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TITLE INSTRUMENTATION TECHNIQUES FOR MONITORING SHOCK AND DETONATION WAVES

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INSTRUMENTATION TECHNIQUES FOR MONITORING SHOCK AND DETONATION WAVES

Richard D. Dick and R. Leon Parrish

ABSTRACT

CORRTEX (Continuous Reflectometry for Radius Versus Time Experiments), SLIFER (Shorted Location Indication by Frequency of Electrical Resonance), and pin probes were used to monitor several conditions of blasting such as the detonation velocity of the explosive, the functioning of the stemming column confining the explosive, and rock mass motion. CORRTEX is a passive device that employs time-domain reflectometry to interrogate the two-way transit time of a coaxial cable. SLIFER is an active device that monitors the changing frequency resulting from a change in length of a coaxial cable forming an element of an oscillator circuit. Pin probes in this application consist of RG-174 coaxial cables, each with an open circuit, placed at several known locations within the material. Each cable is connected to a pulse-forming network and a voltage source. When the cables are shorted by the advancing wave, time-distance data are produced from which a velocity can be computed. This paper describes each technique, installation of the gauge, examples of the signals, and interpretation of the records.

INTRODUCTION

Measurements of the performance of the explosive in a blastwell are essential for evaluating the effectiveness of a rock fragmentation round and for computer simulations of the blast. During a recent Department of Energy (DOE) sponsored oil shale fragmentation research program, the explosive column and the stem column containing the explosive were instrumented on a routine basis during the field tests. Using coaxial cables as sensors, the initiation time and the detonation velocity were measured for each explosive. In addition, the functioning of the initiator and initiation schemes were accurately determined. In some tests, separate boreholes were drilled in the rock and instrumented with coaxial cables to obtain information on rock mass motion and crater formation. These diagnostic methods were reliable, easy to install and accurate.

We describe three techniques for interrogating a coaxial sensor cable placed in the explosive and stem columns. The techniques produced time-distance data from which the initiation time and detonation velocity were determined. The propagation speed of the shock wave in the stem column was obtained from two of the methods. Each method used a standard $50\text{-}\Omega$ coaxial cable commonly available. We discuss the basic operating principles of each technique, installation procedures, and signal recording methods. Examples of specific applications and the interpretation of the signal records are also discussed.

TECHNICAL EXPLANATION AND METHODS

General

In rock fragmentation, commercial blasting agents are used. These explosives are "non-ideal," that is, the explosives do not behave according to steady-state theoretical predictions based on equilibrium thermodynamics of the detonation products. For these explosives, the performance depends on the borehole diameter, densification during loading, downhole temperature, moisture contents, and initiation method. Some commerical explosives have been characterized [1] in the laboratory to provide basic data on the energy release. Direct measurements of the explosive energy can not be accomplished in the field, but a good estimate [2] can be made using the measured density and the detonation velocity.

The key element in these measurement techniques is the "crushing" (i.e., mechanical deformation, electrical short, or a large change in the electrical impedance) of a $50\text{-}\Omega$ coaxial sensor cable as the detonation front or a shock wave sweeps along the cable. Each of the methods utilizes a different scheme for accurately determining the progressive shortening of the sensor cable. One method, CORRTEX [3-5] (Continuous Reflectometry of Radius Versus Time Experiments), employs a time domain reflectometry (TDR) technique to measure the change in

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cable length as a function of time. The second method, SLIFER [6-8] (Shorted Location Indication by Frequency of Electrical Resonance), utilizes the coaxial cable as an element in an oscillator circuit to sense a change in frequency of the circuit resulting from a change in length as the sensor crushes. The third method, called pin probes, depends on the shorting of an open-circuit coaxial cable attached to the explosive column. Shorting occurs when the ionization front associated with the detonation wave contacts the cable end or when it is deformed mechanically. CORRTEX and SLIFER accurately provide a continuous record of wave front position as a function of time, while pin probes provide discrete position-time values depending on the number of cables used. CORRTEX and SLIFER also provide accurate data on wave propagation in the stem, but pin probes are not useful for this application. CORRTEX was used on a few fragmentation tests to determine motion within the rock mass during the blast with some success.

Several different types of coaxial cables have been used. Common coaxial cables with a solid dielectric between the center wire and the shield, including RG-58, RG-174, RG-213, RG-214, and RG-223, have proven adequate for measurement of the detonation velocity for many applications [9]. They are, however, inadequate for cases where the shock wave amplitude is low. Specially configured cables with metallic sheaths, such as FSJ1-50 with a foam dielectric and the HJ4-50 with an air dielectric, have been employed for special cases. The lower crush strength (10-20 MPa), together with a more positive short when the shield is crushed against the center wire, makes these types of cables far superior. The lower crush strength also permits measurement of the shock wave upward through the stemming material, providing for an assessment of the stemming performance. Table I is a list of 50-Ω cables used along with features of each and the technique used.

CORRTEX System

The CORRTEX system is based on pulsed TDR methods and includes the data acquisition electronics, a minicomputer, and data reduction programs. The microprocessor-controlled unit periodically samples 50-Ω sensor cable and stores this information as three digital words representing two-way transit times and one real-time clock data word. Resolution of the two-way transit time is 125 ps, resulting in 30-mm resolution of the relative cable length over a several hundred meter cable length. Pulsed TDR consists of a series of pulses transmitted down the cable. At the start of each pulse, a clock is started in the unit. When the pulse encounters the change in impedance due to crushing, it reflects and propagates back to the unit. The return pulse is detected, a clock-stop pulse is issued, and the microprocessor counts the elapsed time and stores the time in memory. This sequence is repeated for each pulse and the results are stored in long-life memory. The entire system is portable and can be easily carried and deployed by one person. Figure 1 is a schematic of the unit and operation. The latest CORRTEX units are capable of interrogating the sensor 4000 times with pulse rates of 5-90 μs. This provides 20-360 ms of recording time. The sampling rate depends upon the two-way travel time of the pulse of the combined length of sensor and signal cable. Otherwise, the rate should be compatible with the desired resolution.

The CORRTEX units are triggered from a 5 V signal generated by an external computer-controlled timing and firing (T and F) system. Generally, the units are started a few milliseconds prior to the detonation to provide baseline and initiation time data

After an experiment, the time-cable shortening data stored in memory are reduced by built in software to provide detonation velocity and initiation time data a few minutes after the experiment is conducted.

SLIFER System

SLIFER sensors consist of a coaxial cable emplaced in a wellbore along the path where the wave velocity measurement is to be made and connected by messenger cable to the data recording/reduction system. When the explosive detonation velocity is to be monitored, the cable is emplaced in the blast-well prior to loading of the explosive. Crushing of the cable takes place up the explosive column as the explosive detonates, providing a continuous record of the shortened cable length as a function of time

The SLIFER method of data acquisition utilizes the fact that for lengths less than a quarter wave length of a cable, the cable inductance is proportional to length. The cable, as the inductive element of an oscillator, modulates the frequency as a proportional measure of shorted length. The frequency is directly frequency-modulated (FM) and is recorded as an indication of wavefront position. A sketch of the basic SLIFER system is depicted in

Table I Coaxial Sensor Cables of 50-Ω Impedance

Cable Type	Dielectric	Diam. (mm)	Crush (GPa)	Technique	Application
RG-174F	Foam	2.5	0.005	CORRTEX	Stem, Grout
RG-174	Polyethylene	3.0	0.01	CORRTEX, Pin Probe	Explosive, Stem, Grout
HJ4-50	Air	6.4	0.01	SLIFER	Explosive, Stem, Grout
FSJ1-50	Foam	6.4	0.1	CORRTEX	Explosive, Stem, Grout
RG-58	Polyethylene	6.4	0.2	SLIFER	Explosive, Stem, Grout
RG-223	Polyethylene	6.4	0.3	CORRTEX	Explosive, Stem, Grout, Rock
RG-214	Polyethylene	12.7	2.0	CORRTEX	Rock, Crater
RF-214	Foam	12.7	2.0	CORRTEX	Rock, Crater
RG-225	Polyethylene	12.7	3.0	CORRTEX	Rock, Crater

Figure 2. As the cable is crushed by the detonating explosive, the oscillator frequency changes and becomes a record of the shock front position as a function of time (Figure 3). Before installation, the system is calibrated by shorting the cable with a pin at various positions along its length. The results (Figure 4) are quite linear, providing a simple and convenient conversion from frequency to shorted length. The FM frequency of the oscillator ranges from 800 kHz to 1.2 MHz, permitting derivation of the shorted length at microsecond intervals. Recording is on analog tapes: one tape track per sensor. Recording times of 30 minutes are available: the data can be recorded from times well before the scheduled detonation time (to pick premature detonations), to well after (recording any late time detonations or other events).

Pin Probes

The pin-probe technique involves the shorting by ionization or mechanical crushing of a coaxial cable electrically charged by a pulse-forming network. Figure 5 is the charging circuit and the pulse-forming network. The cable is an open circuit that is configured as a switch. At closure, current flows in the pulse-forming network generating a pulse in the signal line that in turn is recorded by a fast oscilloscope or transient signal recorder. This pulse represents the arrival time of an ionized front; by placing several cables terminating at different spatial positions within the explosive charge, the arrival times of the detonation front at each of the pins or cable ends are determined. The slope from the plot of time of arrival versus position of the cable end is the detonation velocity. The pins provide reliable data when monitoring the detonation but are erratic in other uses.

Typically, RG-174 coaxial cable is used as the pin-probe wire. In an experiment, the open-circuit end of several RG-174 cables are attached to a plastic or wooden rod at accurately measured locations. The rod is inserted in the borehole, and then the explosive and stem material is placed in the hole. The ends of each cable are connected to the circuit box containing the charging voltage circuit and the pulse-forming network. Each pin probe is then connected to a signal cable.

APPLICATIONS

Typical applications of sensor cables in oil shale fragmentation experiments [10,11] are depicted in Figures 6 and 7. In each case, the sensors are emplaced in the blastwell with the end a known distance below or wrapped around the detonator/booster system, anchored in place, and pulled taut. The blastwell is then loaded with a column of explosive and a column of stem to confine the charge. Depending on the recording technique, the sensors are connected to either the CORRTEX units, the SLIFER electronics, or the pin-probe boxes.

When the explosive is detonated, the sensor cable is crushed at the detonator/booster location providing the time of initiation. The CORRTEX and SLIFER cables are crushed continuously at the velocity of detonation. The pin probes short as the ionized detonation front intercepts the open-circuit ends of the sensors. Crushing of the cable continues through the stemming column providing a measurement of the decreasing shock wave velocity in the stem material. Figure 7 illustrates the placement of sensor cables in grouted satellite instrument holes to monitor motion and shock wave propagation in the oil shale rock.

An idealized signal record, which might be obtained from either the SLIFER or CORRTEX methods, is shown in Figure 8 along with the test geometry. When the explosive is detonated, the sensor is immediately crushed by the booster at the 0.1 m level. The sensor continues to crush another 2.5 m at the detonation speed of 5.65 km/s. Then, a significant change in slope occurs at the explosive-stem interface indicating a decreasing shock wave velocity in the stem column. Eventually it reduces to nearly zero at the borehole collar. In this test, the measured detonation velocity indicated the explosive performed as expected as did the stem material. The following two examples illustrate deviations from the normal or classic behavior.

Test B-4

Test B-4 was a five-borehole cratering and rubblization experiment in oil shale. Four boreholes were located at the corners of a square approximately 3.5 m on a side and a borehole in the center. Figure 9 illustrates the test geometry and the CORRTEX sensor placement within the borehole. The borehole depth was 5.0 m and the explosive column was 3.5 m. FSJ1-50 and RG-174 coaxial cables were used as sensors. Pin probes were also used to monitor the detonation wave in each borehole. The time-distance plot shown in Figure 9 is a composite of the signal records from a sensor cable in each borehole. Also shown is a pin probe time and location point. The charge column in the four corner holes detonated properly, as noted by the 5 km/s velocity from the plot for sensors K2 through K5. However, the signal from the K1 sensor indicated improper detonation of the center-hole explosive leading to the conclusion that the borehole contained undetonated explosive. This conclusion was verified during a careful post-test excavation of the crater.

SLIFER Test

The second example shows the SLIFER system in an explosive evaluation test. A blastwell 0.15 m in diameter and 12 m depth was drilled in limestone. A HJ4-50 sensor cable was tied to the detonator/booster, and a 0.95 m length "sausage" of water-in-gel explosive and lowered into the well. Loading was continued with a 2.87 m length of ANFO prills, another 0.95 m of gel, 3.51 m of ANFO, 1.07 m of gel, and 2.74 m of crushed stone stemming. The wellbore was "making water," i.e. though it was dewatered prior to loading, water coming into the well between the loading and detonation was sufficient to wet the bottom portion of the well. The SLIFER record is shown in Figure 10. The detonation velocity through the lower gel was 6.10 km/s. The wave velocity slowed to 0.61 km/s through the first 1.27 m of wet ANFO, increased to 5.94 km/s in the first 0.24 m of the next gel, dropped to 3.96 km/s in the next interval of ANFO, then dropped further to 1.94 km/s in the top gel, and decreased with distance as it traveled through the 3.74 m of stemming.

The SLIFER record provided an accurate assessment of the test. The reduction of wave velocity in the wet ANFO to less than critical detonation velocity showed that deflagration rather than detonation had occurred. Of even greater importance was the observation that the energy was still sufficient to detonate the next sausage of water-in-gel slurry at its normal velocity. The detonation velocity of the next interval of ANFO was normal. However, the top sausage of water-in-gel deflagrated, indicating that bridging had probably occurred during loading (the emplaced length of 1.07 m rather than 0.94 m also indicated bridging). This is an example of the dexterity of the measurement and the benefit of using the HJ4-50 air dielectric cable with low (10 MPa) crush strength.

Pin-Probe Data

Figure 11 shows a pin-probe record in which six RG-174 ionization pin cables were placed in a column of TNT explosive at 0.3 m intervals. Each fast-rising pulse is an electrical short at the time the detonation front arrived at the sensor location. A detonation velocity of 4.78 km/s was computed from this record, which compares with 4.84 km/s determined by CORRTEX. Each pin was charged with a negative 24 V and had a decay constant of about 100 ms. The rise time was approximately 10 s. These are very good data and provide an accurate measurement of the velocity.

SUMMARY

The techniques described represent three methods by which coaxial cables are used to monitor the performance of explosive and stem columns in a wellbore. The CORRTEX and SLIFER techniques provide a continuous record of the wave propagation, while pin probes provide a discontinuous record. However, pin probes require the least amount of electronics and recording equipment. SLIFER relies on a change in frequency as a function of cable shortening to provide the time-distance data, while CORRTEX relies on pulsed TDR methods. The methods are accurate, versatile, and easy to install.

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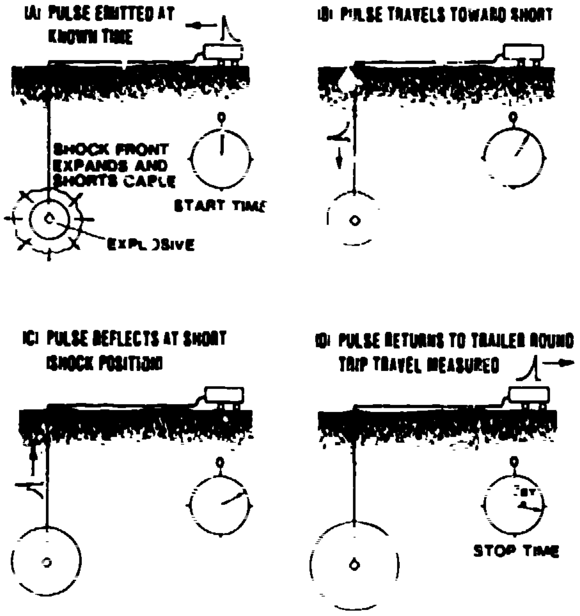

Figure 1   Schematic of the CORRTEX method

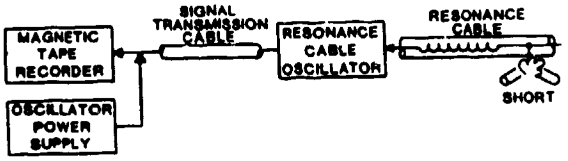

Figure 2. Schematic of the SLIFER method.

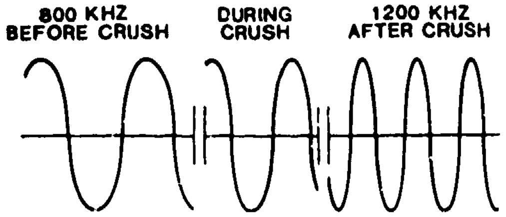

Figure 3. Change in oscillator frequency caused by shorting of a sensor cable for SLIFER.

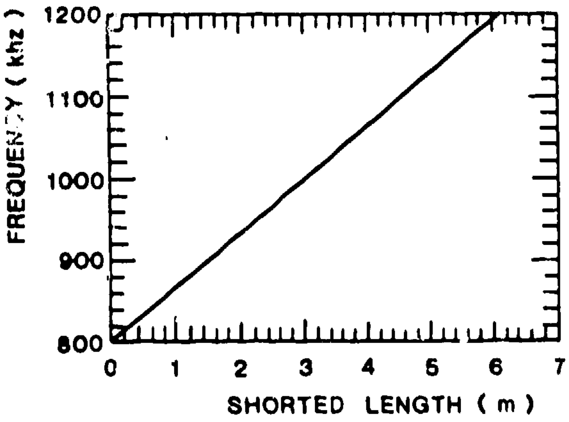

Figure 4. SLIFER oscillator frequency versus length of the sensor.

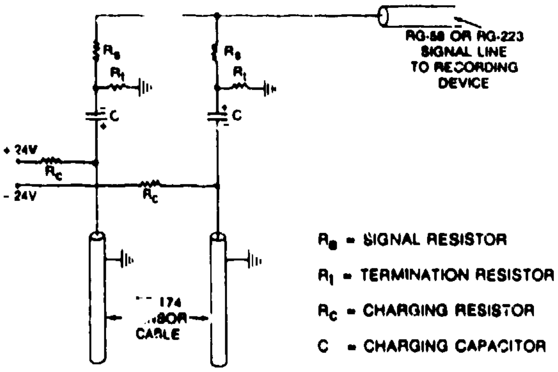

Figure 5. Circuit diagram for the pin probe.

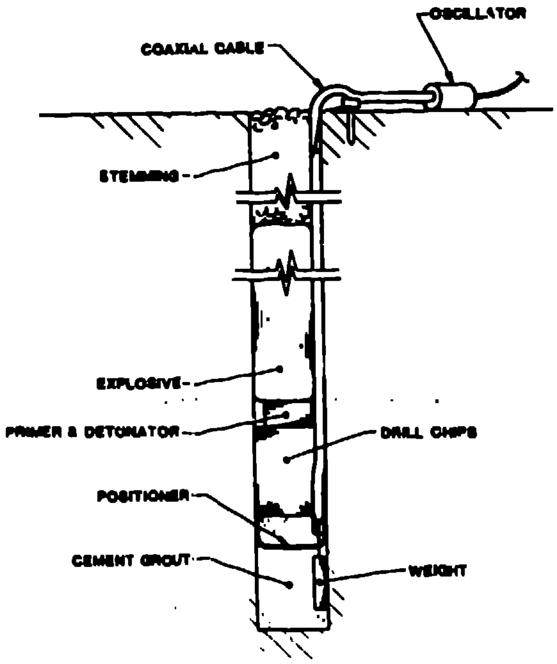

Figure 6. SLIFER placement in a blastwell.

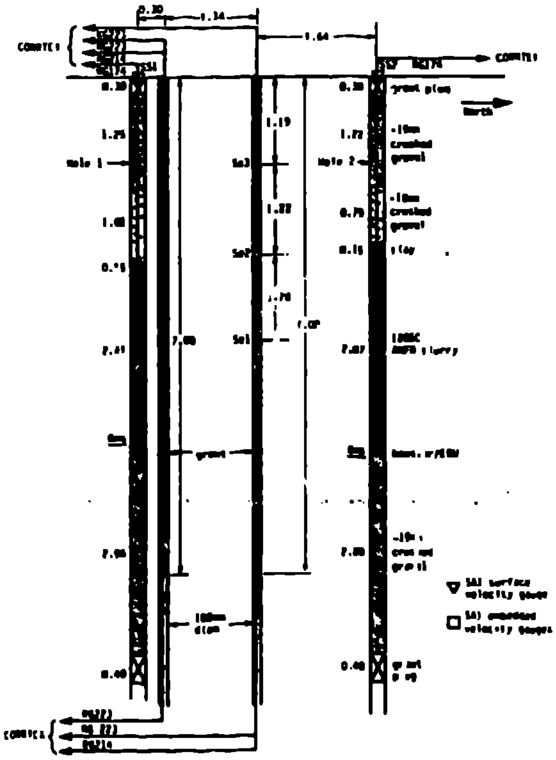

Figure 7. Installation of CORRTEX sensor cables in a fragmentation test.

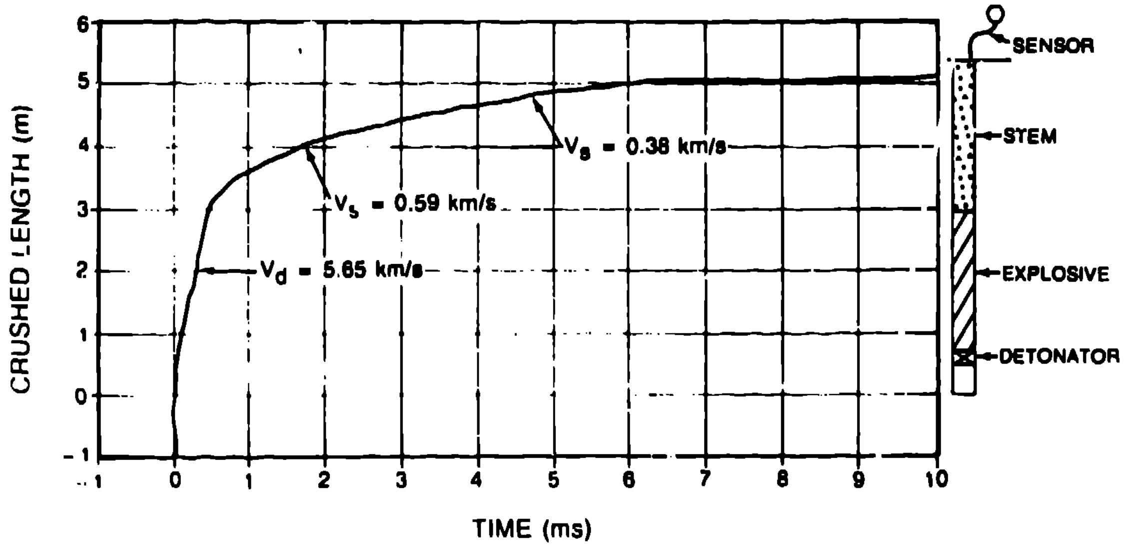

Figure 8. Idealized signal record from CORRTEX or SLIFER showing explosive detonation and shock wave propagation the stem column.

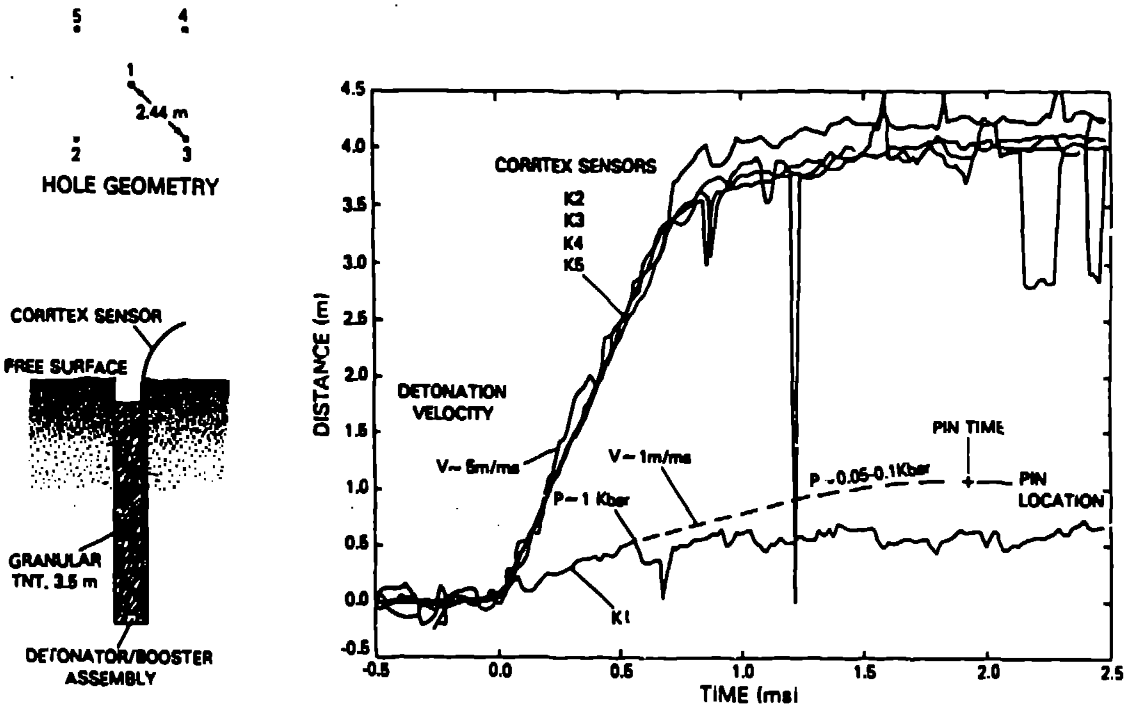

Figure 9. CORRTEX signal record from a five-borehole test showing proper burn of the explosive in four holes and deflagration in the other hole.

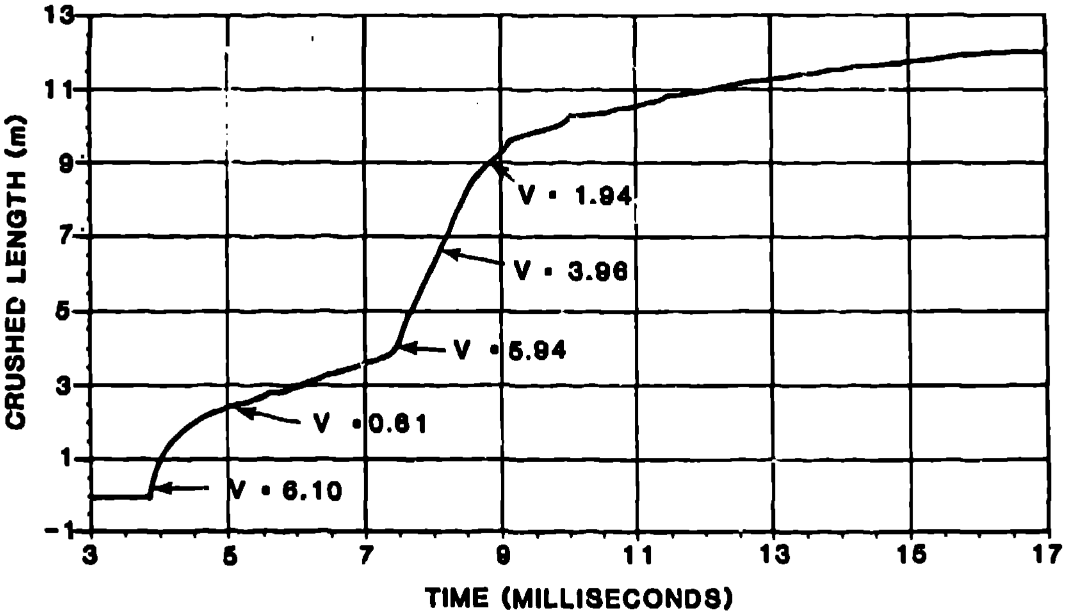

Figure 10. Explosive evaluation test using SLIFER.

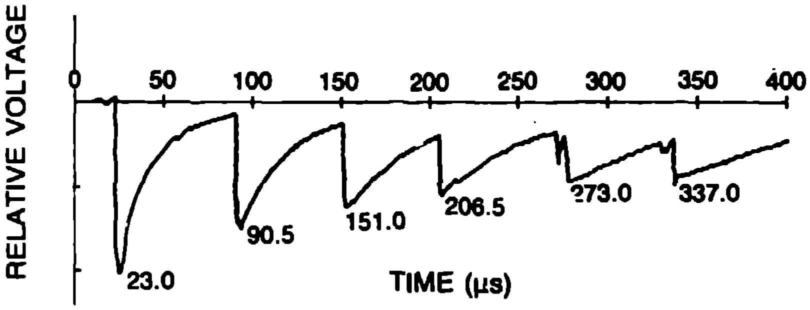

Figure 11. Typical pin-probe signal record.