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AN EVALUATION OF THE RESISTANCE ELEMENT METHOD FOR MEASURING DETONATION VELOCITY OF AN-FO MIXTURES CONFINED IN SMALL DIAMETER BOREHOLES

BY

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A

THESIS

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Approved by

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ABSTRACT

Instrumentation and techniques employing a constant current in a 4 ft. length of Nichrome resistance wire embedded in an explosive mixture were developed to measure detonation velocity in small diameter boreholes.

The resistance element technique was evaluated by detonating mixtures in iron and clay pipes, and it was shown that the current in the circuit was not constant. Velocity measurements varied from 8,000 fps to 16,000 fps. Low velocity material provided poor time - voltage traces.

The resistance element method was compared to a pin oscillograph technique, and an explanation was offered for observed differences in velocity. The standard deviation for the corrected resistance element velocity records was found to be approximately two and one-half times larger than the standard deviation for pin oscillograph velocity records.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. George B. Clark, Associate Director of the Missouri School of Mines Research Laboratories, for his guidance throughout the course of this work. Especial thanks are due to Mr. R.D. Caudle, Research Engineer, M.S.M. Research Laboratories, and Mr. J.E. Lyon, Inorganic Research Department, Monsanto Chemical Company, for assistance with instrumentation; Mr. R.F. Bruzewski, Associate Professor of Mining Engineering, for aid with photographs; and Mr. E. Ragan for his assistance with the field work.

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INTRODUCTION

Since 1957, the Missouri School of Mines has been actively engaged in research on ammonium nitrate - fuel oil (AN-FO) mixtures. This research has been financially supported by the Monsanto Chemical Company of St. Louis, Missouri. The results of this program have been reported in a Master's thesis by Hopler (1961), a Ph.D. dissertation by Yancik (1960) and in the Master's theses by Kohler (1959) and Warga-Dalem (1958). An excellent summary of research work may be found in the thesis by Hopler (1961).

Recently, many articles have appeared in the literature indicating a definite trend towards the use of AN-FO mixtures for blasting in small diameter boreholes in underground workings.

Of the important parameters of AN-FO mixtures which can be measured, the detonation velocity provides a meaningful measure of the effectiveness of the explosive mixture. It was apparent however, that conventional methods of measuring detonation velocity were not readily applicable to small diameter boreholes drilled in rock.

Maurer (1961) successfully modified a resistance element technique developed by Gibson (1959), and measured the propagation velocity of AN-FO mixtures confined in boreholes drilled in rock.

OBJECT OF THE INVESTIGATION.

The object of this investigation was threefold: (1) to develop instrumentation and techniques employing a resistance element to measure the detonation velocity of AN-FO mixtures confined in small diameter boreholes drilled in rock, (2) to compare the velocity records of the resistance element method with records taken simultaneously by the pin oscillograph technique which is the standard for comparison, (3) to investigate the observed differences in velocity between the two methods and derive an appropriate correction constant.

CHAPTER 1

PIN OSCILLOGRAPH METHOD OF MEASURING DETONATION VELOCITY

Many of the methods used in the measurement of detonation velocities can be divided into two basic categories: optical or photographic, and chronographic methods (Taylor 1952). Of the chronographic methods, the pin oscillograph technique as used at the Missouri School of Mines has been highly developed in electrical instrumentation and in technique of use. The method shows the time of arrival of an ionized shock wave at discrete pin stations along the length of an explosive charge. The distance between pin switches, and the time required for the wave to travel between them is known, thus the detonation velocity can be readily calculated. Increased accuracy in the measurement is achieved by taking an average velocity from a number of pin stations along the charge length.

DESCRIPTION AND OPERATION OF EQUIPMENT

The components of the pin oscillograph (Pound 1954) consist of a triangular wave generator, a crystal controlled marker generator, a pulse forming circuit and a modified Tektronix 535 oscilloscope. The triangular wave generator lengthens the recorded trace from a straight line to a zig-zag sweep to obtain sufficient time resolution for a reasonable accuracy in the determination of velocity. The crystal controlled marker generator superimposes time markers on the trace to facilitate reading of the records. The pulse forming or mixer circuit is a network of resistors, capacitors and diodes which form and send to the oscillograph electrical pulses indicating the arrival of the detonation wave at the various pin stations along the explosive charge.

The pins are constructed as follows: Two small holes are drilled in a # 3 lab cork, and a # 28 gage copper wire is threaded through the cork and twisted tight on the upper side. A maximum of eleven corks is placed in accurately spaced holes drilled along the length of an iron pipe, 3" in diameter, and 48" long. One wire is attached to the pipe which acts as a ground for the system. A potential of approximately two thousand volts is applied to the pins just prior to firing a shot. Each pipe is primed with a # 6 cap and 4-1/2 sticks of 60%

ammonia dynamite. No velocity measurements are made over the first twelve inches of the pipe to allow the explosive material to stabilize at its characteristic velocity. Iron pipe has been found to closely approximate conditions of confinement found in a borehole drilled in solid rock (Yancik 1960).

After initiation, the shock wave proceeds along the explosive column, and strikes pin switch # 1, which acts as a trigger, unblanking the oscilloscope tube and starting the sweep. As the ionized shock wave strikes each succeeding pin switch it completes a circuit, and a signal is sent to the pulse forming circuit, which differentiates it and sends it through a co-axial cable to the pin oscillograph which superimposes it on the triangular wave seen on the oscillograph trace. The trace is then photographed on polaroid film to provide a permanent record.

The pin method of measuring detonation velocities of explosives works very well in the field when using mixtures of ammonium nitrate and fuel oil confined in iron pipes. However some modification of the technique is required to measure velocity in boreholes drilled in rock, and shot under actual field conditions. One modification adopted which provided good success is described as follows: A series of small holes was drilled in a rectangular wooden dowel, 5/16" x 1/2" x 51" long at the same spacing as those on the iron pipes. The # 28 was threaded through these holes and pulled tight. A ground wire was also threaded through the dowel beside each pin wire. Some extra care is required when building this type of borehole cable. Each pin wire should be covered with a few turns of electrical tape to prevent shorting of the pins to ground when the unit is placed in a borehole filled with explosive.

This type of borehole cable can be used in holes where the area of the hole is large compared to the area occupied by the dowel and cable. For small holes, the area of the dowel could be reduced, however some minimum size of dowel is required to support the pin wires at the proper spacing. In field trials where this type of borehole was used, it occupied approximately 3% of the area of the hole.

Measuring velocities in small diameter boreholes of the order of 1 1/2" to 1 1/4" requires some other type of measuring device, since the wooden dowel and cable would occupy a considerable area of the hole, and could interfere with the reaction of the ammonium nitrate-fuel oil mixture to the extent that detonation would fail.

CHAPTER II

RESISTANCE ELEMENT METHOD OF MEASURING DETONATION VELOCITY

Electrical methods have been devised (Gibson *et al* 1959), (Amster *et al* 1959) for the continuous determination of propagation velocity in opaque materials under total confinement. These techniques utilized the reduction in resistance of Nichrome wire as it is consumed by a detonation front advancing through a column of explosive. A voltage is applied to the Nichrome wire from a constant current source. As the wire is consumed, the voltage across it changes at a rate proportional to the detonation velocity. The measurement of the change in voltage, and its change with time is a measure of the detonation velocity.

THEORY

Consider the case where a stable detonation wave travels along a column of explosive. Inside the column a narrow loop of Nichrome wire is placed parallel to the long axis of the explosive. If a potential has been placed across the wires from a constant current supply, at any time after initiation of the detonation wave the potential drop across the wire is directly proportional to the resistance of the wire remaining in the circuit.

then $$E \propto RLn \;\ldots\ldots\ldots\ldots\ldots (1)$$

where: $R =$ resistance of the wire per unit length

$L =$ length of charge

$n =$ number of wires

when current is present,

$$E = IRLn \;\ldots\ldots\ldots\ldots (2)$$

Differentiating (2) with respect to time yields

$$\frac{dE}{dT} = IRn\,\frac{dL}{dT} \;\ldots\ldots\ldots\ldots (3)$$

transposing:

$$\frac{dL}{dT} = \frac{dE}{dT} \times \frac{1}{IRn} \;\ldots\ldots\ldots (4)$$

where dL/dt is the rate of propagation of the detonation front, and dE/dt is the slope of the time-voltage trace recorded on the oscilloscope. The slope is equal to:

$$\frac{dE}{dt} = \frac{\text{y sensitivity (v/cm)}}{\text{x sensitivity (sec/cm)}} \times \frac{\text{y displacement (cm)}}{\text{x displacement (cm)}}$$

or $$\frac{dE}{dt} = K \tan \emptyset \text{ ....(5)}$$

substitution in (4) yields:

$$\frac{dL}{dt} = \frac{K}{IRn} \tan \emptyset \text{ ....(6)}$$

or $$D = \frac{K}{IRn} \tan \emptyset \text{ ....(7)}$$

Thus the calculation of the detonation velocity D requires that I, R, n, tan Ø and the constants of the oscilloscope be known.

IONIZATION

Associated with the detonation front is an ionized zone, which for practical purposes and small charge diameter has a negligible resistance. Cook (1958, p146) lists a table of ionization measurements in 5.1 cm. diameter cylindrical charges. Resistivity for a number of granular military explosives varies from 1.13 ohm-cms. to 2.73 ohm-cms. A resistivity of 28.5 ohm-cms. is shown for a granular mixture of 80/20 AN-TNT. The particles of the mixture were 0.042 cm. in diameter, (USSS mesh size approximately 40/50). The high resistivity indicates less ionization in the detonation head for this type of explosive. It is possible that the same high resistivity would be exhibited by AN-FO mixtures. Jaffe *et al* (1961) indicate in preliminary measurements that the resistance in the detonation front for a number of cast military explosives is less than 0.2 ohms, for small charge radii.

The two resistance element methods under discussion take advantage of the ionization present in the detonation front, to either make a circuit or maintain an existing circuit. Both methods assume the resistance of the ionized zone is small and exercise little influence over the measurements taken during a test. This assumption may not be true for AN-FO mixtures.

PREVIOUS EXPERIMENTAL PROCEDURES

The two resistance element methods are based on the same principle, however they have been applied somewhat differently by various investigators. Four techniques of placing resistance elements in columns of explosives have been utilized successfully:

i. Gibson (1959) wound a # 40 Nichrome wire under tension around a nylon insulated # 34 copper wire. The copper wire served as a core for the element as well as one of the leads. A constant linear resistance of 12 ohms/cm. was obtained with this technique. Current was maintained at approximately 50 milliamps in the circuit. The performance of the method was evaluated using short charge lengths(10 cms) of composite propellents, fuel oxidized systems and high explosives. Velocities of detonation determined under steady state conditions agreed with counter chronograph methods within 3%. This method depends upon ionization in the detonation front to maintain a complete circuit between the two wires.

ii. Amster (1959) placed a single wire along the inside wall of a mild steel seamless tube. The tube was two inches in outside diameter and approximately twenty-four inches long. The wire was supported by lucite blocks which held it parallel to the long axis of the pipe. The explosive was then cast around the wire, the lucite blocks removed and the wire trimmed to the required length. A negative potential of approximately 30 volts was applied to the wire. Current was maintained at 200 milliamps. The technique depends upon the ionization to make a circuit between the wire and the confining steel casing which is held at ground potential. The method was evaluated by confirming the known detonation velocity of Composition B, a military explosive. Results indicated that the method was proven within an experimental error of 3%. An oscilloscope record of the detonation velocity of Composition B is shown at the end of the report. The trace exhibits a remarkably linear form.

iii. Jaffe (1960) employed the same circuit as in (ii) above, to determine the critical diameters of a number of propellent and explosive compositions. A number of experiments were performed using three different systems of resistance elements.

a. A co-axial wire 0.5 mm. in diameter, consisting of a Nichrome wire core insulated from a copper shield, the unit being cast in the centre of a test charge.

b. A bare # 40 Nichrome wire, and a bare copper wire cast approximately 3mm apart, parallel to the axis of the charge.

c. A bare # 40 Nichrome wire cast in the charge, together with a copper strip taped to the outside of the charge.

The co-axial wire provided records which were the most difficult to read of the three types evaluated. Distances between two wires varied from 0.2 mm in (a) up to 10 mm. in the case of (c).

iv. Maurer (1961) successfully applied Gibson's technique to measuring detonation velocities of AN-FO mixtures in small diameter boreholes (1 1/2" to 2 1/2") drilled in a rock face. The circuit used was similar to Gibson's, except a Type 815 beam power pentode electron tube was substituted for a Type 813. Measurements of detonation velocity were obtained for eleven different brands of AN-FO mixtures. Effects of primers, stemming, fuel oil, moisture, inert materials, prill size, overdrive and primacord were evaluated.

ESTIMATES OF ACCURACY

Gibson based his method on the operating characteristics of an 813 beam power pentode. At 600 volts plate voltage and approximately -20 volts grid bias, the tube operates on the flat portion of the characteristic plate voltage-grid current curve and the change in grid current for a full load-no load condition in the field would be very small. Overall accuracy is estimated at 3%. Amster indicates several estimates of accuracy in the various components of his technique:

1. Variation in resistance wire, less than 0.1%
2. Variation in current, ± 0.1%
3. Instability of electrical components, less than 0.7%
4. Change in resistance of the wire during detonation, less than 0.5%
5. Open circuit voltage, ± 0.05%
6. Error in reading the slopes (computed by a telereader and desk calculator) ± 0.03%

Overall error in the determination of detonation velocity is approximately 2%. Maurer indicates the error in the resistance of the wires, the constant current and the calibration of the oscilloscope is less than ± 0.5%. It will be shown later in the thesis that the operating characteristics of the Type 815 tube are not as good as the Type 813 tube, and that there is some variation of the current in the circuit.

ANALYSIS OF METHOD

The records of the change in voltage with the change in time readily show irregularities in trace continuity when non-stable conditions exist, and smooth continuous traces where detonation is well established. These methods of determining velocity are particularly suited to observing detonations which exhibit variations in the velocity, such as transitions from deflagration to detonation or the effects of overdriving a mixture of AN-FO with a high velocity primer. Analysis of records yields the position of the detonation front and the velocity at any time after detonation of the charge.

CHAPTER III

EXPERIMENTAL INSTRUMENTATION

COMPONENTS

Figure (1) shows a schematic diagram of the detonation velocity instrumentation used in this investigation. The following is a description of the components:

1. Power Supply. Two power supplies have been used to furnish constant current for the tests. They will be discussed in detail in a subsequent section.

2. Resistance Element. The resistance element consists of approximately ninety-six inches of # 36 liquid nylon coated Nichrome wire. The wire had a resistance of 27.71 ohms per foot.

3. Oscilloscope (v). A Tektronix oscilloscope, type 535A together with a 53/54 C plug-in amplifier was used to measure the change in voltage with the change in time.

4. Voltmeter. A Video Model ENO - 2, Manual Digital Voltmeter was used to take current readings with an accuracy of 0.5%. This instrument was a null-balance type meter.

5. Resistor. A 0.1% precision resistor was used to provide a means of observing the regulation of the current at the same time the detonation velocity was measured.

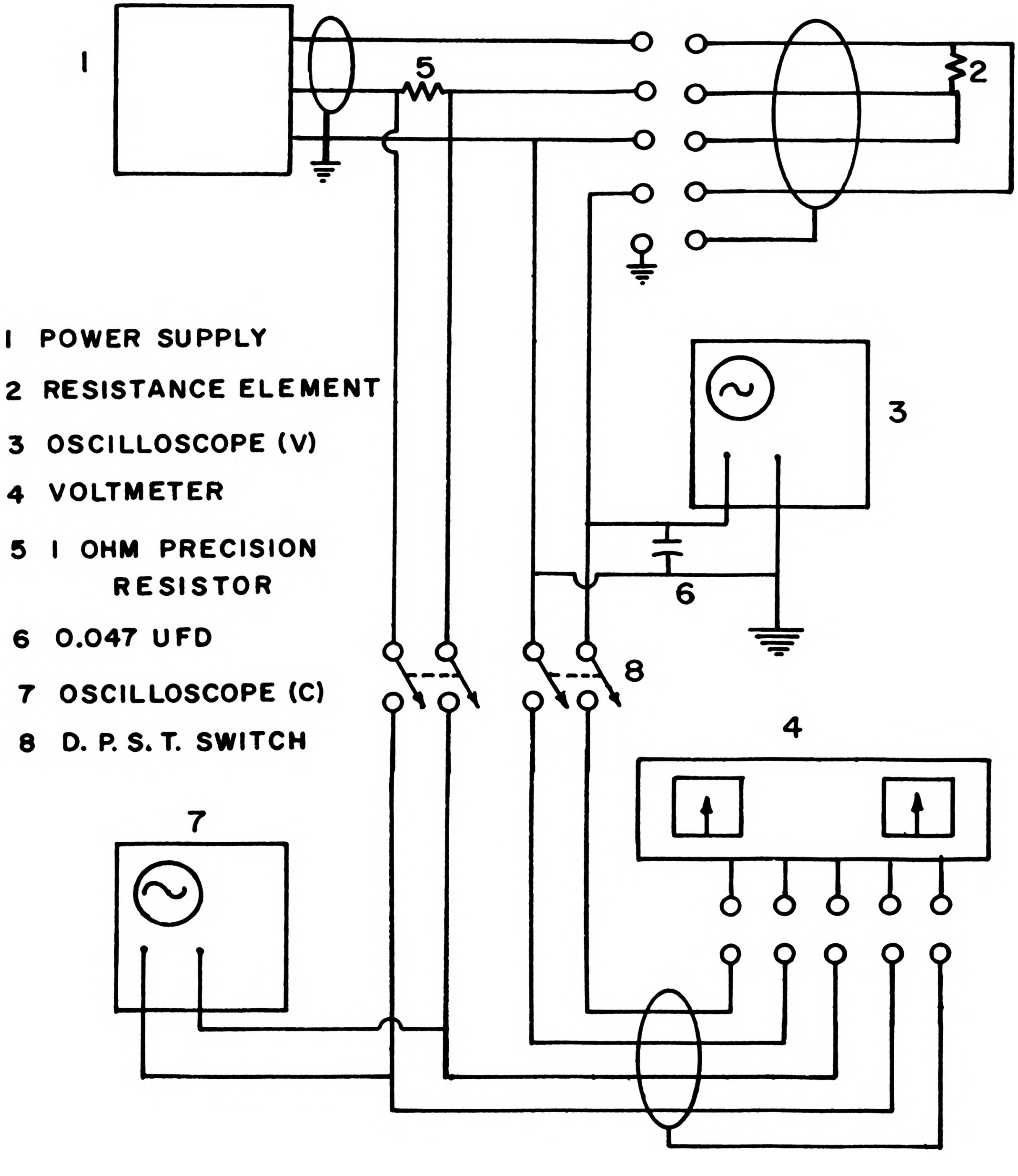
6. Capacitor. A 0.047 μfd. capacitor was placed across the voltage input to the oscilloscope to cut down on the high frequency noise in the signal.

7. Oscilloscope (c). A Tektronix oscilloscope, type 533 together with a 53/54 A input amplifier was used to record the current regulation of the power supply.

8. Switches. Two D.P.S.T. switches were used to check the current and the voltage present in the resistance element. Normally the meter was out of the circuit.

POWER SUPPLIES.

i. Commercial Type. A commercial transistorized regulated power supply(Perkin Model TVRC 040-04) was used in the early stages of this investigation to provide constant current in the resistance element.



DETONATION VELOCITY INSTRUMENTATION

Figure 1

Important specifications for the unit were as follows:

voltage range - (0 - 40) volts.
current range - (0 - 500) milliamps.
static load regulation, voltage ± 0.01%
current ± 0.02%
recovery time - 25 microseconds.

The performance of this unit in the field was not satisfactory. There appeared to be too much high frequency noise in the records. Analysis of the records indicated that the power supply could not respond quickly enough to maintain a constant current in the circuit.

Ionization in the detonation front for some AN-FO mixtures is very weak, and the detonation front can exhibit an irregular velocity. Cook (1958 p57) describes a 94/6 AN-FO test shot that propagated its entire length in a pulsing motion. If the detonation does proceed in this manner, then the irregular motion in the detonation front could cause the resistance element to be consumed in an erratic manner. Consider the case when there is a momentary open circuit at any time (t) during a test shot, and there is no current flow in the circuit. The open circuit could be caused by very weak ionization in the detonation front, or in the extreme case, no ionization at all. At time $(t + \Delta t)$, current begins to flow in the circuit and the power supply is required to respond to this instantaneous change in current. Should there be a large number of momentary open circuits during a test shot, then it is entirely possible that the power supply could not regulate the current at any constant value.

A test procedure was devised to simulate a condition where the power supply is required to respond to an instantaneous change in current. The circuit shown in figure (2) was employed. Figure (3) is a diagram of a typical response time of an abrupt change in load for a regulated power supply.

Figure (4) shows the response of the Perkin power supply when a square wave was applied to the circuit. The following constants were employed:

square wave generator, - 50,000 cps.
oscilloscope (current) - time per cm. = 10 μ sec.
volts per cm. = 50 millivolts

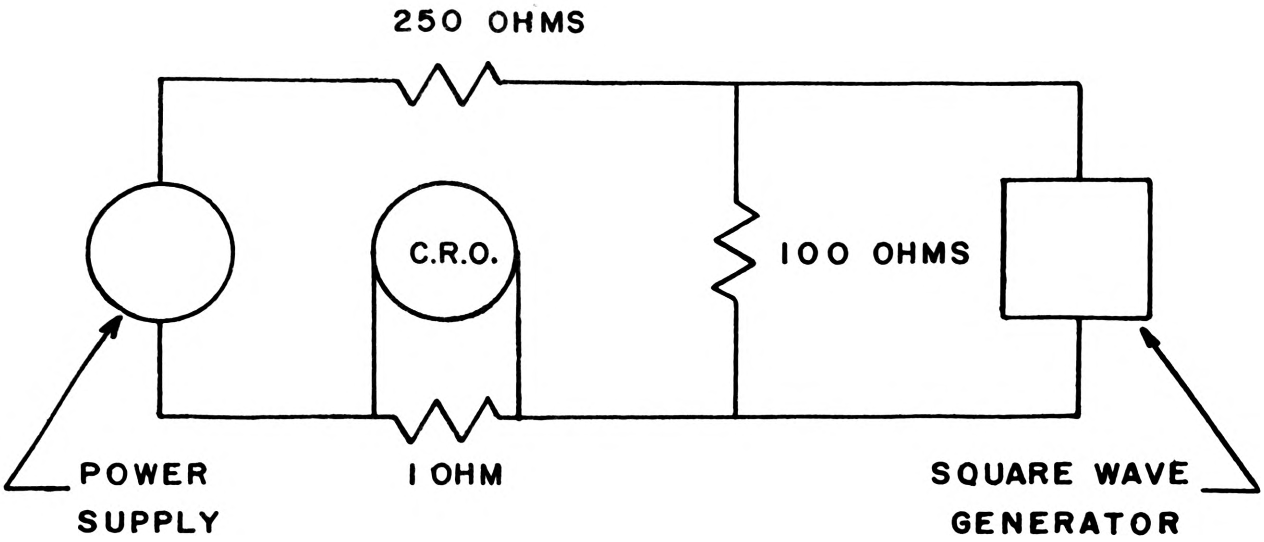


Figure 2. Circuit Employed to Simulate the Application of an Instantaneous Change in Current in the Circuit.

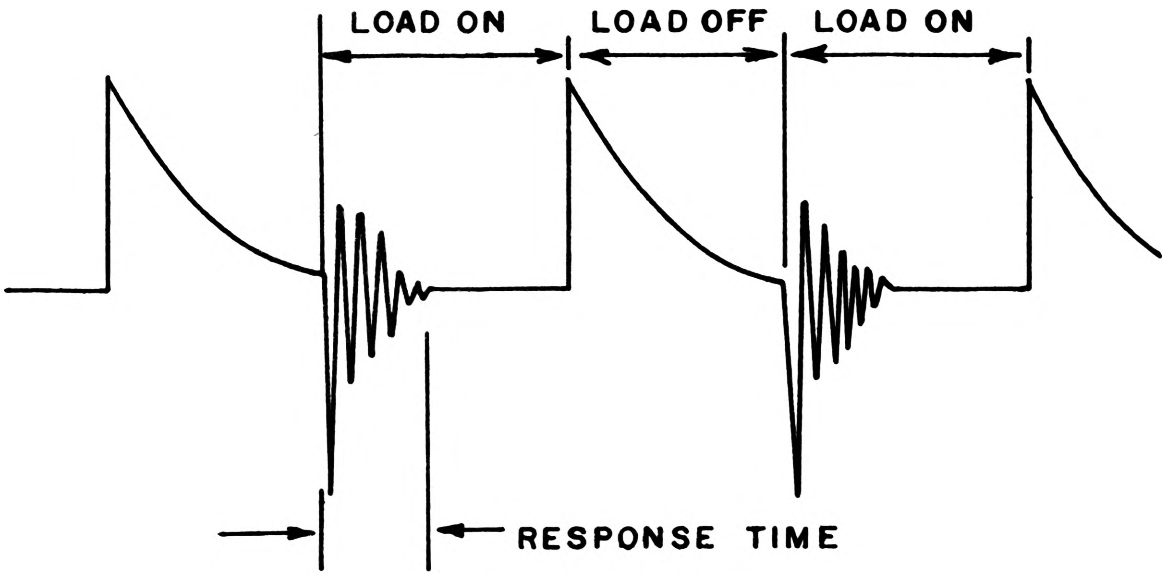
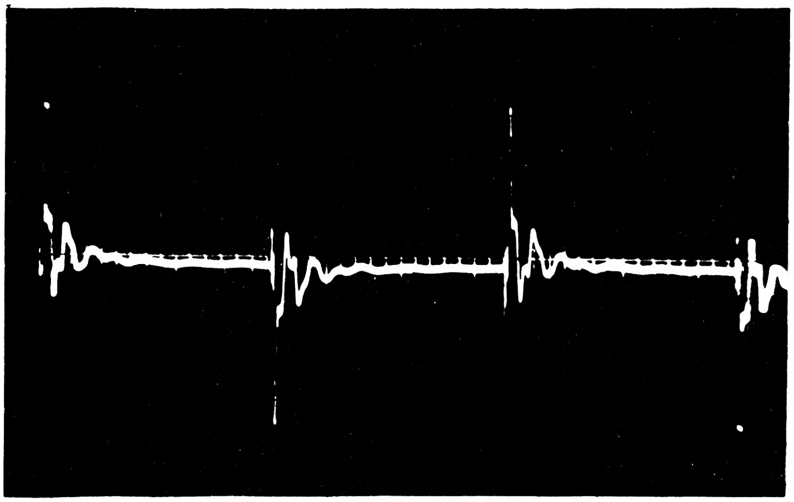
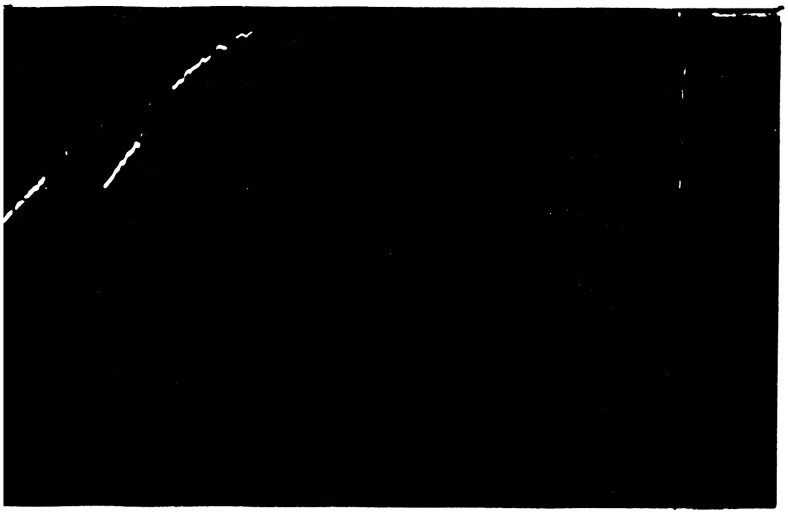


Figure 3. Typical Response Time of an Abrupt Change in Load For a Regulated Power Supply.



Response of the Perkin power supply to an instantaneous change of current in the circuit.

Figure 4.



Photograph of current in the circuit under actual test shot conditions.

Figure 5

constant current from the power supply - 66.5 milliamps.

voltage across the resistance element - 30 volts

The peak change in current was 139 milliamps and the current oscillations in the circuit died down in approximately 8 to 10 μ seconds. The average length of record for a test shot in an iron pipe is approximately 250 μ seconds. If there are as few as thirty to forty momentary open circuits during a test shot, then the power supply could not be expected to regulate the current within an acceptable tolerance. A number of inductances were placed in series with the resistance element in an attempt to control the current oscillations in the power supply, however an inductance of suitable size to provide some control also inhibited the flow of current.

Several reasons why there is some delay time involved before a regulated power supply becomes stabilized after there has been an abrupt change in the load are as follows (Gottlieb 1962 p 15):

1. Shock exitation of inductances and capacitances frequently takes the form of damped oscillations.
2. Energy storage elements impose time constants which do not permit instantaneous changes in current or voltage level.
3. Low frequency response of certain transistors having frequency cut-off characteristics of several kilocycles have a much longer response time than that which can be obtained with a vacuum tube.

Figure (5) is a photograph of the current in the circuit when a velocity test shot was made. It is obvious that there is no current regulation, and the power supply is unable to perform the duty required of it in this type of test.

ii. <u>Project type</u>. A power supply was constructed employing a circuit similar to Gibson's when it became apparent that the Perkin device could not regulate the current within required limits. Figure (6) is a circuit diagram of the power supply. A Type 815 pentode was used to control the current primarily because Maurer appeared to have good success with this tube. However examination of the characteristics of the Type 815 shows a recommended screen voltage of 225 volts maximum and a plate voltage of 550 volts maximum. The voltage regulating tubes in this circuit provide for 290 volts on the screen, which is excessive and will contribute to a short tube life. The capacity of the 813 tube is

CONSTANT CURRENT POWER SUPPLY

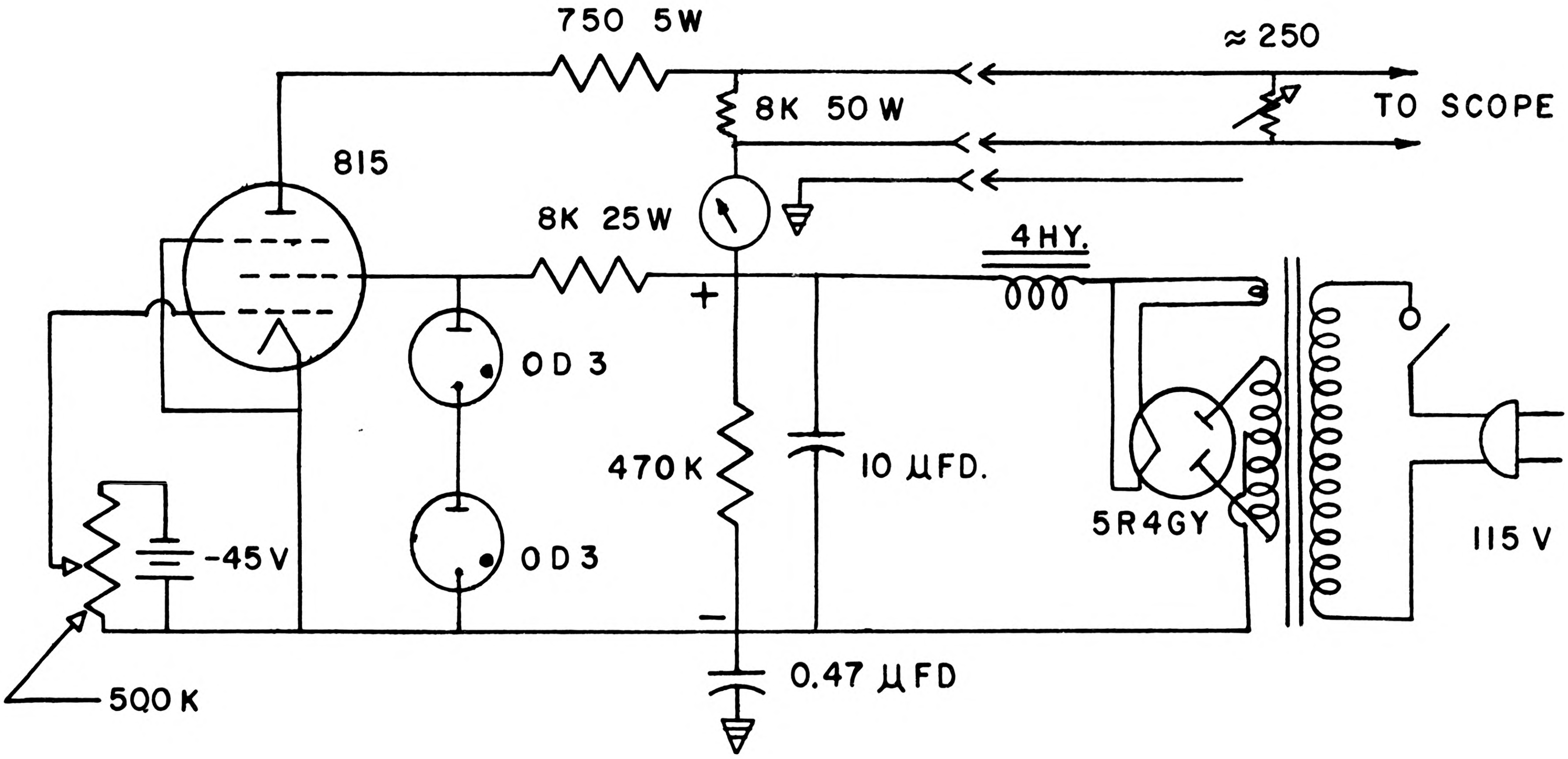


Figure 6

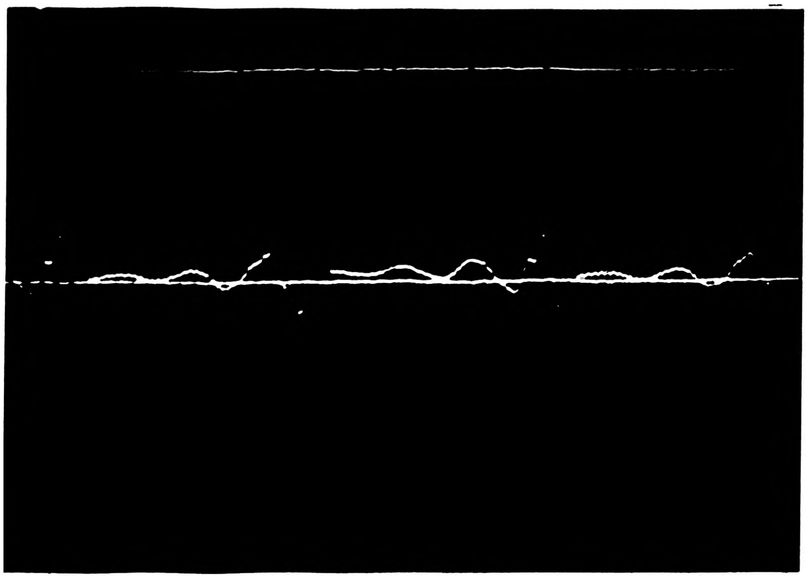
1100 volts maximum on the screen, and 2250 volts maximum on the plate, and it appears to be a superior tube for the type of service required. In the present circuit dc voltage is obtained from a 600-0-600 volt transformer through a full wave rectifier and one L-section filter.

A number of modifications have been incorporated into the basic design referred to previously (Gibson). The 1 meg-ohm resistor which was in series with the grid and the bias voltage control has been removed and replaced with a 500 K-ohm potentiometer. This allows sensitive control of the current in the tube. The 500 ohm resistor in series with the plate and the resistance element in the field has been increased to 750 ohms. This increased resistance lowers the plate voltage on the tube to approximately 400 volts maximum. The third modification of the equipment is a protective measure which prevents an excessive amount of screen current being drawn when there is an open circuit in the field after a test shot has been fired. A resistance of 8 K-ohms has been placed in parallel with the field resistance element. When the Nichrome wire has been consumed in the test shot, the load in the circuit consists of 8.75 K-ohms in series with the plate. This load limits the screen current in the tube to approximately 50 milliamps, and the plate voltage to 113 volts. When the circuit is open in the field without the 8 K-ohms present, the plate voltage drops to zero volts, and the screen current rises to an excessive value.

Figure (7) is a photograph of the response time of the Project power supply at the time when a square wave is applied to the circuit. the constants employed in the circuit were as follows:

square wave generator - 50,000 cps.
oscilloscope (current) - time per cm. = 10 μ sec.
- volts per cm. = 20 millivolts.
constant current from power supply - 58 milliamps.

The peak current was 12 milliamps. The ringing in the circuit does not die down before the next pulse of the square wave is applied, however the amplitude is very small. In order to compare this trace with Figure (4) it is necessary to divide the 12 milliamps by the ratio of 50/20, which results in 4.8 milliamps peak current at the same sensitivity as in Figure (4). The present power supply is approximately twenty-eight times more stable than the Perkin in responding to an



Response of the Project power supply
to an instantaneous change in current
in the circuit.

Figure 7.

instantaneous change in the current. Figure (8) shows the quiescent points for two load conditions in the circuit. Plate current in milliamps is shown for the whole tube, while the characteristic curves illustrating the flat portion where the tube operates are drawn for one-half the tube. These curves are representative only, since they are drawn for a screen voltage of 200 volts.

The insert on Figure (8) shows the quiescent points for the following load conditions:

a. <u>Solid lines</u>. The 8 K-ohm resistor is in parallel with an approximate 250 ohm field resistance element.

At point A the following readings are obtained:

current = 125 milliamps. (250 ohms in the field)
plate voltage = 372 volts.

At point B the following readings are obtained:

current = 129 milliamps. (≈ 0 ohms in the field)

At point E, when there is an open circuit in the field:

current = 50 milliamps.
plate voltage = 113 volts.

Two hundred and fifty ohms represents a loop of Nichrome wire (27.71 ohms per foot) 4 1/2' long, which is approximately the length of a pipe or a borehole used for test shots. The current in the circuit increases 4 milliamps during the time taken to consume the wire in a test.

b. <u>Dotted lines</u>. The 8 K-ohm resistor is not in the circuit.

At point C the following readings are obtained:

current = 125 milliamps. (250 ohms in the field)
plate voltage = 378 volts.

At point D the following readings are obtained:

current = 127.5 milliamps. (≈ 0 ohms in the field)
plate voltage = 400 volts.

In the above case the current change was only 2.5 milliamps. The 2.5 and the 4 milliamp changes in current are inherent characteristics of the power supply, and illustrate that the current is not constant for these load conditions. These changes in current will be included as part of a correction factor which is to be applied to detonation velocities obtained with this method.

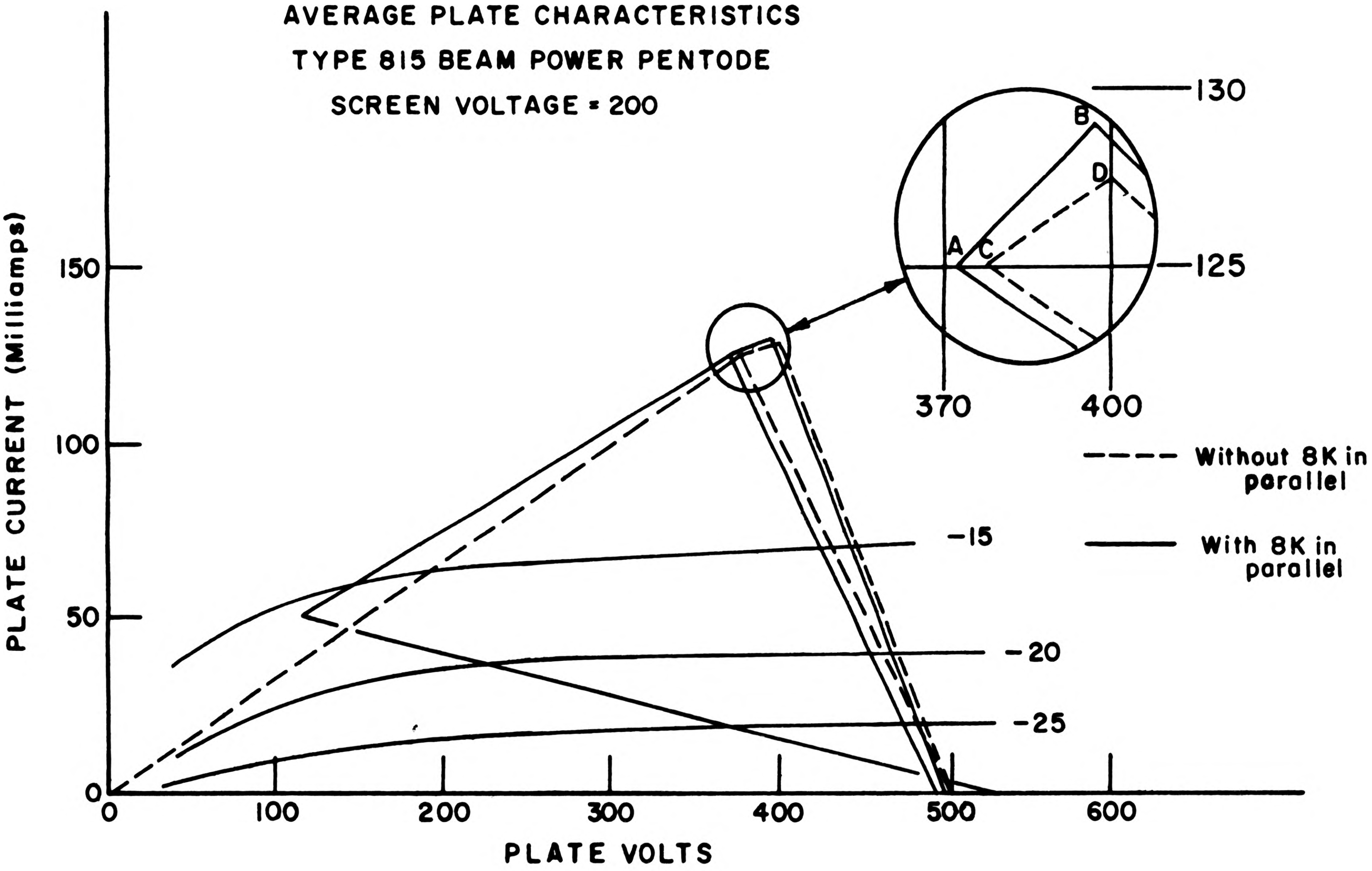

AVERAGE PLATE CHARACTERISTICS
TYPE 815 BEAM POWER PENTODE
SCREEN VOLTAGE = 200
PLATE CURRENT (Milliamps)
PLATE VOLTS
0
50
100
150
0
100
200
300
400
500
600
-15
-20
-25
A
B
C
D
130
125
370
400
Without 8K in parallel
With 8K in parallel

Figure 8

CHAPTER IV

TESTING TECHNIQUES

It was proposed early in this investigation to evaluate the performance of the resistance element method for measuring detonation velocity in iron pipes, and then attempt a number of tests in boreholes drilled in rock.

First attempts were made using the Perkin constant current device. A loop of Nichrome wire was taped to a 3/16" x 3/16" wooden dowel, and the unit inserted into an iron pipe 4' long. The pipe was then filled with a 94/6 AN-FO mixture. Results from these tests were very poor. The wire did not appear to short out continuously, and the photographed records were very erratic. It was obvious at this point that the resistance wires had to be in much more intimate contact in order to have continuous current flow in the ionization zone.

EFFECT OF TWISTING RESISTANCE WIRES TOGETHER

Numerous tests were made using a varying number of twists in a 4' loop of wire. Results of these tests are shown in Table I. Analysis of the records indicated that reasonable traces could be obtained with a minimum of 500 turns per 4' length of wire.

It has been stated (Campbell, 1956) that strong detonation waves progressing along a column of explosive commonly have associated with them a potential difference of a few hundred to a thousand or more volts above ground. A number of resistance elements were wound 100 times on a # 30 enamel coated copper wire. The copper wire was grounded to the iron pipe, in an attempt to ground the detonation wave during a test shot. No discernable difference in records was observed between grounded and ungrounded shots. Grounding the copper wire to the iron pipe was not particularly satisfactory however, because the iron pipe was just resting on the earth and was not positively tied to a grounding rod buried at some depth in the earth. Most plastics and insulating materials also develop strong potentials when hit by strong shock waves. The effect of the shock wave on the nylon insulation around the # 36 Nichrome wire appears to be negligible.

Currently, wires are twisted by means of a lathe and a small

TABLE I

QUALITY AND LINEARITY OF RECORDS COMPARED WITH THE NUMBER OF TURNS IN THE RESISTANCE WIRE

Test No.	Turns in 4' of Wire	Quality of Record	Linearity of Record
14*	200	poor	no trend
15*	200	poor	no trend
20*	300	poor	weak trend
21*	300	poor	no trend
18*	400	poor	weak trend
19*	400	poor	weak trend
16*	500	poor	no trend
17*	500	fair	linear trend
22**	500	good	linear trend
23**	500	good	linear trend
24**	500	good	linear trend
29**	650	fair	lenear trend
30**	650	fair	linear trend
27**	700	very good	very linear
31***	700	good	very linear
34***	700	good	linear trend

---

* 94/6 mixture of fertilizer grade ammonium nitrate and # 2 fuel oil.

** 94/6 mixture of Monsanto CD ammonium nitrate and # 2 fuel oil.

*** 94/6 mixture of Monsanto E-3 ammonium nitrate and # 2 fuel oil.

counting device to record the turns. Six hundred turns are applied to the # 36 wire, and then this wire and a # 30 enameled copper wire are twisted together 100 times. The ends of the Nichrome wire are scraped to remove the insulation and a 1" length of 1/16" inside diameter copper tubing is crimped on each wire. The two copper connections are then set in small holes drilled 1/2" apart in a small wooden block. Current and voltage wires are crimped on the other end of the copper connectors when a test shot is made.

Figure (9 - A) is a photograph of the copper connectors crimped on the # 36 Nichrome wire. The twists in the wire can also be observed.

EFFECT ON RESISTANCE OF TWISTING WIRES TOGETHER.

Table II shows the change of resistance of a 4' loop of Nichrome wire twisted for various numbers of turns.

TABLE II

CHANGE IN RESISTANCE OF A LOOP OF NICHROME WIRE

FOR VARIOUS NUMBERS OF TURNS

Number of Turns	Resistance in Ohms
0	244.5
100	244.5
200	244.5
300	244.5
400	245.0
500	245.0
600	245.3
700	246.2

Resistance change is 1.7 ohms in a 4' loop of wire.

Percentage change = .70%

ACCURACY OF MEASUREMENTS

i. Pin Oscillograph Method. The pin oscillograph, the cork pins and the borehole cables described previously, were used to provide a check on the accuracy of the detonation velocity measurements observed

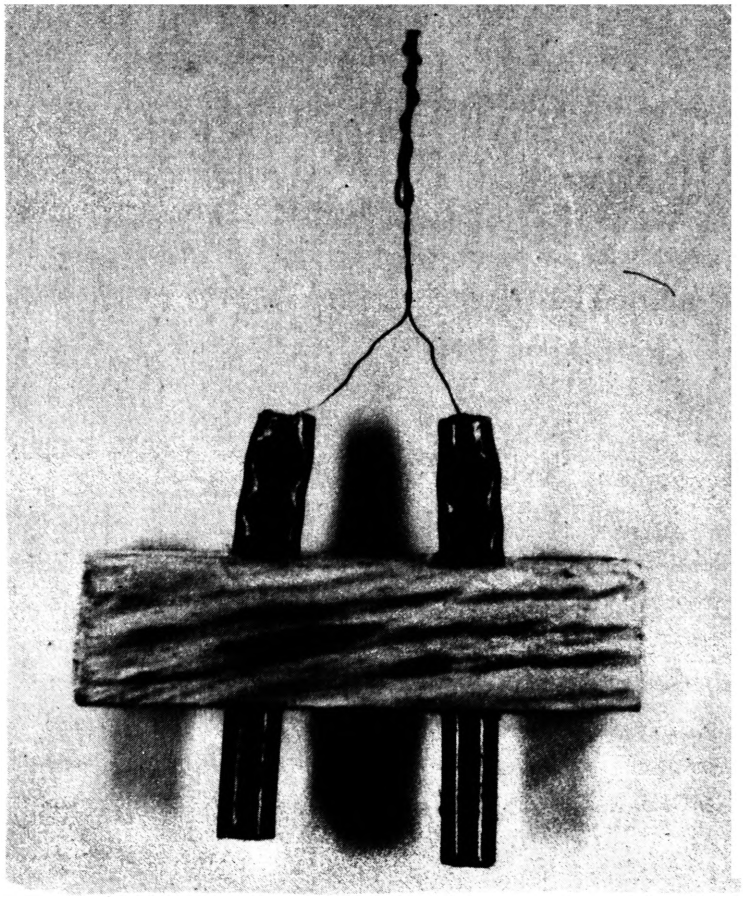


Figure 9-A Photograph Showing The Copper Tubing Crimped onto The # 36 Nichrome Wire, Also Showing The Twist in The Wire.

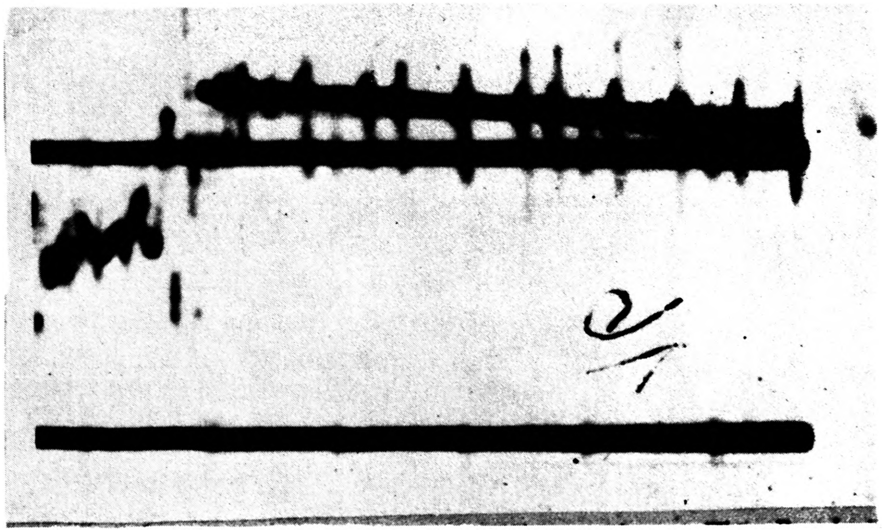


Figure 9-B Effect of The Pin Oscillograph on The Resistance Element Current Trace.

with the resistance element method. The pin technique for measuring the velocity is capable of high precision under ideal conditions (Campbell 1955). However, for AN-FO mixtures confined in iron pipes, some variations in velocity can be expected because of the following: (1) non-homogeneous composition, (2) charge density variations in a column of mixture, (3) displacement of cork pin stations from their assumed positions, (4) actual pulsations of the detonation wave front. Table III (Yancik 1960) shows expected variations in velocities for identical 3" diameter charges of AN-FO mixtures confined in iron pipes. The detonation velocities were computed by four different methods, and a least squares analysis gave the most consistent results. Maximum variation in average velocities was ± 80 fps, however ± 250 fps was considered a more realistic estimate of accuracy for AN-FO mixtures confined in iron pipes.

TABLE III

VARIATION IN AVERAGE DETONATION VELOCITY RATES FOR IDENTICAL CHARGES

Test Number	Averaged Intervals	Average	Squared Method	Least Squares
1*	11,210	11,190	11,210	11,240
2	11,280	11,200	11,220	11,260
3	11,260	11,220	11,250	11,260
4	11,180	11,000	11,010	11,100
5	11,170	11,130	11,130	11,170
6	11,170	11,020	11,070	11,110
7	11,050	11,080	11,110	11,180
Maximum variation	230	220	240	160

* 94/6 FGAN-fuel oil, density 0.85 gms. per cc., 3" diameter iron pipe 60% amm. dyn. primer.

ii. Resistance Element Method. Examination of equation (6) indicates that values for I (current in milliamps), R (resistance of Nichrome wire per foot of length), tan ϕ, and constants of the oscilloscope are required to calculate the detonation velocity of an explosive mixture.

a. Current. The current in the circuit is measured by observing the voltage drop across a 0.1% precision resistor. The current is not constant , and errors from an assumed pre-set value appear from two different sources: (1) The characteristics in the power supply; current varies from 100 to 103.2 (100 mils pre-set) or 125 to 129 (125 mils pre-set) milliamps for a full load to a no load condition. (2) An analysis of all current records made during the investigation show that the current did not at any time follow the calibration trace of the current taken immediately before each test shot. In every case except one, the current reading was larger than the calibration value. For many of the records, the current started at some value larger than the calibration setting, and then increased linearly until the detonation was complete. For a number of the records, the current jumped to an initial value greater than the calibration setting, and then remained at this level during the remainder of the test shot. Table IV shows the variation of the current during a number of test shots. Figure (10) shows the relationship between the detonation velocity and the current, for increasing current.

b. Resistance Wire. The change in resistance due to twisting the Nichrome wires together amounts to approximately 1.7 ohms in 8' of wire. The change in resistance per foot of Nichrome wire is therefore negligible and will have little effect on the accuracy of the results.

c. Tan ϕ. Appreciable errors can be expected in the measurement of the slope of the voltage-time trace unless those persons reading the records are very objective. Judgement by the reader is necessary as to where the best line should drawn, and it is difficult to eliminate personal bias because the approximate value of the slope is usually known. Ideally, the slopes should be read by some device, and calculated, similar to the method used by Amster.

d. Constants of the Oscilloscope. Vertical sensitivity of the oscilloscope is correct to within 3% of the indicated setting,

TABLE IV

VARIATION OF CURRENT DURING TEST SHOTS

Pipe	Test No:	Calibration Current	Start	Finish	Average
iron	70*	125	125.0	111.2	118.2
clay	72*	"	135.2	148.0	141.6
"	73**	"	134,0	157.6	145.8
"	74**	"	134.0	149.0	141.5
"	75***	"	no regular variation		
"	76***	"	138.6	138.6	138.6
iron	77**	"	140.0	140.0	140.0
"	78*	"	140.0	140.0	140.0
"	79***	"	131.0	134.0	132.5
clay	81*	"	Difficult to read > 125.0		
"	82*	"	Difficult to read > 125.0		
"	83*	"	137.0	137.0	137.0
"	85*	"	136.0	136.0	136.0
borehole	97*	"	no regular variation		
"	98*	100	108.0	108.0	108.0
"	99*	100	103.8	103.8	103.8
"	100*	100	no regular variation		

* 94/6 mixture of CD.

** 94/6 mixture of E-3

*** Commercial blasting agent (B-A-1)

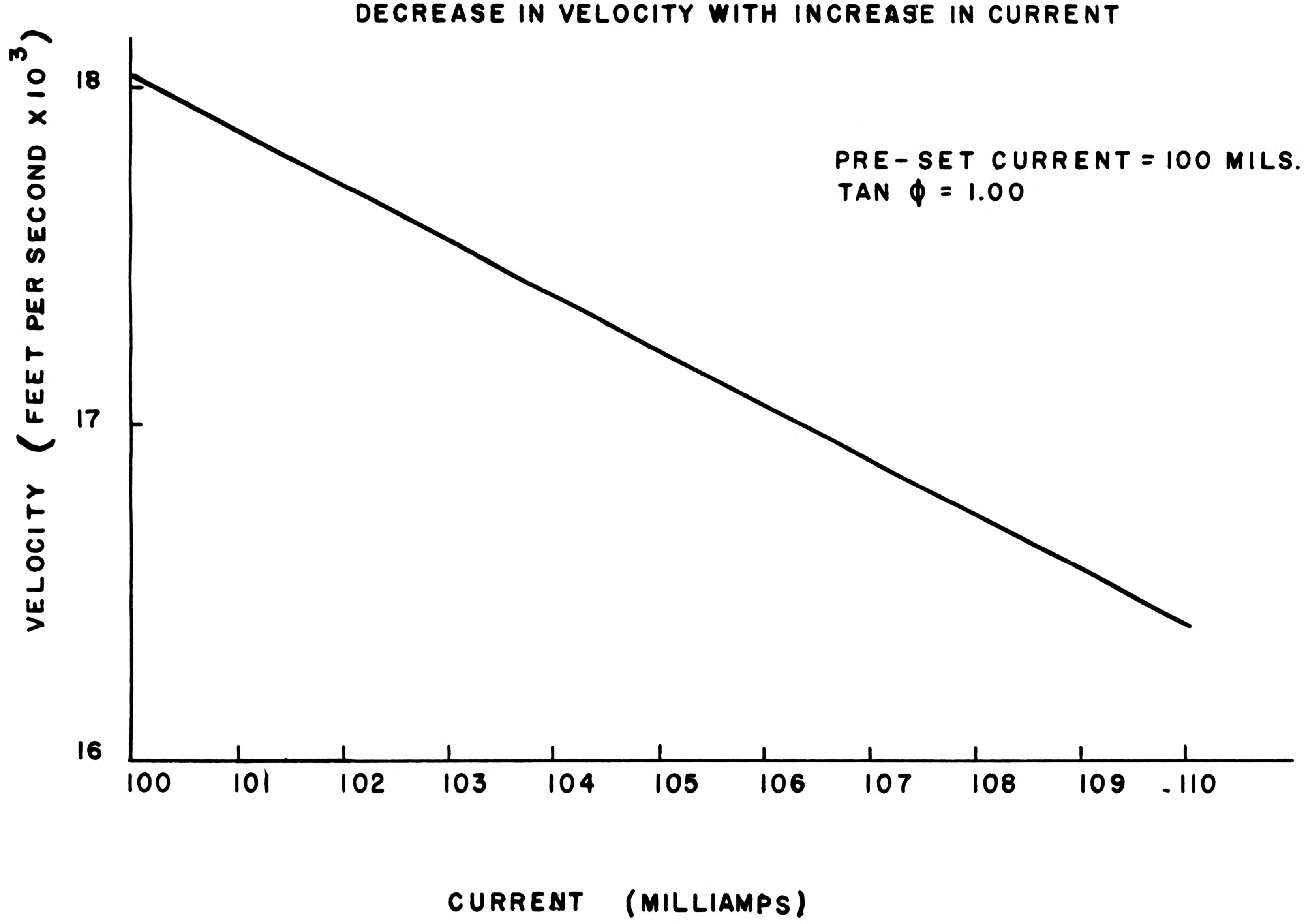

DECREASE IN VELOCITY WITH INCREASE IN CURRENT
PRE-SET CURRENT = 100 MILS.
TAN ϕ = 1.00
VELOCITY (FEET PER SECOND X 10^3)
18
17
16
100
101
102
103
104
105
106
107
108
109
.110
CURRENT (MILLIAMPS)

Figure 10

however, two sweeps are used to calibrate for current and the difference between the two values will be correct. Sweep speeds are typically within 1% and in all cases within 3% of the indicated sweep rate, provided the oscilloscope is not out of calibration.

CHAPTER V

ANALYSIS OF RECORDS

PERKIN POWER SUPPLY

Table V shows the calculated detonation velocities for a number of E-3 mixtures shot in 3" diameter iron pipes. The average for the pin oscillograph records was 15,190 fps while the average of the resistance element records was 10,820 fps. Test shot number 27, (CD in a 2" diameter iron pipe) indicated a resistance element record of 10,050fps, and test shot number 28, (CD in a 2" diameter iron pipe) gave a pin oscillograph reading of 10,770 fps, and a resistance element reading of 10,120 fps.

The resistance element method with the Perkin power supply providing constant current in the circuit indicated almost identical velocity records for CD and E-3, while the pin oscillograph detected a difference of approximately 4500 fps between the two mixtures. It appeared possible that the Perkin device had an upper limit in response time under test conditions, and it could not follow the higher velocity of the E-3 mixture. The test shots shown in Table V were made before the photograph showing the poor current regulation was taken in test shot number 41 (see Figure 5).

The results of Table V and Figure 5 provided conclusive evidence that the Perkin power supply was an unsuitable source of constant current for this type of test.

PROJECT POWER SUPPLY

Table VI shows the results of the velocity records observed with both measuring techniques for four different types of AN-FO or Nitro-Carbo-Nitrate mixtures under varying conditions of charge confinement and diameter. Current for the resistance element method was provided by the power supply shown in Figure 6. A number of tests were not included in the table. For these records, either there was no velocity reading at all, or the resistance wire failed part way along the length of charge due to a short in the wire, or in some cases to poor ionization in the detonation front.

The resistance element method indicated higher velocities than the

TABLE V

PIN OSCILLOGRAPH VELOCITIES VERSES RESISTANCE ELEMENT VELOCITIES (PERKIN POWER SUPPLY)

Explosive	Pin Reading	Resistance Element
E-3, lot 1493	15,510*	-- ---
	14,870**	10,470
	15,395**	-- ---
E-3, lot 1494	15,450*	-- ---
	15,035**	10,390
	15,690**	11,160
E-3, lot 1490	15,140*	-- ---
	14,700**	11,750
	15,200**	11,255
E-3, lot 1492	15,740*	-- ---
	14,705**	9,520
	15,025**	11,180

* 94/6 mixed February 8, 1962, shot same day.

** 94/6 mixed February 8, 1962, shot February 10, 1962.

All tests in 3" diameter iron pipes, primed with 4-1/2 sticks of 60% ammonia dynamite

E-3, Monsanto brand of dense ammonium nitrate prills.

pin oscillograph technique in nearly every test shot. This observation is in agreement with results calculated from Table IV, which shows the current in the circuit for a number of test shots. In the majority of tests the current increased from the pre-set calibration level. Figure (10) shows that velocity decreases for increasing current. If the current increased during a test shot, then, from equation (6) any calculated detonation velocity utilizing the value of the calibration current would indicate a higher velocity than that which actually existed at the time of detonation of the mixture. Therefore any correction factor derived from Table IV would force the resistance element velocity towards the pin oscillograph reading. Conversely, if the value of the current decreased, then the resistance element velocity would increase. This behavior was observed in some of the shots.

TABLE VI

COMPARISON OF PIN OSCILLOGRAPH AND RESISTANCE ELEMENT DETONATION VELOCITIES FOR A NUMBER OF TEST SHOTS

Material Container	Test No.	Pin fps	R.E. (corr.) fps	R.E. (uncorr.) fps
CD + I[1]	52	11,810	9,735	10,050
"	53	11,450	13,990	14,435
"	54	-- ---	11,910	12,310
"	55	11,580	12,450	12,840
"	57	12,050	13,310	14,000
"	58	11,860	13,990	15,160
"	60	12,715	15,230	15,760
CD + C[2]	61	11,030	11,550	12,180
"	62	11,070	11,620	12,030
"	63	10,975	11,280	11,710
"	64	11,060	11,740	12,140
"	65	11,070	11,950	12,350
"	66	11,065	11,330	11,645
"	67	10,880	11,590	11,860
"	68	11,375	13,040	13,590
"	71	11,290	11,660	13,160

TABLE VI (CONTINUED)

Material + Container	Test No.	Pin fps	R.E.(corr.) fps	R.E.(uncorr.) fps
CD + C[2]	72	11,410	11,900	13,860
B-A-1 + C[3]	76	9,800	12,260	13,980
CD + I[2]	78	11,760	10,040	11,490
B-A-1 + I[4]	79	9,240	9,180	9,400
CD + C[2]	80	------	9,820	10,130
"	81	11,260	10,490	9,830
"	82	10,950	11,070	10,490
"	83	11,090	10,070	11,760
"	84	-- ---	11,000	11,350
"	85	"	11,450	12,890
CD + I[1]	86	"	11,320	11,685
E-3 + I[5]	88	"	13,990	14,435
"	89	"	15,560	16,240
"	90	"	16,410	16,940
"	92	"	14,060	14,590
"	93	"	14,800	15,890
B-A-2 + I[6]	94	"	9,000	9,250
B-A-2 + I[6]	95	"	9,790	10,150
CD + B[7]	98	"	7,780	8,720
"	99	"	8,510	9,170

---

1. CD in a 3" diameter iron pipe.
2. CD in a 4" diameter clay pipe
3. B-A-1, Commercial blasting agent in a 4" diameter clay pipe.
4. B-A-1, Commercial blasting agent in a 3" diameter iron pipe.
5. E-3 in a 3" diameter iron pipe.
6. B-A-2, Commercial blasting agent in a 3" diameter iron pipe.
7. CD in a 1 1/2" diameter borehole drilled in rock.

i. Determination of Tan Ø. Determination of the slope on the majority of the records presented no difficulties as shown in Figures 11 - D, 12 - A, 13 - A,B. Figure 13 - D is a record that exhibits no linear portion on the trace, and Tan Ø could not be calculated. Figures 13 - C,D, display a feature which was observed on 5 of 9 identical tests, shot on the same day. The oscilloscope triggered at the appropriate place on the CRO screen, approximately 2 to 4 volts below the circuit voltage calibration trace, then the sweep jumped to a new voltage level above the calibration value, and decreased in a linear manner towards the zero volts calibration line. The slope of all 5 records was obviously in error, and calculated detonation velocities were in the order of 18,000 fps, approximately 6,000 fps higher than the expected value. Immediately after these records were taken, the modification to protect the device from the effects of an open circuit, referred to on page 17 was installed on the power supply. Records similar to Figure 13 - C,D, have not been seen again.

Error in Tan Ø. The resistance element (uncorrected) velocity records in Table VI were calculated by applying equation 6 and calculating Tan Ø from the recorded time-voltage trace. The record was marked with a sharp stylus along the best apparent linear trend from the zero voltage calibration to the circuit voltage calibration line. The angle was calculated from measurements taken with a scale divided into 0.5 mm segments, which could be read easily to 0.25 mm. A typical slope is as follows:

$$\text{Tan } \phi = \frac{4.450 \text{ cms.}}{5.400 \text{ cms.}}$$

$$\text{error in the ordinate} = \frac{.025}{4.450} = .55\%$$

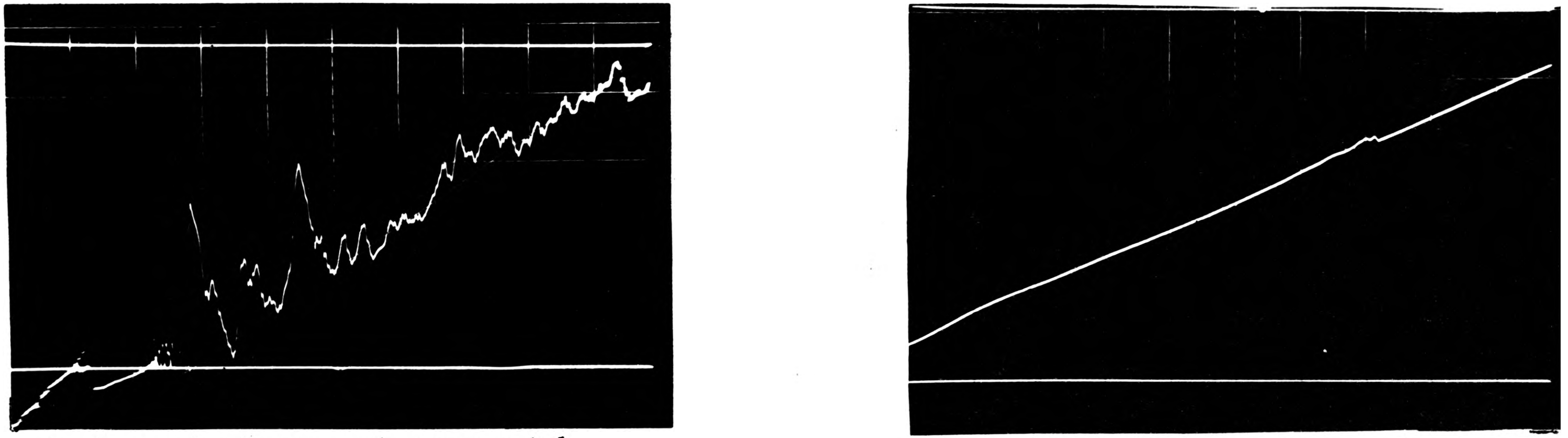
$$\text{error in the abcissa} = \frac{.025}{5.400} = .46\%$$

The maximum error which could be expected in the determination of Tan Ø for this record is 1.01%. For the general case, an error of at least 1% would be expected.

ii. Effect of the Pin Oscillograph on the Resistance Element Records . Figure 13 - C,D, and Figure 9 -B show the effects of the high

A. Shows the effect of not enough twist in resistance wires. 94/6 FGAN, 2" diameter iron pipe. density 0.85

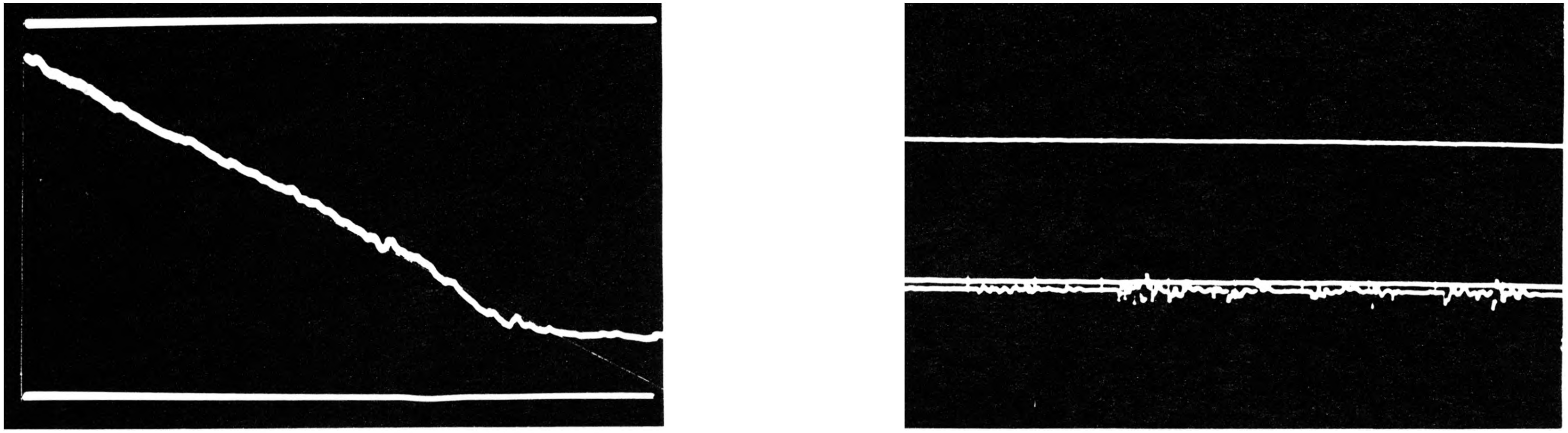
B. Typical trace from the Perkin Power Supply. 94/6 FGAN, 2" diameter iron pipe. density 0.85



C. Low velocity record, commercial blasting agent 2, 3" diameter iron pipe. density 1.10

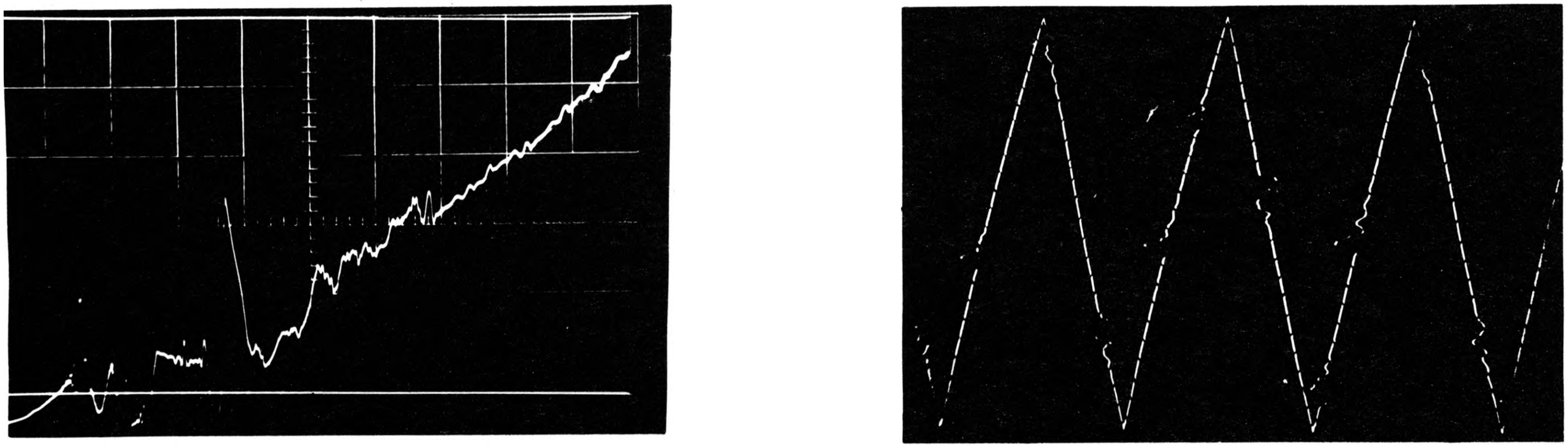
D. High velocity record Monsanto E-3 94/6 mixture in a 3" diameter iron pipe. density 1.05

Figure 11



A. Borehole velocity record, Monsanto CD 94/6 mixture in a 1 1/2" diameter borehole

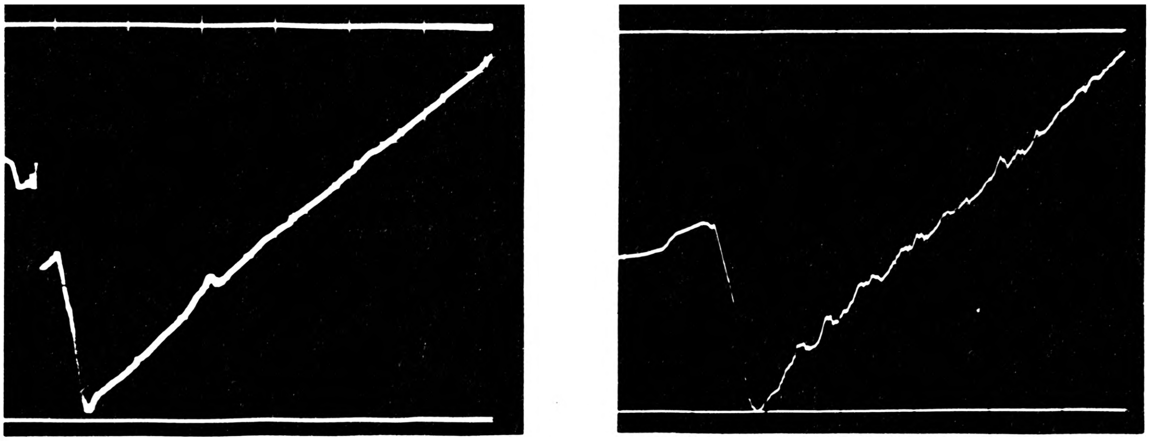
B. Current regulation for A



C. Monsanto CD, 94/6 mixture in a 4" diameter clay pipe. density 0.85

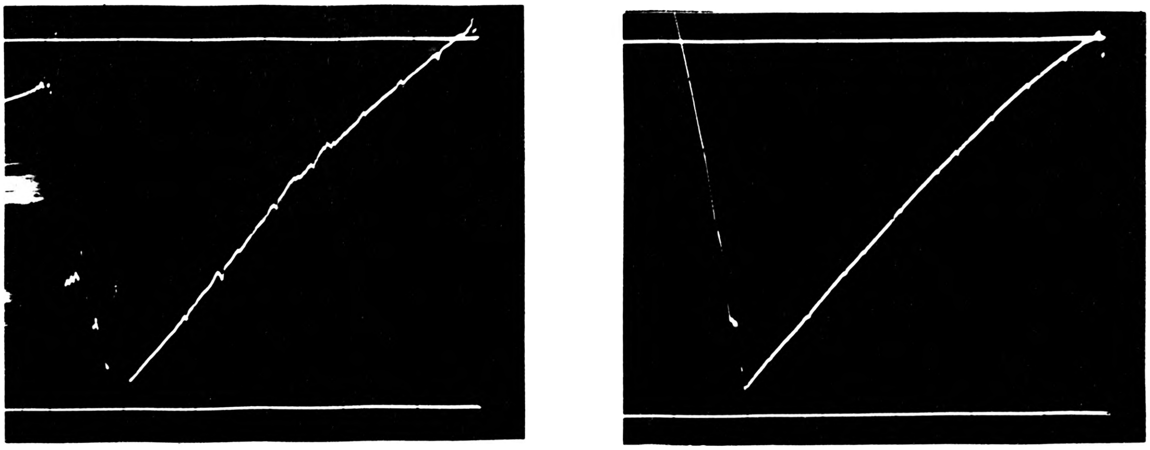
D. Pin oscillograph velocity reading for C

Figure 12



A. Monsanto CD, 94/6 mixture in a 4" diameter clay pipe. density 0.85

B. Commercial blasting agent 1, 94/6 mixture in a 4" diameter clay pipe. density 0.83



C. Monsanto E-3, 94/6 mixture in a 4" diameter clay pipe. density 1.03

D. Monsanto E-3, 94/6 mixture in a 4" diameter clay pipe. density 1.03

Figure 13

voltage on the pin switches discharging to ground through the explosive mixture during a test shot. Figure 9 - B is a photograph of the current in the circuit for test shot # 76. The high frequency noise appearing on the record corresponds exactly to the spacing of the pin switches on the wooden dowel. The photographs show the effect of 11 pins shorting to ground. The pins were spaced on the dowel so that measurements would not be taken over the first 10 to 12 inches of the explosive charge. The current trace (Figure 9 - B) shows the first pin discharging, therefore at least 10 to 12 inches of the mixture had been consumed before the oscilloscope triggered for the current trace. It is apparent that both velocity measurements were taken over the same length of charge.

The high frequency noise on Figure 9 - B does not appear to interfere with the trend of the current, and will not affect the calculations.

iii. Overdrive and Underdrive in the AN-FO Mixtures. Cook (1958) indicates that an explosive will assume its characteristic velocity after initiation in a distance equal to 3 or 3½ charge diameters. It would be expected that for 3" diameter iron pipes, no overdrive or underdrive would be observed in any of the resistance element records. This expectation proved true in practice.

Figure 13 C shows the effect of underdrive in a 94/6 mixture of E-3 confined in a 4" diameter clay pipe. Ten pin discharges to ground are indicated on the record, showing that the trace represents the velocity for less than 3' of the mixture. The transition from the low velocity of the primer(4 - 1/2 sticks of 60% ammonia dynamite) approximately 12,000 fps, to the characteristic high velocity of E-3 takes place half way across the the trace, or approximately 2 1/2' from the point of initiation of the explosive. This distance represents 7 charge diameters. The poor confinement provided by the clay pipe probably accounts for the long period of time before the E-3 assumes its characteristic velocity.

Figure 12 - C shows the effect of overdrive in a 4" diameter clay pipe filled with a 94/6 mixture of CD, primed with 4- 1/2 sticks of 60% ammonia dynamite. The transition zone from high to lower velocity is much less pronounced, and it occurs at approximately 5 charge diameters from the point of initiation.

iv. Quality of the Records. Explosive material which has a high detonation velocity appears to provide the most satisfactory time-voltage traces. Figure 11 - D is an exceptionally good record of a 94/6 mixture of Monsanto E-3 detonated in a 3" diameter iron pipe. High frequency noise was completely absent, and the current in the circuit regulated well. Sixty per cent gelatin and Composition C-4, both high velocity explosives provided clear records also. E-3 detonates at a velocity of approximately 15,500 fps, which is equivalent to a 45% straight dynamite, a 40% straight gelatin or a 40% ammonia gelatin. Figures 13 - C,D, are good clear traces, however the slope of the records was in error and no velocity determination could be made.

Monsanto CD detonates at an average velocity of approximately 12,000 fps in 3" diameter iron pipes, and 11,100 fps in 4" diameter clay pipes. Figures 12 - A,C, and 13 - A show traces of the detonation velocity of CD. These records were not as clear as the high velocity traces, however they were superior to the low velocity materials B-A-1 and B-A-2, shown in Figure 11 - C and 13 - B.

v. Tabulated results. The quiescent points on Figure (8) show the variation in current for a change in load in the field from ≈ 250 ohms to ≈ 0 ohms. These values represent the Nichrome wire before and after a shot is fired. The value of the current increases 4 milliamps, which is a characteristic of the power supply, and will be present in every shot.

For many of the tests, a photograph of the current regulation was taken at the same instant as the time-voltage velocity trace. Table IV shows the current variation from a pre-set calibration level.

The calculated detonation velocity for a typical test is as follows:

Test shot # 85

Uncorrected

(equation 7) $$D = \frac{K}{IRn} \tan \phi$$

where $K = \frac{5 \text{ volts/cm.}}{50 \ \mu \text{ sec/cm.}}$, I = 125 milliamps, R = 27.71 ohms/ft.

n = 2 (two wires), $\tan \phi = .889$

$$D = \frac{5 \times .889}{50 \times 125} \times 27.71 \times 2$$

$$D = 12{,}850 \text{ fps}$$

Corrected. Table IV shows that the current increased to 136 milliamps from 125 milliamps. The constant in the power supply is 4 milliamps, therefore the actual current in the circuit at the end of the shot was 140 milliamps.

then:
$$D = \frac{5 \times .889}{50 \times 140} \times 27.71 \times 2$$
$$D = 11{,}450 \text{ fps}$$

The error in the calculated velocity is 1,400 fps if the current is neglected. The corrected value of the velocity is very near the average of 11,120 for CD confined in 4" diameter clay pipes.

STATISTICAL RESULTS OF TEST SHOTS

Table VII shows the stastical results of the test shots shown in Table VI. Two Monsanto mixtures were used: CD and E-3 confined in 3" diameter iron pipes and 4" diameter clay pipes. A number of other commercial mixtures were tested to provide an additional check on the instrumentation. Finally, 8 test shots were detonated in 1 1/2" diameter boreholes drilled in rock. The pin method provided the most accurate results in all tests where it was used to measure the detonation velocity. The standard deviation (S.D.) of CD confined in 4" diameter clay pipes was 158 fps which compared favourably with calculations by Yancik (1960) of 160 fps. The S.D. for mixtures confined in iron pipes was considerably larger.

The resistance element (corrected) method provided the next most reliable results when compared to the pin method. The average velocities for CD confined in 3" diameter iron pipes and 4" diameter clay pipes are nearer the pin velocities than the resistance element (uncorrected) velocities. There is little difference in the standard deviations, and statistically there is no difference in the accuracy of the two methods. The resistance element (corrected) method gave a much lower average velocity fot E-3 confined in iron pipes, than the uncorrected method indicated. A probable explanation may be found in the effect of the iron pipes on the current in the circuit. All current records taken from tests shot in iron pipes were characterized by some high frequency noise on the trace. These records were difficult to read, and some error may have been introduced into the calculation of the value of the current.

The resistance element velocities for commercial mixtures B-A-1 and

TABLE VII

STATISTICAL RESULTS OF TEST SHOTS

MIXTURE	PIPE DIAMETER	PIN METHOD (fps)		RESISTANCE ELEMENT (corrected, fps)		RESISTANCE ELEMENT (uncorrected, fps)	
CD, 94/6	4" Clay	Average	11,120	Average	11,475	Average	11,890
		S.D.*	158	S.D.*	660	S.D.*	1,029
CD, 94/6	3" Iron	Average	11,890	Average	12,440	Average	13,080
		S.D.*	381	S.D.*	1,848	S.D.*	1,753
E-3, 94/6	3" Iron	Average	15,740	Average	14,960	Average	15,620
		S.D.*	406	S.D.*	920	S.D.*	966
B-A-1** 94/6	4" Clay		9,800		12,260		13,980
B-A-1** 94/6	3" Iron		9,240		9,180		9,400
B-A-2***	3" Iron	No. 4943***	10,210	No. 94	9,000	No. 94	9,250
		No. 4944***	10,580	No. 95	9,790	No. 95	10,150
CD, 94/6	1½" bore-hole.		-- ---	No. 98****	7,780	No. 98	8,720
				No. 99****	8,510	No. 99	9,180

---

* Standard Deviation.

** Averaged from a number of previous tests.

*** Commercial blasting agent.

**** Estimated velocity from a chronographic method is 8,700 fps.

B-A-2 provided a reasonably good check of the instrumentation. Generally the calculated results were lower than the pin method, however the records were poor, and it was difficult to calculate Tan 0.

The borehole tests were successful, in that two very good records were photographed. Of the eight shots attempted, five were lost because the resistance wires were damaged when the explosive mixture was placed in the hole. One of the remaining three did not display any linear trend, however 98 and 99 checked reasonably well with velocities determined by a chronograph method.

SUMMARY AND CONCLUSIONS

Summary. Instrumentation and techniques have been developed to measure the detonation velocity of explosive mixtures confined in small diameter boreholes drilled in rock.

The method employs a loop of Nichrome resistance wire 54" long twisted 600 times and placed axially along the edge of a borehole. A constant current of 100 milliamps is applied to the wire immediately before a shot is fired. At any time after initiation, the detonation velocity of the explosive mixture is proportional to the resistance remaining in the wire. The slope of the time-voltage trace plus an appropriate equation provides a means of calculating detonation velocity.

The resistance element technique was evaluated by comparing the velocity from time-voltage records with velocity records taken simultaneously on the same charge by a pin oscillograph method. Various types of ammonium nitrate - fuel mixtures confined in iron and clay pipes were used to provide a range of velocities in the mixtures.

Conclusions. A number of conclusions may be drawn from this investigation. They are as follows:

i. Commercial Power Supply. The commercial constant current power supply was not suitable for velocity measurement tests. The response time of the device was not fast enough to control the current.

ii. Project Power Supply. The Project constant current supply regulated the current well in the circuit. However, the current does not remain at a pre-set calibration level. The current increased for nearly all test shots. There is another increase of 4 milliamps in the circuit for every shot, due to the characteristics of the current regulating tube.

iii. <u>Determination of Tan Ø</u>. Normally no difficulty was encountered in reading records shot with medium to high velocity material. Error due to judgement of the individual is present when the tangent is drawn to the time-velocity trace. Error in measuring the value of the angle is in the order of 1%.

iv. <u>Overdrive and Underdrive</u>. Overdrive and underdrive of the explosive mixtures was observed in a number of test shots confined in clay pipe. No overdrive or underdrive was observed in shots confined in iron pipes or boreholes drilled in rock.

v. <u>Quality of Records</u>. High velocity E-3 mixtures provided the clearest traces, followed by the intermediate velocity CD material. The low velocity mixtures B-A-1 and B-A-2 invariably provided poor time voltage traces.

vi. <u>Tabulated Results</u>. Errors as large as 1500 fps are to be expected in velocity tests made with this instrumentation, unless observations are made on any changes of current during the detonation of the charge.

vii. <u>Effects of the Pin Oscillograph</u>. The discharging of the pins to ground potential in the iron pipes or in the borehole cables can be seen on the current records, but these discharges do not interfere with the trend of the record.

viii. <u>Statistical Results</u>. The pin oscillograph technique provided the most accurate velocity records. In general the resistance element (corrected) velocities were within 3% to 6%, and the resistance element (uncorrected) velocities were within 6% to 10% of the pin oscillograph velocities.

BIBLIOGRAPHY

AMSTER, A.B., KENDALL, P.A., VEILLETTE, L.J., HARRELL, B., (1959) A continuous oscillographic method for the determination of detonation velocities in solid cast explosives. NAVORD Report 6280, Chem. Research Dept., U.S. Naval Ordnance Lab., White Oak, Maryland. 12p.

BRINKLY, S.R., JR., SYKES, W.G., MEYERS, S., (1960) Some effects of particle size reduction on the explosive properties of ammonium nitrate - fuel oil blasting agents. Technical Bulletin No. 98, University of Missouri, School of Mines and Metallurgy, Rolla, Missouri. p. 12 - 28.

BRUZEWSKI, R.F., CLARK, G.B., YANCIK, J.J., KOHLER, K.M., (1959) An investigation of some basic performance parameters of ammonium nitrate explosives. Technical Bulletin No. 97 University of Missouri, School of Mines and Metallurgy, Rolla, Missouri. p. 175 - 203.

CAMPBELL, A.W. <u>et al</u>, (1955) Technique for the measurement of detonation velocity. Second ONR Symposium on Detonation, Washington D.C. p 26.

_______________, MALIN, M.E., BOYD, T.J., HULL, J.A., (1956) Precision measurement of detonation velocities in liquid and solid explosives. Rev. of Sci. Inst., 27, p567.

COOK, M.A., (1958) The science of high explosives. ACS Mono. No. 139, New York, Reinhold, 440 p.

COOLEY, C.M., (1958) Properties and recommended practices for use of ammonium nitrate in field-compounded explosives. Technical Bulletin No. 95, University of Missouri, School of Mines and Metallurgy, Rolla, Missouri. p. 123 - 128

CLARK, G.B., BRUZEWSKI, R.F., STITES, J.G., LYON, J.E., YANCIK, J.J., (1961) Performance parameters of densified microprilled ammonium nitrate-fuel blasting agents. International Symposium on Mining Research, Missouri School of Mines and Metallurgy, Rolla, Missouri, Feb. 22-25. p. 3-1 to 3-24 (preprint)

EYRING, H., POWELL, R.F., DUFFY, G.M., PARLIN, R.B., (1949) The stability of detonation. Chem. Reviews, no.1, vol 45, p. 69 - 181

FITZGERALD, A.E., HIGGINBOTHAM, D.E., (1957) Basic electrical engineering, Chapter 15, p. 329 - 352. McGraw Hill, New York.

FOWLER, E.M., (1960) Safety and current techniques in underground blasting. Technical Bulletin No. 98, University of Missouri, School of Mines and Metallurgy, Rolla Missouri. p. 143 - 147.

GIBSON, F.C., BOWSER, M.L., MASON, C.M. (1959) Method for the study of deflagration to detonation transition. Rev. of Sci. Inst. No. 10, 30, p. 916 - 919.

GOTTLIEB, I.M., (1962) Design and operation of regulated power supplies, Howard K. Sams Inc., Indianapolis.

HENNING, U., (1961) Blasting with ammonium nitrate-fuel oil explosives at Boliden. International Symposium on Mining Research, Missouri School of Mines and Metallurgy, Rolla Missouri, Feb. 22 - 25. p. 5.1 - 5.11 (Preprint)

HYSLOP, J., (1960) Some safety considerations in the use of ammonium nitrate blasting agents. Technical Bulletin No. 98, University of Missouri, School of Mines and Metallurgy Rolla Missouri. p. 149 - 152.

JAFFE, I., (1960) A method for the determination of the critical diameter of explosives. NAVWEPS Report, U.S. Naval Ordnance Lab., White Oak, Maryland.

MAURER, W.C., (1961) Detonation of ammonium nitrate in small drill holes. D.Sc. Thesis, T938, Colorado School of Mines, Golden Colorado. 166 p.

MILLMAN, J., (1958) Vacuum-tube and semiconductor electronics. Chapters 7,11,12,13,14,19. McGraw Hill, New York.

POUND, E.F., (1954) Pin oscillograph for measurement of detonation velocity. Tech. Report no. XXXIII, Contract no. N7-ONR-45107, Project 357 239 Explosives Research Group, Inst. for the Study of Rate Processes, University of Utah, Salt Lake City, Utah.

____________, Notes on special pin oscillograph system for the Missouri School of Mines and Metallurgy, Rolla, Missouri. The Cordin Co., 1356 Thornton Ave., Salt Lake City, Utah.

RYON, J.L., JR., (1960) Underground use of ammonium nitrate for blasting at the Detroit Mine of the Int. Salt Co., Inc. Technical Bulletin No. 98, University of Missouri, School of Mines and Metallurgy, Rolla Missouri. p. 136 - 142.

SADWIN, L.D., COOLEY, C.M., PORTER, S.J., STRESAU, R.M., (1961) Underwater evaluation of the performance of explosives. International Symposium on Mining Research, Missouri School of Mines and Metallurgy, Rolla Missouri, Feb. 22 - 25.

____________, PORTER, S.J., SAVITT, J., (1960) Nonideal detonation of ammonium nitrate-fuel mixtures. Third Symposium on Detonation, ONR Symposium Report ACR-52, vol 1, p. 309 - 325.

STITES, J.G. JR., (1959) New developments and use of ammonium nitrate explosives. Technical Bulletin No. 97 University of Missouri, School of Mines and Metallurgy, Rolla Missouri, p. 204 - 207.

____________, BARNES, M.D., McFARLIN, R.J., (1960) A survey of the physical and chemical characteristics of fertilizer grade ammonium nitrate. Technical Bulletin No. 98, University of Missouri, School of Mines and Metallurgy, Rolla, Missouri. p. 1 - 11.

TAYLOR, J., (1952) Detonation in condensed explosives. Monographs on Physics and Chemistry of Materials, Oxford at the Clarendon Press. 196 p.

VAN DOLAH, R.W., MURPHY, R.W., HANNA, N.E., (1961) Fumes from ammonium nitrate-hydrocarbon mixtures. International Symposium on Mining Research, Missouri School of Mines and Metallurgy Rolla, Missouri. Feb. 22 - 25

YANCIK, J.J., (1960) Some physical, chemical and thermo-hydrodynamic parameters of explosive ammonium nitrate-fuel oil mixtures. Ph.D. Thesis, University of Missouri, Columbia, Missouri. 276 p.

____________, BRUZEWSKI, R.F., CLARK, G.B., (1960) Some detonation properties of ammonium nitrate. Technical Bulletin No. 98, University of Missouri, School of Mines and Metallurgy, Rolla, Missouri. p. 67 - 89.

APPENDIX

EXPERIMENTAL DATA

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
1		60% amm dyn		# 6 cap	No Reading (NR)	4 stks. 60% amm dyn taped to a dowel wire threaded down center of explosive 0.5 ufd across scope. 50 usec/cm.
2		60% amm dyn		# 6 cap	NR	Same 20 u sec/cm.
3		60% amm dyn		# 6 cap	NR	Same 50 u sec/cm.
4	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	Wires not twisted, taped to a small dowel. Trace readable. Much high frequency hash. Velocity estimate only. 89 mils, 50 u sec/cm.
5	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	Wires not twisted, taped to a small dowel. 95 mils, 50 u sec/cm. .10 ufd.
6	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	Wires not twisted together taped to dowel linear trend on trace. Much high frequency hash. 92.5 mils, 50 u sec/cm. .047 ufd.
7	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	Wires not twisted together, taped to dowel. Trace very irregular. High frequencies very noticeable. 93 mils, 50 u sec/cm. .01 ufd.

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
8	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	Wires not twisted. Trace very irregular. Little high frequency hash. 92 mils, 50 u sec/cm. .047 ufd.
9	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	Wires twisted together, taped to wooden dowel. Much high frequency hash. 94 mils, 50 u sec/cm. .047 ufd.
10	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	Wires twisted together, taped to dowel. Trace very irregular. No high frequencies present. 125 mils, 50 u sec/cm. .147 ufd. possibly not enough twist in wires.
11	2"	FGAN-94/6	.85	½ stk. 1½" 60% Giant Gelatin	NR	Wires twisted together. Not taped to dowel. Trace irregular. No high frequencies present. 125 mils, 50 μ sec/cm. .147 ufd.
12	2"	FGAN-94/6	.85	½ stk. 1½" 60% Giant Gelatin	12,600	Wires twisted together not taped to dowel. Trace reasonably regular. No high frequencies present. 125 mils 50 u sec/cm. .147 ufd. First part of trace very steep.
13	2"	FGAN-94/6	.85	1 stk-60% amm dyn	14,600	Wires twisted together. Not taped to dowel. Trace quite regular. No high frequencies present. 125 mils, 50 u sec/cm. .147 ufd.

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
14	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	200 * - equipment failure. 125 mils, 20 u sec/cm. .147 ufd.
15	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	200 * - linear trend in trace, no high freq. 125 mils, 20 u sec/cm. .147 ufd.
16	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	500 * - poor trace, very irregular, 125 mils, 50 u sec/cm. .147 ufd.
17	2"	FGAN-94/6	.85	1 stk-60% amm dyn	NR	500 * - definite linear trend in trace. 125 mils, 20 u sec/cm. .147 ufd.
18	2"	FGAN-94/6	.85	½ stk-1½" 60% Giant Gelatin	NR	400 * - definite linear trend in trace. 125 mils, 20 u sec/cm. .147 ufd.
19	2"	FGAN-94/6	.85	½ stk-1½" 60% Giant Gelatin	NR	400 * - definite linear trend in trace. 125 mils, 20 u sec/cm. .32 ufd.
20	2"	FGAN-94/6	.85	½ stk-1½" 60% Giant Gelatin	10,900	300 * - poor record, started regularly, but wild variations at the end, 125 mils, 50 u sec/cm. .32 ufd.
21	2"	FGAN-94/6	.85	½ stk-1½" 60% Giant Gelatin	NR	300 * - poor record, 125 mils, 50 u sec/cm. .32 ufd.

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* turns in 4-ft. length wire.

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
22	2"	CD-94/6	.88	½ stk-1½" 60% Giant Gelatin	**$\tan \phi =$ .370	500 * - good trace, some high freq. hash. Trace has a slight concave down appearance. Best trace to date. 125 mils, 20 u sec/cm. no capacitor.
23	2"	CD-94/6	.88	½ stk-1½" 60% Giant Gelatin	**$\tan \phi =$ .362	500 * - good trace, quite linear. Some hash. 125 mils, no capacitor. 20 u sec/cm.
24	2"	CD-94/6	.88	½ stk-1½" 60% Giant Gelatin	**$\tan \phi =$ .371	500 * - good trace, some concave down appearance, some low freq. hash 125 mils, 20 u sec/cm. .047 ufd.
25	2"	CD-94/6	.88	½ stk-1½" 60% Giant Gelatin	**$\tan \phi =$ .381	500 * - fair trace, some concave down appearance. 125 mils, 20 u sec/cm. .047 ufd.
26	2"	CD-94/6	.88	½ stk-1½" Giant Gelatin-60%	NR	500 * - record very poor. No trend of any kind. 125 mils, 20 u sec/cm. .047 ufd.
27	2"	CD-94/6	.88	½ stk-1½" 60% Giant Gelatin	10,050	700 * - good record, not absolutely linear, some wiggles here and there. 125 mil, 20 u sec/cm. .047 ufd.
28	2"	CD-94/6	.88	½ stk-1½" 60% Giant Gelatin	13,700	600 * - wire only partly consumed, appeared to be mechanical failure of wire. 125 mils, 20 u sec/cm. .047 ufd.

** time / cm. was not calibrated

* turns in 4-ft. length wire

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
29	2"	CD-94/6	.88	½ stk-1½" 60% Giant Gelatin	pin 10,880 probe (pr) NR	650 * - poor record. No readable slope. 125 mils, 20 u sec/cm. .047 ufd.
30	2"	CD-94/6	.88	½ stk-1½" 60% Giant Gelatin	pin 10,770 pr 10,120	650 * - trace fairly good. Line tails off at the end. Some fluctuations on line. 125 mils, 20 u sec/cm. .047 ufd.
31	3"	E-3 lot 1493 94/6	1.0	IRECO Booster 100 gms	pin 14,870 pr 10,470	700 * - trace fairly good. Some wiggles, effect of primer very noticible, i.e. initial part of trace very steep. 125 mils, 20 u sec/cm. .047 ufd.
32	3"	E-3 lot 1493 94/6	1.0	IRECO Booster 100 gms	pin 15,395 pr NR	725 * - no trace. Failure in equipment.
33	3"	E-3 lot 1494 94/6	1.0	IRECO Booster 100 gms	pin 15,035 pr 10,390	650 * - trace fair. Effect of fast primer noticible. 125 mils, 20 u sec/cm. .047 ufd.
34	3"	E-3 lot 1494 94/6	1.0	IRECO Booster 100 gms	pin 15,690 pr 11,160	700 * - trace fair, similar to previous shot, effect of fast primer noticeable. Constants same as previous.
35	3"	E-3 lot 1490 94/6	1.0	IRECO Booster 100 gms	pin 14,700 pr 11,750	650 * - trace poor. Primer effect noticeable. Trace cloudy. 125 mils, 50 u sec/cm. .047 ufd.

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* turns in 4 ft. length wire

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
36	3"	E-3 lot 1480	1.0	IRECO Booster 100 gms	pin 15,000 pr 11,245	650 * - trace poor. Primer effect noticeable, trace cloudy light leak in camera. 125 mils, 50 u sec/cm. .047 ufd. Pin trace excellent.
37	3"	E-3 lot 1492 94/6	1.0	IRECO Booster 100 gms	pin 14,705 pr 9,520	500 * - trace poor. Primer effect noticeable. Some hash. 125 mils, 20 u sec/cm. .047 ufd.
38	3"	E-3 lot 1492 94/6	1.0	4-½ stks 60% amm dyn	pin 15,025 pr 11,180	600 * - trace poor. Primer effect less noticeable. 125 mils. 20 u sec/cm. .047 ufd.
39	3"	E-3 lot 1492 94/6	1.0	4-½ stks 60% amm dyn	pin NR pr NR	650 * - shot misfired.
40	2"	pipe filled with Giant Gel.	--	# 6 cap	pin NR pr 19,260	650 * - trace had a good start but deviated about half way down. 125 mils, 20 u sec/cm. .047 ufd.
41	3"	E-3 94/6	1.0	4-½ stks 60% amm dyn	pin NR pr NR	650 * - shot to check on regulation current. Current trace had several places where it fluctuated. 125 mils.
42	3"	E-3 94/6	1.0	4-½ stks 60% amm dyn	pin NR pr NR	650 * - current trace nearly off scale. No regulation of current. 125 mils.

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* turns in 4-ft. length wire

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
43	3"	"A" reg prills	.85	4-½ stks 60% amm dyn	pin 11,910 pr NR	400 * - enamel Nichrome with 100 * around #30 enameled copper wire. Operator failure on probe trace. 125 mils, 20 u sec/cm. .047 ufd.
44	3"	"A" reg prills	.85	4-½ stks 60% amm dyn	pin 13,330 (approx) pr NR	500 * - liquid Nylon Nichrome 100 * around #30 enameled copper wire. Poor probe trace. 125 mils, 20 u sec/cm. .047 ufd.
45	3"	"Ac" reg prills	.85	4-½ stks 60% amm dyn	pin 9,580 pr 8,000	500 * - liquid Nylon Nichrome 200 * around #30 enameled copper wire. Very poor probe trace. 125 mils, 20 u sec/cm. .047 ufd.
46	3"	"Ac" reg prills	.85	4-½ stks 60% amm dyn	pin 10,000 pr 5,720	400 * - on 200 *. Poor traces, low ionization. 125 mils, 20 u sec/cm. .047 ufd.
47	3"	E-3 lot 1490 94/6	1.0	4-½ stks 60% amm dyn	pin 12,830 pr 17,250	600 * on 100 * - poor probe trace. Same constants E-3 mixed Feb.8, used March 6.
48	3"	E-3 lot 1485 94/6	1.0	4-½ stks 60% amm dyn	pin 12,820 pr 12,280	600 * on 200 * - probe trace not good. Same constants. E-3 mixed Feb. 2, used March 6.
49	3"	E-3 lot 1485 94/6	1.0	4-½ stks 60% amm dyn	pin 13,500 pr 15,520	700 * no copper wire. Probe trace not good. Same constants. E-3 mixed Feb. 8, used March 6.

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* turns on 4-ft. length wire.

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
50	3"	E-3 lot 1485 94/6	1.00	4-½ stks 60% amm dyn	pin 15,870 pr 16,040	700* no copper wire. probe traces not good. Same constants. E-3 mixed Feb. 8, esed March 6.
51	3"	CD, 94/6	.90	4-½ stks 60% amm dyn	pin NR pr NR	600* - 100* wire core grounded to pipe. No. photographs, usual constants.
52	3"	CD, 94/6	.85	4-½ stks 60% amm dyn	pin 11,810 pr 10,710	600* - 100* wire core grounded to pipe. Good r.e. record. Difficult to read, concave down.
53	3"	CD, 94/6	.86	4-½ stks 60% amm dyn	pin 11,540	600* - 100* wire core grounded to pipe poor r.e. record.
54	3"	CD, 94/6	.87	4-½ stks 60% amm dyn	pin NR pr 11,920	600* - 100* Wire core grounded to pipe. poor r.e. record.
55	3"	CD, 94/6	.89	4-½ stks 60% amm dyn	pin 11,580 pr 12,630	600* - 100* wire core grounded to pipe poor r.e. record. Wire failed about half way down the pipe
56	3"	CD, 94/6	.86	4-½ stks 60% amm dyn	pin 12,615 pr 11,690	600* no copper wire, very poor trace. estimate on the slope.
57	3"	CD, 94/6	.86	4-½ stks 60% amm dyn	pin 12,050 pr 13,600	600* no copper wire, trace fairly good except for then end .

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* turns on 4-ft. length of wire

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
58	3"	CD, 94/6	.86	4-½ stks 60% amm dyn	pin 11,860 pr 13,310	600* no copper wire, good clear trace, slight bow as if increasing in velocity
59	3"	CD, 94/6	.86	4-½ stks 60% amm dyn	pin 11,950 pr NR	600* no copper wire poor trace. seemed to be a delay at the start of the trace.
60	3"	CD, 94/6	.86	4-½ stks 60% amm dyn	pin 12,715 pr 15,380	600* good clear trace. Appeared to be increasing in velocity.
61	4"	CD, 94/6 mixed Mar. 15	.80	4-½ stks 60% amm dyn	pin 11,030 pr 11,550	600* on 100* copper wire, excellent trace not quite linear, appeared to be increasing in velocity toward the latter part of the trace. 4" clay
62	4"	CD, 94/6 mixed Mar. 15	.80	4-½ stks 60% amm dyn	pin 11,070 pr 11,620	600* on 100* copper wire. Excellent trace, increased in velocity toward the last part of the trace. 4" clay
63	4"	CD, 94/6 mixed Mar. 15	.80	4-½ stks 60% amm dyn	pin 10,975 pr 11,280	600* on 100* excellent trace, increased in velocity towards the end of trace 4" clay.
64	4"	CD, 94/6 mixed Mar. 15	.80	4-½ stks 60% amm dyn	pin 11,060 pr 11,740	600* on 100* good trace, quite linear over the first 2/3, then slope steepens. 4" clay
65	4"	CD, 94/6 mixed Mar. 15	.80	4-½ stks 60% amm dyn	pin 11,070 pr 11,950	600* on 100* excellent trace, very linear over the first part of the trace then slope steepens. 4" clay

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* turns in 4 ft. of wire

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
66	4"	CD, 94/6 Mar. 15	.80	4-½ stks 60% amm dyn	pin 11,065 pr 11,330	600* on 100* excellent trace. not too linear. 4" clay
67	4"	CD, 94/6 Mar. 15	.80	4-½ stks 60% amm dyn	pin 10,880 pr 11,590	600* on 100* excellent trace very linear for 2/3 of trace, then slope increases. 4" clay
68	4"	CD, 94/6	.80	4-½ stks 60% amm dyn	pin 11,375 pr 13,040	600* on 100* good trace, linear over central portion only 4" clay
69	3"	1' CD, 3' Comp C-4	--	"	pin NR pr NR	600* on 100* fairly good trace. Definite break between CD and C-4 3" iron pipe
70	4"	CD, 94/6 Mar.15	.80	4-½ stks 60% amm dyn	pin NR pr NR	600* on 100* poor trace, measured current at the same time. Current not constant.
71	4"	"	.83	"	pin 11,290 pr 11,660	600* on 100* fair trace on central part, very linear. no current .wire appeared to fail at 3/4 length 4" clay.
72	4"	"	.83	"	pin 11,410 pr 11,900	600* on 100* good trace, record increases in velocity about 1/3 way down. last part very linear
73	4"	E-3 94/6 Mixed Mar 15	.91	"	pin 13,360 pr 13,100	600* On 100* trace showed a definite break between primer and E-3. Trace jumped initially and gives a faulty reading 4" clay

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* Turns on a 4' length of wire

No.	Pipe Dia	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
74	4"	E-3, 94/6 mixed Mar 22	.91	4-½ stks 60% amm dyn	pin 12,950 pr 13,850	Similar to preceding trace. More curved. sharp break at the end of wire
75	4"	B-A-1** 94/6 mixed Mar. 22	.85	"	pin 9,800 pr NR	600* on 100* very poor trace. A lot of hash. Voltage jumped after triggering, cannot estimate velocity
76	4"	"	.83	"	pin 9,800 pr 12,260	600* on 100* better than previous trace, obviously in error for some reason
77	3"	E-3, 94/6 Mar. 22	.91	"	pin 13,240 pr 16,000	600* on 100* trace very short, also very linear. 3" iron pipe
78	3"	CD, 94/6 Mar 10	.85	"	pin 11,760 pr 10,040	600* on 100* excellent trace, quite linear. 3" iron pipe
79	3"	B-A-1** 94/6 mixed Mar 22	.83	"	pin 9,240 pr 9,180	600* On 100* trace failed about1/2 way along pipe. 3" iron pipe
80	4"	CD, 94/6 mixed Apr. 10	.85	"	pin NR pr 9,820	600* on 100* trace regular, and fairly linear. 4" clay. no current
81	"	"	"	"	pin 11,260 pr 10,490	600* On 100* trace fairly regular pronounced difference between primer and CD. 4" clay pipe
82	"	"	"	"	pin 10,950 pr 11,070	600* On 100*trace good for the first half, then it began to fluctuate. 4" clay pipe

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* turns on a 4' wire. ** commercial blasting agent

No.	Pipe Dia.	Explosives	Filling Density	Primer	Detonation Velocity	Remarks
83	4"	CD, 94/6 mixed Apr. 10	.85	4-½ stks 60% amm dyn	pin 11,090 pr 10,070	600* on 100* trace fairly good. Definite break between primer velocity and AN velocity 4" clay pipe.
84	"	"	"	"	pin ** pr 11,000	600* on 100* trace good. 4" clay. no current.
85	"	"	"	"	pin ** pr 11,450	600* On 100* trace good. 4" clay
86	3"	"	"	"	pin ** pr 11,320	600* On 100* trace fairly good, hash appears to have a long wave length. current reading was very poor. possibly should have grounded copper wire.
87	"	E-3, 94/6 mixed Apr. 13	1.04	"	pin ** pr NR	600* on 100* scope on ac instead of dc. No current trace either.
88	"	"	1.08	"	pin ** pr 13,990	600* on 100* very good trace, current regulated well. 3" iron pipe
89	"	"	1.04	"	pin ** pr. 15,560	600* on 100* Very good trace for 3/4 of pipe, then wire broke. 3" iron pipe
90	"	"	"	"	pin ** pr 16,410	600* on 100* very good trace. voltage trace failed after 80% of pipe was consumed. Current regulated well. 3" iron pipe.
91	"	"	"	"	pin ** pr NR	600* on 100* trace was too short to read, failed 1/5 of way down pipe. 3" diameter iron pipe

** no reading attempted   * turns on a 4' length of wire

No.	Pipe Dia.	Explosive	Filling Density	Primer	Detonation Velocity	Remarks
92	3"	E-3, 94/6 mixed Apr 13	1.03	4-½ stks 60% amm dyn	pin ** pr 14,060	600* on 100* Excellent trace, poor current regulation. Trace very linear, 20µ sec. 3" iron pipe
93	"	"	"	150 gms. TITAN	pin ** pr 14,800	600* on 100* good trace, failed about 3/4 way down the pipe. No overdrive from primer
94	"	B-A-2,*** 94/6	.85	150 gms. TITAN	pin ** pr 9,000	600* on 100* poor trace. Nitrate does not appear to be ionized very well.
95	"	"	"	"	pin ** pr 9,790	same as above
96	"	Composition C-4	--	"	pin ** pr **	600* on 100* No voltage, wires damaged when tamping explosive in pipe. Good current regulation
97	1½"	CD, 94/6	.85	1 stk 60% gelatin	pin ** pr NR	600* on 100* wires damaged when loading hole, current held for awhile the wire shorted.
98	"	"	"	"	pin ** pr NR	600* on 100* wires were damaged when hole was loaded.
99	"	"	"	"	pin ** pr 7,780	600* On 100* excellent trace, current regulated well.
100	"	"	"	"	pin ** pr 8,510	600* on 100* Excellent trace, current regulated well.

***Commercial blasting agent ** no pin reading was attempted * turns on 4' of wire

VITA

William S. Breakey was born April 24, 1935 in Morden Manitoba Canada, the son of William J. Breakey and Isabel Smith. He received his elementary and high school education at Morden.

In September 1955 he enrolled in the University of Manitoba where he pursued two years of general engineering. In September 1957 he transferred to the University of British Columbia, graduating in May 1959 with a B.A.Sc. in Mining Engineering.

During the months of summer vacation he was employed as a miner in iron mines in Ontario, nickel mines in Manitoba and uranium mines in Ontario. After graduation he accepted a position in the mine production department of Falconbridge Nickel Mines, Falconbridge, Ontario.

In September 1960 he enrolled in the Graduate School of the Missouri School of Mines and Metallurgy. In February 1961 he was appointed a Graduate Assistant in the Department of Mining Engineering. On June 1, 1961 he resigned this appointment and received a Research Fellowship sponsored by the Monsanto Chemical Co. of St. Louis, Missouri. He completed all requirements for the degree of Master of Science in Mining Engineering in May 1962.

He is a member of Sigma Gamma Epsilon, a junior member of the Canadian Institute of Mining and Metallurgy, a student member of the American Institute of Mining Engineers and an associate member of Sigma Xi.