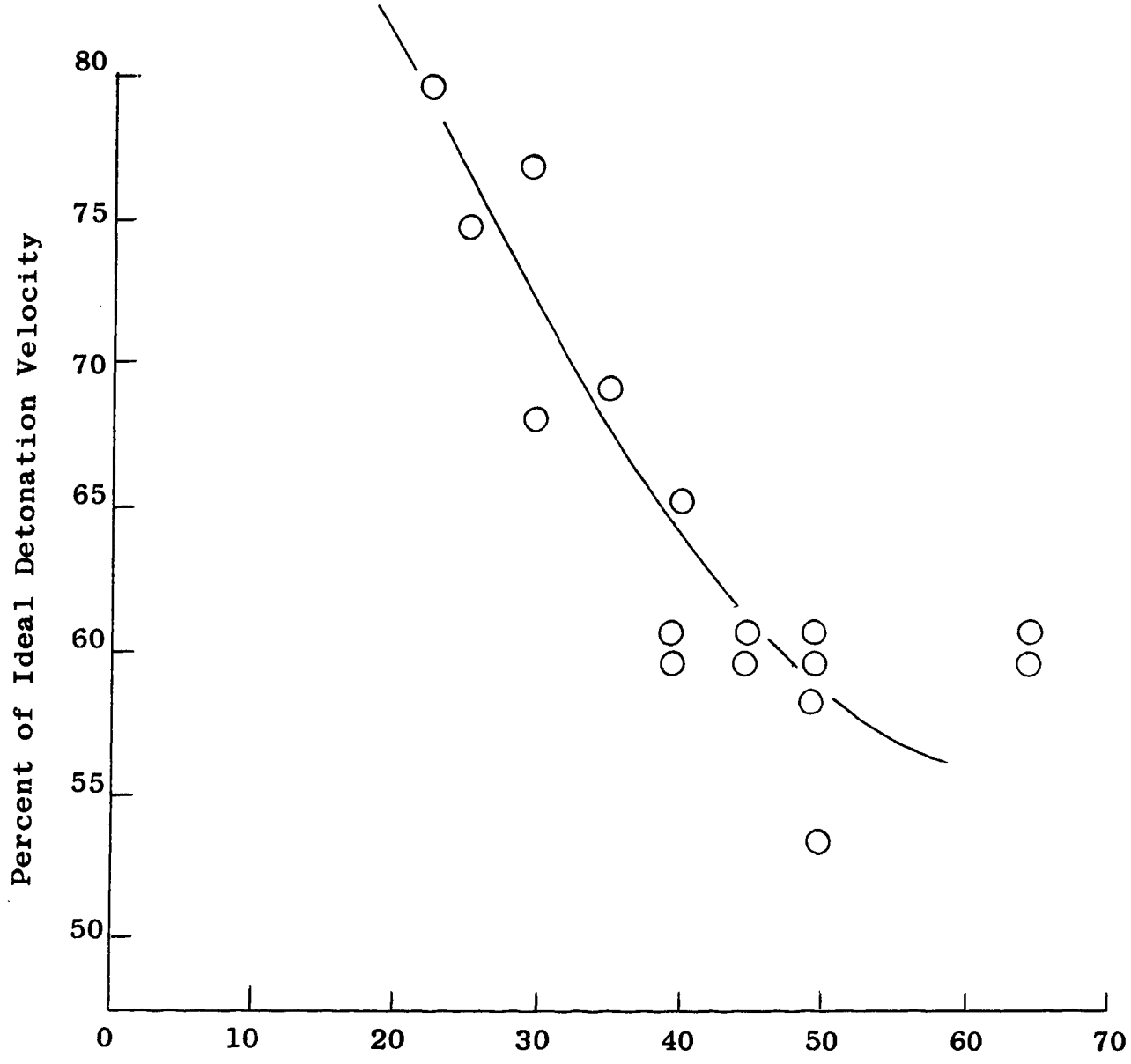


Figure 17. Relationship of Detonation Velocity to Ignition Time-Lag (1.60-inch Diameter, Confined, Explosive B).

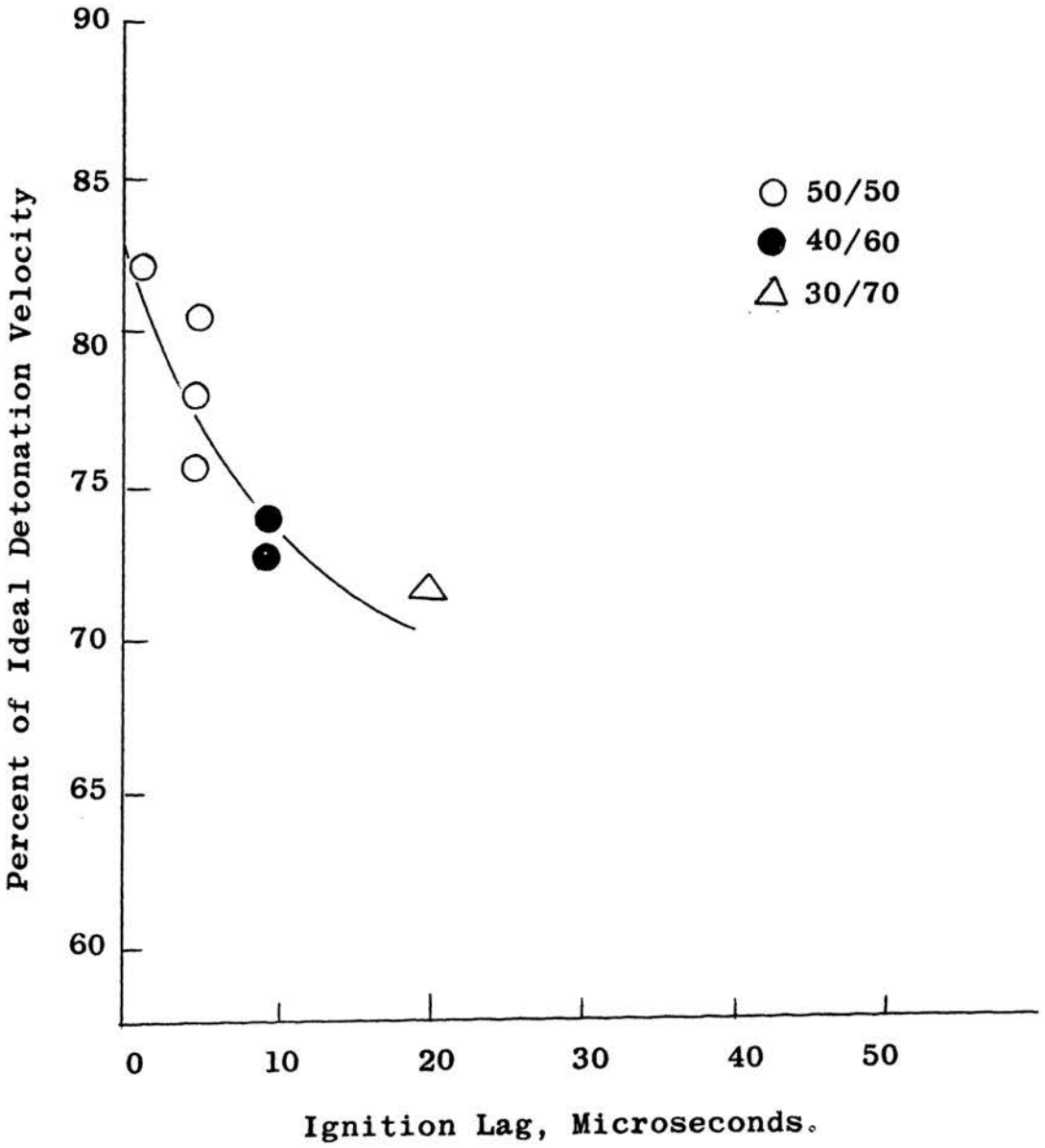


Figure 18. Relationship of Detonation Velocity to Ignition Time-Lag with Constant Primer Thrust for Medium Diameter Charges (3.0-inch Diameter, Confined, Explosive A/E Mixtures).

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS.

Photographic records obtained from probe-wire studies of AN/FO 94/6 blasting agents showed that variations in the efficiency of explosive reactions could be expected if environmental conditions were not suitable. Accuracy of the records was assured by the fact that a constant current to the probe-wire test element was maintained to within a standard deviation of 0.5 percent. Measured detonation velocities were thus within 100 to 200 fps of their true values. The probe-wire technique was simple to use and could be equally adaptable for both laboratory and in-situ field-testing.

Of particular significance, the studies revealed that the ignition time-lags were variable in duration, even though the chemical composition of explosives mixtures and the effective primer thrust were kept constant. The amount of time-lag varied exponentially but inversely with changes in charge diameter and the degree of confinement, of which the latter appeared to exert the strongest influence. When critical charge diameters existed, time-lags did not follow their normal rate of change with varying charge diameter, but increased markedly, with reactions frequently ending in failure. Ingredient coatings, on the other hand, seemed to have little effect on ignition time-lags, probably because of the small differences in amounts used. However, propagation sensitivities and reaction intensities were more greatly affected. When charges were unconfined and used in larger

sizes than the characteristic critical diameter, the ignition time-lags were found to be much greater than normal in duration but had less influence on lowering velocities. These results would be expected, however, since good propagation sensitivity existed as a result of the large diameter; however, initiation was more difficult because of the lack of confinement.

For cartridged materials used untamped in dry pipes, ignition time-lags appeared similar to those attained by semi-confined or unconfined conditions. If the pipe was water-filled, not only was the ignition time-lag greatly reduced but so also were the time-lags between individual cartridges. This result would be expected since the water would act as a confining medium.

A. Evaluation of the recorded time-lags showed that the amount of lag was indicative of the degree of total potential energy released, providing that the contention was true that detonation velocities vary directly with density changes. For the mixtures studied, it appeared likely there was a transition from detonation to deflagration for confined small-diameter charges (3-inch and less) when a lag in excess of approximately 50 microseconds occurred. The result at the transition point was that the actual reaction velocity produced was only about 60 percent of the calculated ideal rate. On the assumption that the explosion pressure thus produced from a reaction was a direct function of the detonation velocity squared for materials of similar chemical composition and loading density, it could be reasoned that the effective energy released would then be only about 35 percent of that potentially available.

B. The completeness of an explosive reaction, or the degree of maximum available energy actually released, would have an extremely

important influence on the theoretical analysis of blasting phenomena, as well as on the economics of industrial explosive applications. Knowledge of the limiting parameters for any explosive mixture below which maximum energy release would not be possible would obviously be highly desirable. Therefore, it is recommended that additional studies be conducted and in greater detail for various blasting agent mixtures in order to ascertain more clearly the true significance of the ignition time-lag. In addition, composite studies should be designed which use the probe-wire velocity-measurement technique with in-situ strain-gage stress determinations in various rocks. The tests could provide data that would serve to permit more exact measurements of rock stress-absorption characteristics, the influence of explosive reaction velocities on the wave forms of explosion induced stresses, and a correlation between the induced stress levels themselves and the energy actually released from an explosion.

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VITA

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