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Title: **EXPLOSIVE PERFORMANCE MEASUREMENTS ON LARGE, MULTIPLE-HOLE ARRAYS AND LARGE MASSES OF CONVENTIONAL EXPLOSIVE**

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EXPLOSIVE PERFORMANCE MEASUREMENTS ON LARGE, MULTIPLE-HOLE ARRAYS AND LARGE MASSES OF CONVENTIONAL EXPLOSIVE

by

Thomas O. McKown[1], Donald D. Eilers[2], and Pharis E. Williams[3]

ABSTRACT

The COntinuous Reflectometry for Radius vs. Time EXperiment (CORRTEX) system[4] was developed by the Los Alamos National Laboratory for determining the energy released in a nuclear explosion by measuring the position of its shock front as a function of time. The CORRTEX system, fielding techniques, and the methods and software for data reduction and analysis were developed over a 15 year period with hundreds of measurements made on nuclear tests and high explosive experiments. CORRTEX is a compact, portable, fast-sampling, microprocessor-controlled system, based on time domain reflectometry, requiring only a 24 volt power source and a sensing element. Only the sensing element (a length of 50 ohm coaxial cable) is expended during the detonation.

In 1979, the CORRTEX system was shown to be ideally suited for chemical explosive performance measurements. Its utility for diagnosing chemical explosives was further demonstrated with successful measurements on large multiple-hole chemical shots in rock quarries and strip mines. Accurate timing of the detonation of sequenced or ripple fired arrays, as well as data characterizing the initiation, explosive performance and detonation anomalies are obtained. This information can serve as the basis for empirical or modeled improvements to blasting operations. A summary of the special CORRTEX features and well developed analysis techniques together with the experiment designs, data, and conclusions regarding the measurements and explosive performance from several array detonations and the Chemical Kiloton Experiment, 2.9 million pounds of an ammonium nitrate-fuel oil (ANFO) and emulsion blend conducted on the Nevada Test Site in 1993, are presented.

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[4] The CORRTEX measurement system as described here is not a commercially available system.

INTRODUCTION

The bilateral Threshold Test Ban Treaty (TTBT) and the Peaceful Nuclear Explosion Treaty (PNET) between the former Soviet Union and the United States were signed by the respective heads of state on July 3, 1974, and May 28, 1976, respectively. Both treaties limit the yield of individual nuclear explosions to less than 150 kilotons (TNT equivalent). The treaties as ratified in 1990 provide for onsite measurements to verify compliance with the yield limitation. Approved instrumentation is used to measure the position of the explosion induced shock wave traveling radially outward from the center of the explosion, from which the yield of the explosion can be inferred.

In 1975, Los Alamos National Laboratory (Los Alamos) began development of a Time Domain Reflectometry (TDR) based system to perform these measurements for the United States Department of Energy. The first instrument, known as the PNE recorder or digital TDR system, was fielded and tested in the late 1970's. This unit was also used to demonstrate the utility of the system for diagnosing conventional explosive performance in 1979. A redesign of the hardware in the early 1980's became known as the CORRTEX (COntinuous Reflectometry for Radius vs. Time EXperiment) recorder(*5*).[5] The recording system, fielding techniques, and data reduction and analysis methods were developed and refined on hundreds of measurements made on nuclear tests and high explosive experiments, resulting in the United States Government selecting CORRTEX as its verification system for monitoring compliance with the TTBT and PNET. The verification system was successfully fielded in 1988 performing measurements on the Joint Verification Experiments conducted on the underground nuclear tests Kearsarge (United States Nevada Test Site) and Shagan [Soviet Semipalatinsk (Kazakhstan) Test Site]. The purpose of this paper is to describe the successful application of the CORRTEX system to measure parameters of performance on complex chemical explosions.

CONVENTIONAL EXPLOSIVES APPLICATIONS

An Introduction

The oil embargo of 1974 intensified interest in developing the vast oil shale deposits in the Western United States. Conventional mining methods were considered prohibitively expensive and environmentally destructive. Research undertaken by Los Alamos researchers and others, to develop an in situ retorting process, required the investigation of techniques of explosively rubbling the material in place. A measurement of performance in each explosive drill hole was needed to determine optimal hole spacing and detonation timing. The CORRTEX system provided not only measurement of the detonation timing, but also the explosive detonation velocity and showed any anomalies in the burn. This information was used to evaluate the experiment results, in order to improve subsequent experiments and the computational modeling.

The Measurement Method

A brief description of the CORRTEX system is included with this report as Appendix A. Illustrated with hole 1 of Figure 1, a sensing element is attached to the detonator-booster assembly and installed at the far or "away" end of a drill hole. If additional explosive holes are to be detonated sequentially, the same sensing element may be looped through several holes as shown with holes 2 through n of Figure 1, subject only to the recording time, total cable length, and other CORRTEX system restrictions. With the sensing elements kept taut, the holes are loaded to the planned depth with explosive and then stemmed to the surface.

Figure 1 shows that "loops" are installed in the sensing element in each hole. Although this subject is presented in the CORRTEX description,[6] it is so significant to the accuracy of CORRTEX results that further emphasis is given here. The calculation of the position of the detonation or shock front along the length of the installed sensing element is primarily dependent on knowing two values. The total two-way-transit-time (TWTT) of the sensing element just prior to detonation, obtained by performing a calibration or full cable length measurement shortly before detonation, and the velocity of

[5] Italic numbers in parentheses refer to items in the list of references.

[6] Appendix A.

propagation of an electrical pulse in the sensing element. Cable manufacturers will quote a value of the propagation velocity for their cables as a percentage of the velocity of light and simple calibration techniques may also be employed to measure the value, but these are average values and are not obtained on the installed cable, under the conditions of the experiment, at the time of detonation. The propagation velocity varies with environmental conditions, particularly temperature, along any length of cable and certainly between lengths of cable from separate reels, as are typically required with large array shots. A variation in propagation velocity of as little as 0.5% can result in significant errors in position along the cable, particularly over long lengths of sensing element. Finally, the selected threshold level of the voltage threshold detection circuit on the return pulse, and the amplitude and shape of the reflected pulse can all have a significant impact on the recorded TWTT.

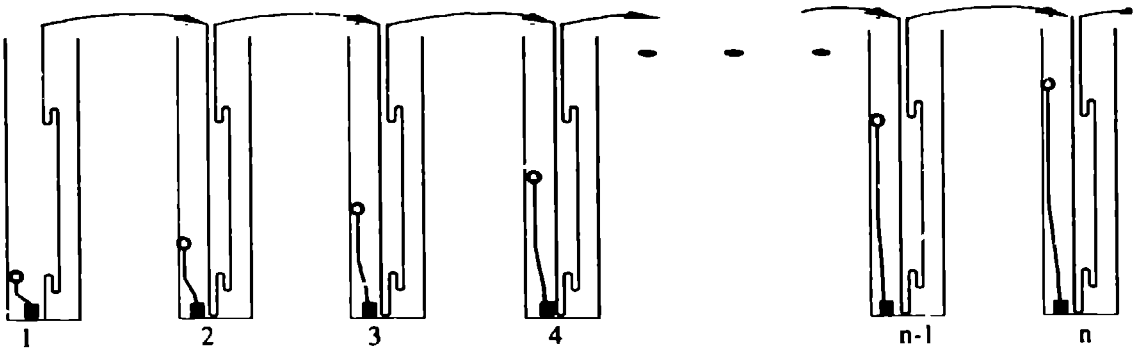

Figure 1. Illustration of a CORRTEX sensing element installed in an array of holes.

The installation of geometric signatures or "loops" of accurate lengths at measured locations along the cable, was designed to produce distinct features in the recorded data, which would permit a determination of the actual propagation velocity during detonation, a dynamic absolute calibration. Figure 2 illustrates the concept. In this case, two loops in the sensing element of known length and known separation distance along the cable, provide two discrete steps in the resulting data. This information can be used to compute a change to the initial propagation velocity used in the data reduction process, to ensure that the reduced cable length data agrees with the measured loop separation distances. Ideally, with the quality of cable typically used as sensing elements for conventional explosive applications, placing two loops in the sensing element, within the explosive of each drill hole, and knowing the position along the cable where each detonator-booster unit is attached, will provide ample information to accurately adjust the resulting cable-length-as-a-function-of-time data.

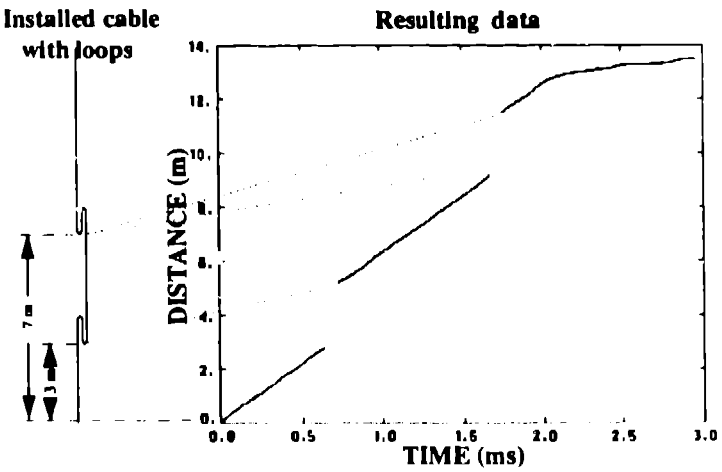

Figure 2. Geometric signatures installed in a CORRTEX sensing element and the results in the data.

Figure 3 shows the results from an array of twelve explosive holes, with the site diagram inserted in the figure. The planned detonation delay for each hole, with respect to hole 1, is shown below each hole designation in the diagram. All detonations were typical of hole 1 whose enlargement is included in Figure 3, except for hole 11. Examination of the data from hole 11, for which an enlargement is also provided in Figure 3, shows that while detonation did occur, the explosive failed to initiate, at least prior to hole 12 detonating. Table 1 compares the measured detonation times to the planned times and gives the explosive detonation velocity for each hole. This illustration is typical of the information obtained from an explosive array. There were no significant detonation problems other than the failure in hole 11 and the large scatter in detonation times. Several examples of the application of these techniques applied to commercial blasting operations will be presented in the following sections.

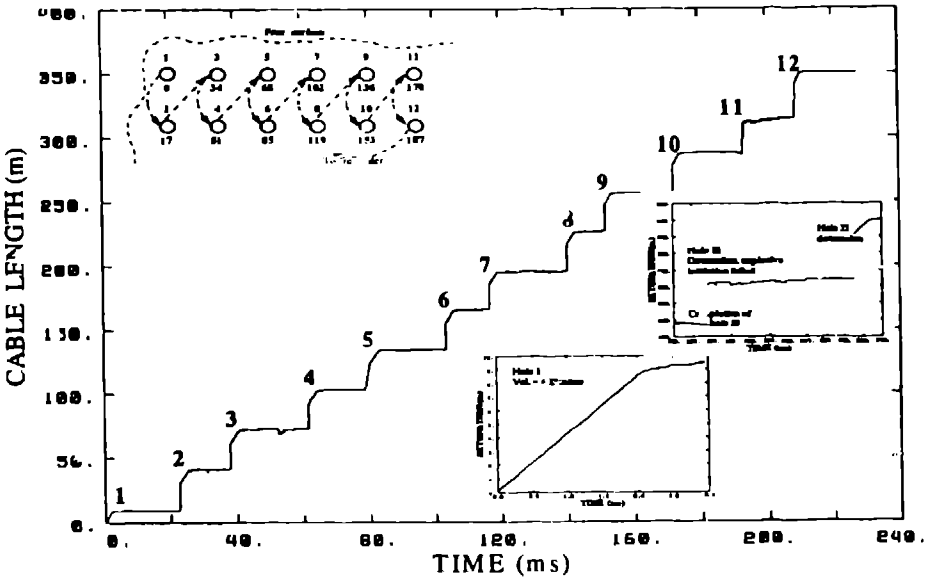

Figure 3. Example of an explosive array diagnosed with CORRTEX measurements.

Table 1. CORRTEX illustration summary of array detonation times and velocities..

Hole	Detonation times (ms) Planned	Measured	Detonation time Difference (ms)*	Detonation Velocity (m/ms)
1	0.0	0.00		4.19
2	17.0	22.72	22.72	4.15
3	34.0	38.72	15.44	4.19
4	51.0	61.52	23.36	4.14
5	68.0	80.08	18.56	3.88
6	85.0	103.12	23.04	4.57
7	102.0	116.80	13.68	4.23
8	119.0	140.48	23.68	4.30
9	136.0	151.68	11.20	4.46
10	153.0	172.16	20.48	4.23
11	170.0	193.52	21.36	No burn
12	187.0	209.12	15.60	5.31

* Hole(n+1) - Hole(n)

Explosives Development Research—Explosive Arrays

Diagnostic measurements were made on a series of experiments in 1986. One of the purposes of the series was the testing of a developmental blasting agent which would produce low ground vibration while also efficiently displacing the burden. The site diagram inserted in Figure 4 shows a small array of twelve holes with burdens of about 5.1 m and spacings of about 4.4 m. The holes were drilled to a depth of 18.3 m with 1.5 m of Tovax placed in the bottom before the detonator-booster assembly and CORRTEX sensing elements. The first and last holes contained a 3.0 m stemming deck about 6.1 m above the bottom and all holes contained about 3.7 m of stemming at the top. The experiment was designed with all holes containing the experimental blasting agent, but mixing problems were encountered in loading holes 1, 12, and possibly 10.(2) The site diagram shows the planned detonation times of each hole or deck with respect to the hole 1 lower deck detonation. Common timing between all holes was achieved by starting all recorders with the detonation of the lower deck of hole 1. The K1 recorder was pulsed in dual cable mode (see Appendix A) on sensing elements designated K1A and K1B. Only the K1A measurements are presented in some detail.

Figure 4 shows the complete record of the detonations in holes 1, 3, and 5. The decked explosive in hole 1, inserted in Figure 4, shows the lower deck detonation, with the pressure falling off rapidly as the induced shock enters the stemming between the two decks. The roughness of the data between the two decks, between holes and within the detonation of holes 3 and 5 is indicative of the response of the sensing element to a low pressure. To obtain uniform crush and a clean data record with the cable type used for the sensing elements on this experiment requires pressures of 10,000 to 15,000 psi.

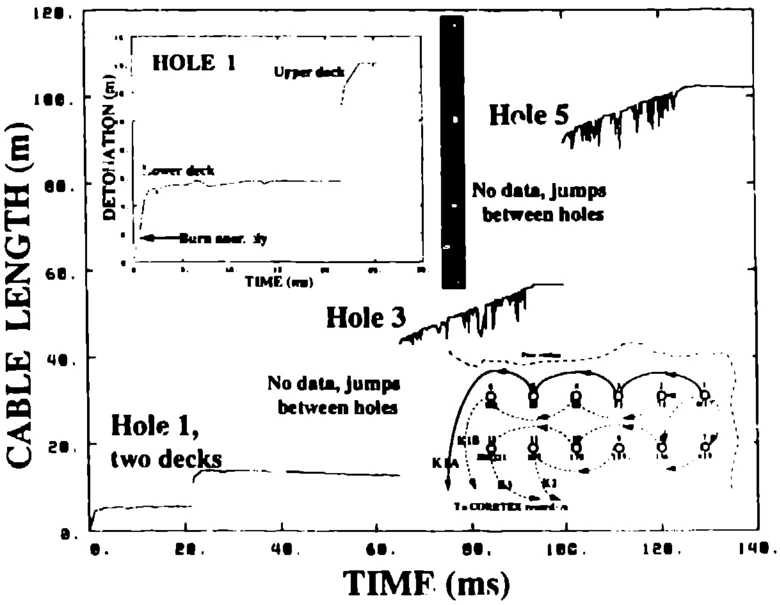

Figure 4. Explosives development, CORRTEX sensing element K1 record.

There are several anomalies noted in the hole 1 lower and upper deck detonations. In the lower deck, at about 0.07 ms or 1.5 m along the cable (marked in the Figure 4 insert), the explosive burn faltered before resuming a linear detonation. The detonation velocity before the problem was 3.56 m/ms while after was 4.20 m/ms. This feature was also present in the K2 and K3 records of hole 1. Excess water or material sloughing from the drill hole into the explosive or in the loading process could have caused the near cutoff. All three data records show that the upper deck detonation begins at about 11.0 m whereas the explosive was loaded beginning at 9.6 m. Apparently the booster-detonator assembly was emplaced higher than expected. Figure 5 contains enlargements of the reduced and edited records from holes 3 and 5, with a smoothed curve approximating a linear fit to the upper envelope of the data. This fit provides an approximation for the detonation velocity. It is noted in both graphs of Figure 5 that the booster overdetonated (high initial velocity, slowing to a constant velocity) the explosive. These measurements contributed to the analysis of the performance of this blasting agent, confirming that a low pressure, nearly linear detonation was achieved, resulting in the subsequent patent application and approval.(2) Table 2 compares the planned to measured detonation times and states the detonation velocities determined from the data for the entire array.

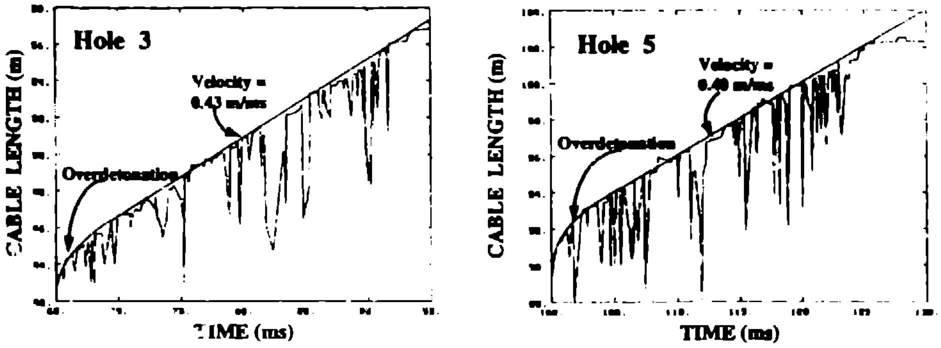

Figure 5. Enlargements of the CORRTEX explosive detonation records from holes 3 and 5

Table 2. Explosives development summary of array detonation times and velocities.

Hole	Detonation times (ms) Planned	Measured		Detonation time Difference (ms)*	Detonation Velocity (m/ms)
1L	0.0	0.0	>	21.6	4.20**
1U	17.0	21.6	>	20.3	4.38
2	34.0	41.9	>	23.3	0.42
3	51.0	65.2	>	15.1	0.44
4	68.0	80.3	>	19.7	0.44
5	85.0	100.0	>	19.1	0.40
6	102.0	119.1	>	23.3	0.43
7	119.0	142.4	>	16.9	0.45
8	136.0	159.3	>	18.1	0.47
9	153.0	177.4	>	16.6	0.45
10	170.0	194.0	>	21.8	0.44
11	187.0	215.8			0.43

* Hole(n+1) - Hole(n) **Terminal velocity, above anomaly

Commercial Mining Operations—A Large Explosive Array

An array of 42 bore holes in the 24.4 to 27.4 m burden over the first of three coal seams of a strip mine was instrumented with CORRTEX, to diagnose explosive performance. Figure 6 is a diagram of the plan for instrumenting all 42 holes with four sensing elements. Each hole of the array is identified by a row-column designation and below each hole symbol is the planned detonation time with respect to hole 1-6, the first hole to be detonated. The holes were arranged with roughly 4.6 m burdens and 5.2 m spacings. The pit face was to the left and up. Only the results from the K1 and K3 sensing elements will be presented here. To achieve common timing, all sensing elements started in hole 1-6, looping through the holes as shown in the site plan. Because of the requirement to obtain a dense set of data from each explosive hole and yet record for a period of time exceeding 535 ms, the last planned detonation, the CORRTEX recorders were programmed for a 50 μs pulse period but with the store-on-change-only (SOCHO) mode of recording active.[7] As the plots of the K1 and K3 data will later indicate, in the SOCHO mode, data are not stored during time intervals when the TWTT is not significantly changing, thus allowing the recorders to obtain data for the entire expected detonation sequence on each sensing element.

[7] This recording option is described in Appendix A.

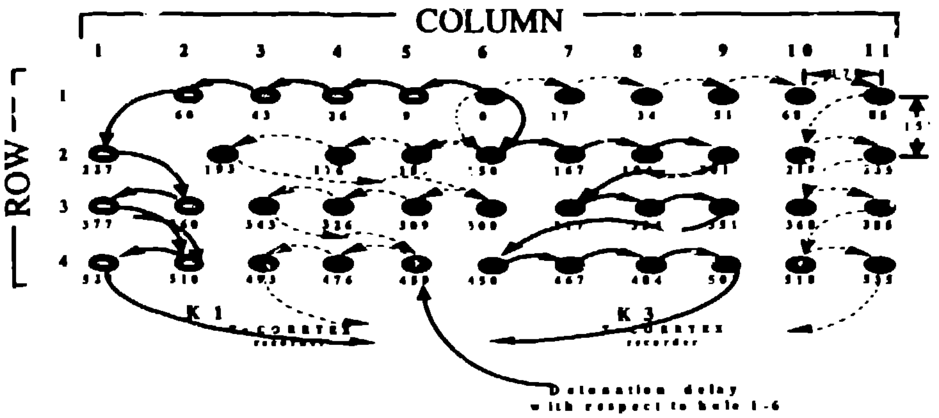

Figure 6. Diagram of the 42 hole array instrumented with four CORRTEX sensing elements.

Figure 7 presents the measured detonation times with the array plan. The Xes indicate that a measured time was not obtained, usually due to the early detonation of the succeeding hole in the sequence for that sensing element. For example, with K3, hole 2-8 detonated at 171.1 ms versus planned times of 184 ms for 2-8 and 167 ms for 2-7. Whether 2-7 detonated after 2-8 cannot be determined. Knowing the location along the K3 sensing element where the 2-7 and 2-8 booster-detonator assemblies were installed, i.e., the location on the cable looped to the bottom of the respective holes, permits the conclusion that the recorded data were from the hole 2-8 detonation and not from hole 2-7. A similar situation holds for holes 4-7 (p=467 ms) and 4-8 (m=466.3 ms, p=484 ms). The failure of holes 2-7 and 4-7 to detonate, before their succeeding holes, and the large deviation of the measured detonation times from the planned times, are not uncommon, at least in these authors' experiences.

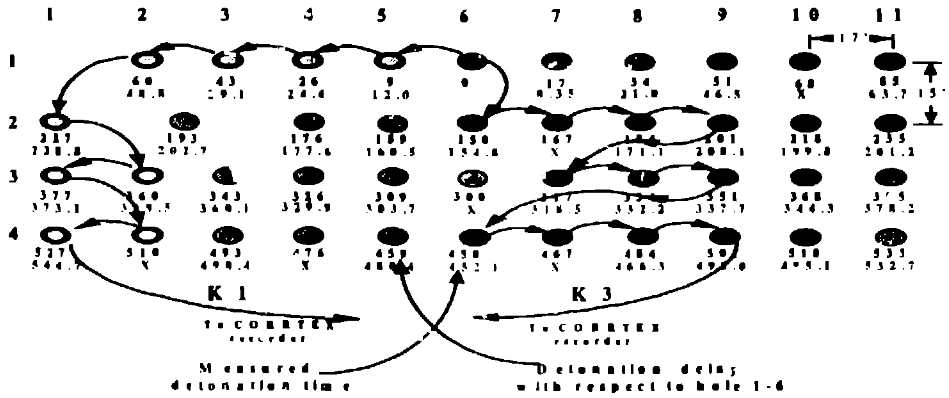

Figure 7. Diagram of the 42 hole array with planned and measured detonation times.

Figure 8 presents the entire record of the K3 sensing element and Figures 8a, b, c, and d are enlargements of the explosive detonations from holes 2-9, 3-7, 4-5, and 4-8 respectively. The first three each show variations of an apparent problem with the explosive columns while 4-8 shows a very nearly perfect steady state detonation. The explosive depth in each hole varied slightly (17.7 to 18.3 m) and each hole contained about a 3.0 m lift of a 50/50 ANFO-emulsion blend on the bottom and top with a 25/75 ANFO-emulsion blend in between. Apparent detonation velocities determined by the plotted 90% confidence function[8] are indicated for each linear section of each explosive column. The hole 2-9 and 4-6 detonations both slow at about 14 m but resumed burning shortly thereafter with very nearly the same velocities. Hole 3-7 is the extreme case where the explosive detonation ceased at about the same level, even though it also contained an

[8] Iterative, linear least squares fit to the data within a 90% confidence interval about the previously fit data. For a complete description, see reference 3.

additional 3 to 4 m of explosive. If there is any slowing of the detonation in hole 4-8, it is not readily apparent and the full 17.7 m burned. These same four features were evident in most of the 42 holes of the array. The transition from the 25/75 explosive blend to the upper level of 50/50 blend was between 14.7 and 15.2 m in each hole.

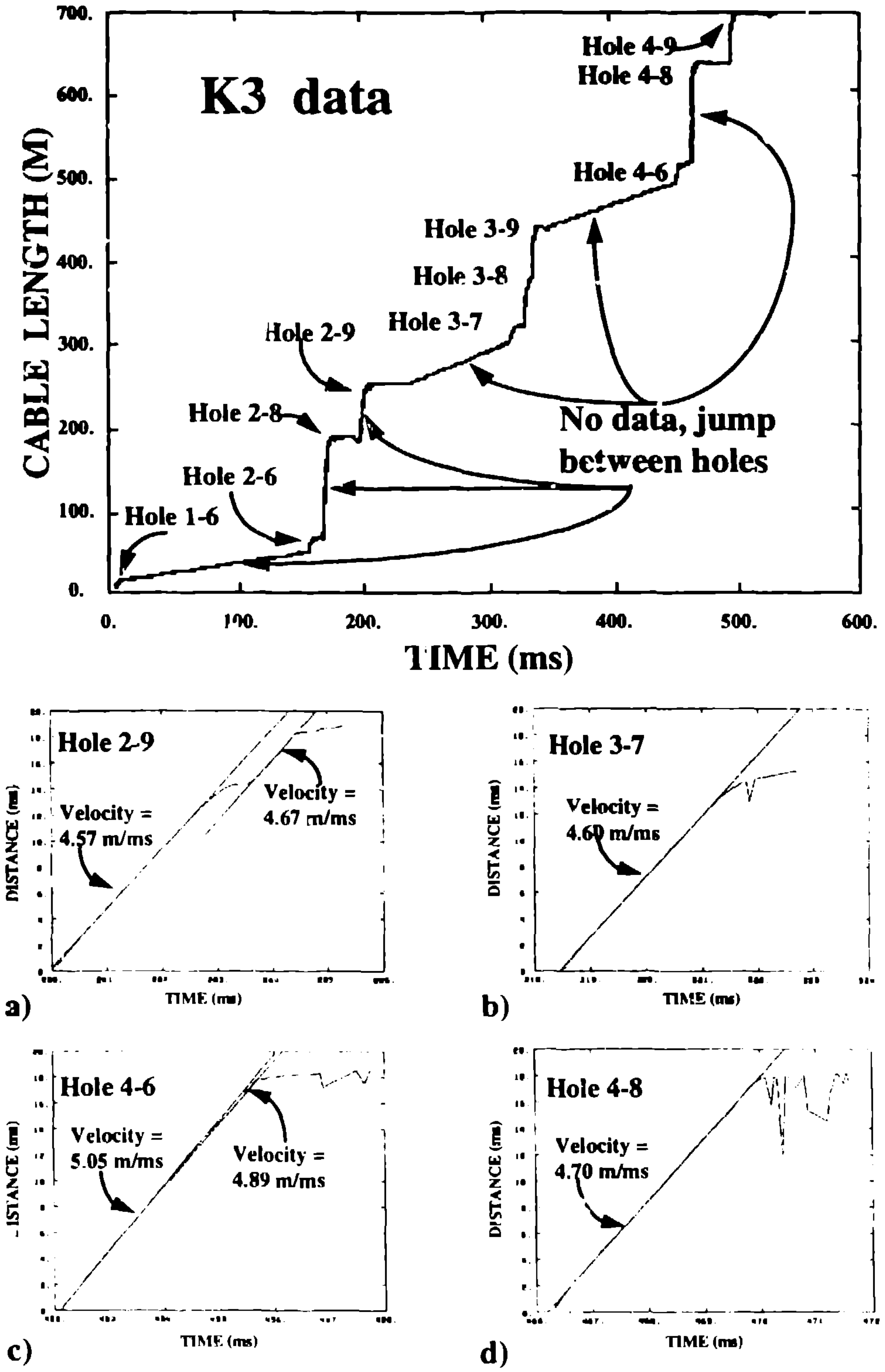

Figure 8. Explosive performance measurements, commercial mining operation, K3 cable.

With less detail of explanation, consider the K1 sensing element plot which appears in Figure 9, with several enlargements. It is apparent from the full data plot that several holes experienced difficulty. Hole 4-2 failed to detonate or failed to detonate before its successor hole, 4-1. Hole 2-1 detonated but based on previous descriptions, "fizzled", producing a very low pressure with no sustained burn.[9] A closer look at this record will follow. Hole 3-2 also detonated but failed to sustain a detonation. The three enlarged plots, Figures 10a, b, and c, for holes 1-5, 1-4 and 1-3 together, and 2-1 represent several observed problems. Figure 10a shows the same problem already illustrated with several holes from the K3 record. There are notations in the figure to detail the similarities. Of additional interest is the apparent underdetonation (low initial velocity, accelerating to a constant velocity) and that a booster-detonator assembly was installed at about 11.3 m, near the point where a temporary acceleration in the slowing burn occurs.

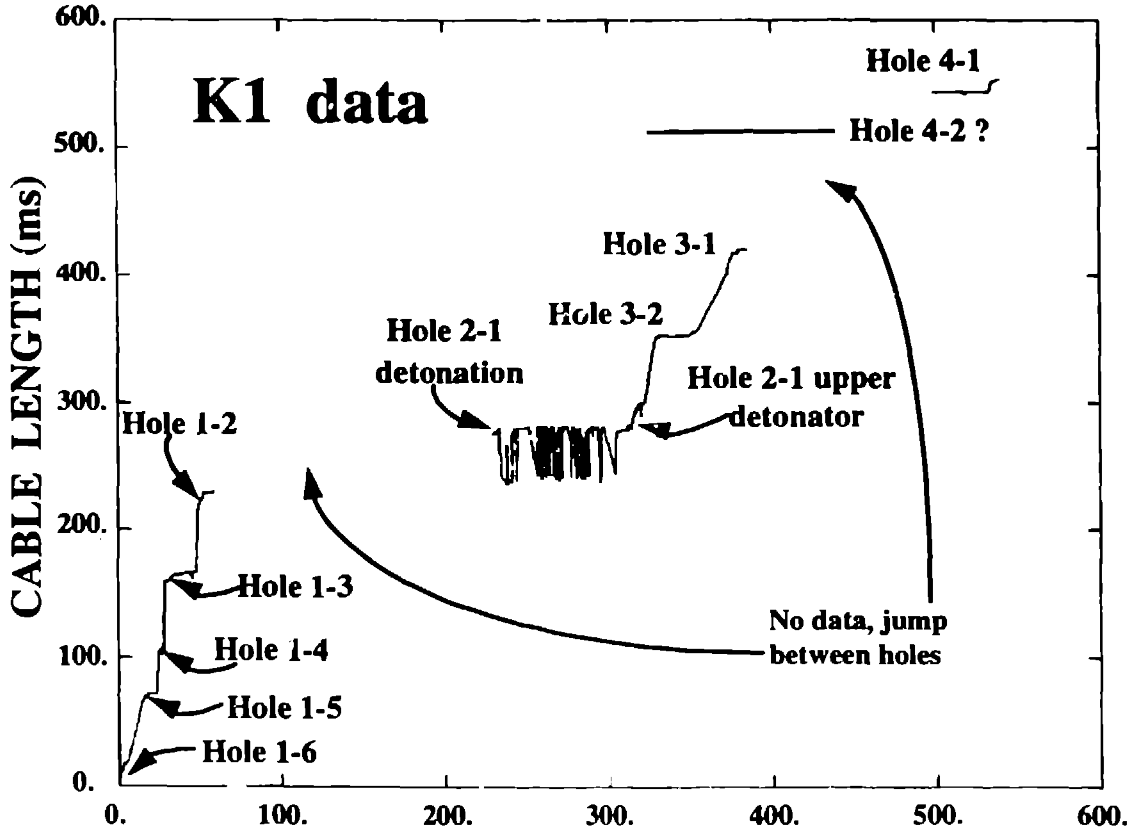

Figure 9. Explosive performance measurements, commercial mining operations, K1 cable.

Figure 10b contains the records for holes 1-4 and 1-3. Both show booster detonation because of the sudden jump in the data records to the respective bottom locations on the cable. Both show that their explosive columns failed to initiate and sustain a detonation, at least prior to the succeeding hole (1-3 in the case of hole 1-4 and 1-2 in the case of hole 1-3) severing the cable with its detonation. It may be noted that a wet coal marker seam was observed in the wall face at the approximate height of detonation problems in several holes and undoubtedly provided for potentially wet holes. As noted earlier, hole 2-1, enlarged in Figure 10c, "fizzled". However, near the end of this record is a small region where the explosive apparently detonated with a measured velocity of 4.34 m/ms. This detonation was apparently initiated by the 100 ms delayed detonator located in the upper portion of the explosive column, about 9.1 m below the surface.

[9] Contrast this with the detonation records of the explosives development section where, although a low pressure shock is described as causing the extremely rough record, the records show a nearly linear, low-velocity detonation.

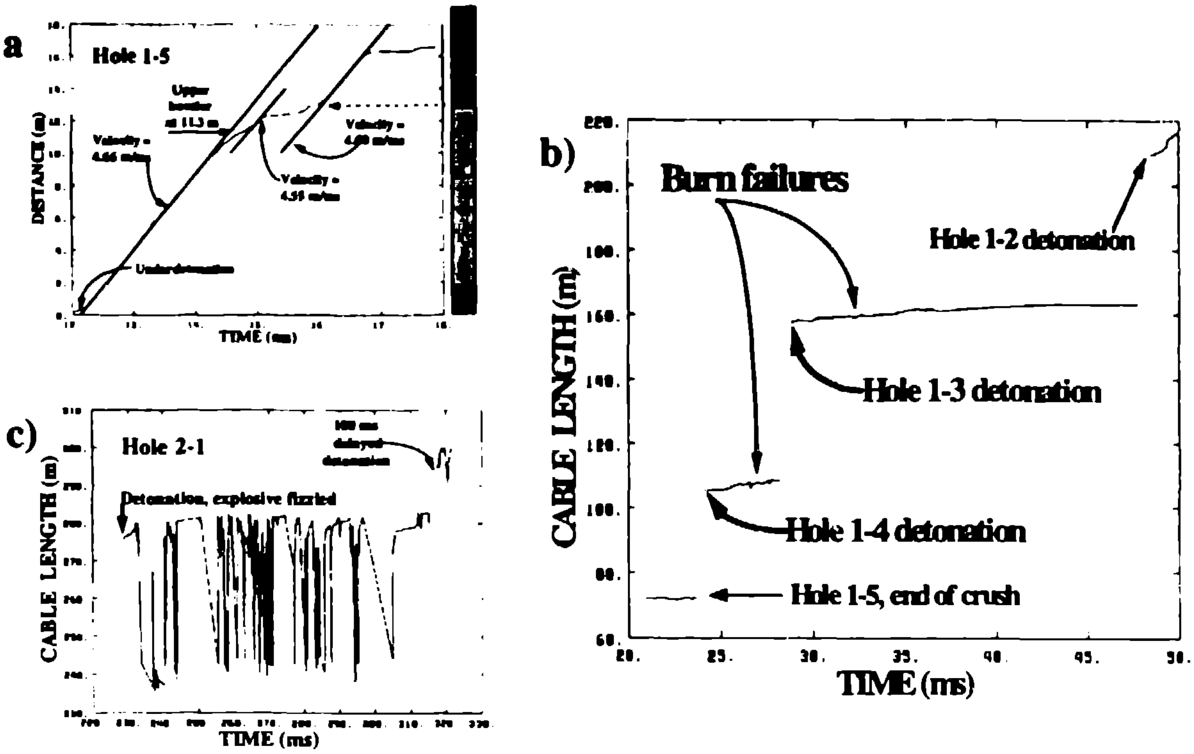

Figure 10. Enlargements of the K1 performance measurements, commercial mining operation.

Non-Proliferation Experiment—A Large Mass Explosion

In September 1993, the United States Department of Energy conducted the Non-Proliferation Experiment (NPE, originally called the Chemical Kiloton Experiment)(*1*) to compare the seismic signals produced by a large conventional explosion to those of a nuclear test. The experiment was conducted on the Nevada Test Site in the N-tunnel complex in the vicinity of previous underground nuclear tests with similar geologic media. The test consisted of approximately 2.9 million pounds of a 50-50 blend of ANFO and emulsion, filling a 15.2 m diameter by 5.2 m high right cylinder (the explosive chamber). Detonation occurred simultaneously at three locations along the axis of the cylinder. A global array of seismic instrumentation monitored this test.

Los Alamos fielded the CORRTEX system with twelve sensing elements, to diagnose the explosive performance(*3*). Figure 11 includes a photograph of the emplaced sensing elements and a sketch of the sensing element installation plan in the explosive chamber. The sensing elements were installed at three levels in the chamber, on Kevlar rope messengers extending radially from the chamber axis. The lower and upper levels, each instrumented with three sensing elements, covered approximately a 90° sector of the chamber. Six sensing elements in a 270° sector instrumented the middle level. The sensing elements exited the explosive chamber in four groups of three through three drill holes and the access drift.

Figure 11 includes the data plots of sensing elements K4, K7, and K12, one from each of the three levels, along with the 90% confidence function.(*3*) As noted in the figure, the data show both underdetonation and overdetonation, possibly the result of the boosters not being centrally-detonated. Eleven of the twelve radial paths support a conclusion that the explosive reached a steady state detonation. (One sensing element was damaged just outside the explosive chamber during stemming operations.) The computed detonation velocities increase with depth in the explosive chamber. This fact is illustrated by the three plots in Figure 11 and the velocities are summarized by installation level in Table 3. This is consistent with an increase in explosive density with depth. All data support the conclusion that a complete and efficient

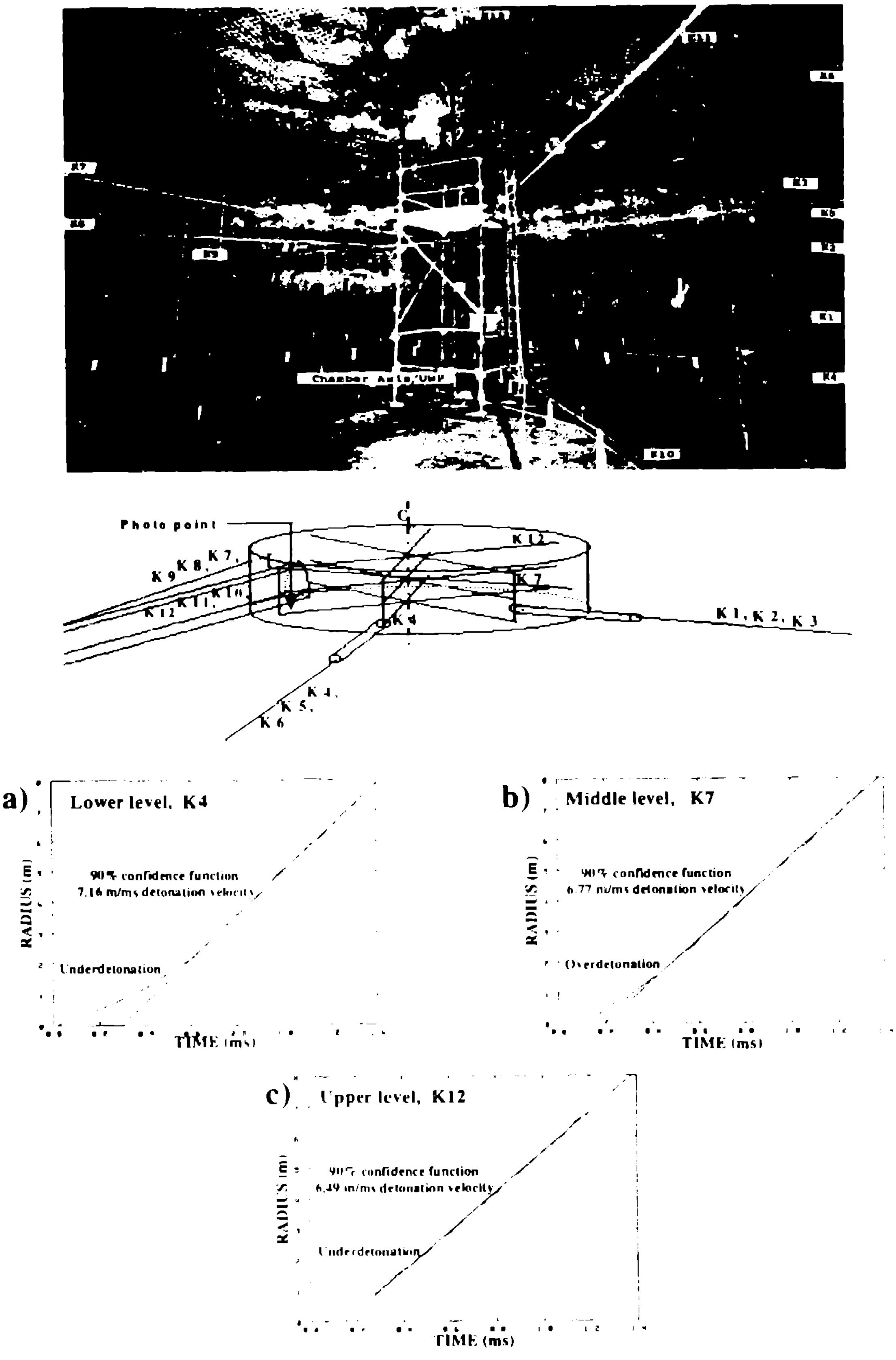

Figure 10. Non-Proliferation Experiment, large mass conventional explosive experiment.

explosive detonation resulted. There was some indication of an asymmetric detonation and certainly asymmetries in the shock induced into the surrounding medium, which produced the seismic signals.

Table 3. Non-Proliferation Experiment computed detonation velocities.

Level	Cable Label	Interval (ms)	Linear Least Squares Velocity (m/ms) All Data	90% Confidence
Lower	K-1	1.10 - 1.35	7.122 ± 0.049	7.119 ± 0.046
	K-4	0.57 - 1.35	7.164 ± 0.010	7.162 ± 0.010
	K-2	0.40 - 1.32	6.810 ± 0.018	6.857 ± 0.009
	K-5	0.50 - 1.33	6.885 ± 0.008	6.873 ± 0.004
Middle	K-11	0.45 - 1.22	6.809 ± 0.009	6.802 ± 0.006
	K-7	0.40 - 1.31	6.772 ± 0.013	6.763 ± 0.006
	K-8	0.40 - 1.27	6.812 ± 0.015	6.723 ± 0.008
	K-9	0.50 - 1.23	6.731 ± 0.014	6.731 ± 0.012
	K-3	0.35 - 1.34	6.448 ± 0.010	6.424 ± 0.007
Upper	K-6	0.33 - 1.30	6.442 ± 0.008	6.427 ± 0.006
	K-12	0.40 - 1.21	6.491 ± 0.011	6.491 ± 0.011

SUMMARY

The historical perspective in which the CORRTEX system was developed has been briefly presented. The yield of a nuclear explosion is determined from a measurement of the time-dependent position of the radially expanding shock wave. The CORRTEX system was developed to provide a simple, compact, and highly accurate system for measuring this time-dependent expansion. In addition to the hundreds of nuclear and high explosive measurements made in developing the recording system, fielding techniques, and data and analysis methods, the system has been employed to make diagnostic measurements on conventional explosives in research and development applications.

The examples presented here were selected to illustrate the results possible when one or more columns of conventional explosive are detonated. Very accurate detonation timing information is easily extracted from the data records and the velocity of detonation may be calculated when a steady state detonation is achieved. But in addition, the actual structure of the explosive detonation may be examined. Under- or overdetonation of the explosive, changes in the velocity of detonation with variations in the explosive blend and a number of other detonation related factors may be examined in detail. For example, as may be seen in the discussion, the diagnostics may reveal an inefficiency in the casting of the overburden due to the presence of bore hole conditions such as a wet marker seam which might quench the detonation of ANFO or a high ANFO-emulsion blend. Such a problem may not be detected by relying solely upon the examination of the resulting muck pile. Diagnostic measurements to support explosives development, to examine detonation failures, to examine methods of reducing the ground vibration while maintaining efficient burden displacement and minimizing other factors such as back break, are just a few of the possible applications of this methodology to the commercial explosives environment. In considering the time required in preparing and installing the sensing elements and in recording setup, and the accuracy required in the documentation, data reduction and analysis, these techniques are most applicable in the research and development environment.

Explosive performance diagnostic measurements of the type presented here provide an opportunity to examine the detonation within each individual hole and the total performance, unobscured by clouds of dust and smoke and unintegrated by the surrounding geologic medium. To draw conclusions from an experiment which is based on explosive detonations without making diagnostic measurements of the individual and total explosive performance, is analogous to the purchase of beach front property in Nevada from a traveling salesman, sight unseen.

ACKNOWLEDGMENTS

The Department of Energy (currently Office of Nonproliferation and National Security and the Office of Defense Programs) sponsored the development and testing of the CORRTEX system. The examples presented here have been taken from several diverse experiments. EG&G Energy Measurements, Inc., Las Vegas, NV, provided the engineering and technician support for the CORRTEX system development, maintenance, and field operations. D. Linn Coursen, formerly with the Explosives Research and Development Div. of DuPont, and the Vulcan Material Co., Manassas, VA, provided the support for the explosive development experiments. Tony Nelson, executive vice-president of Nelson Brothers, Inc., Parrish, AL, sponsored the commercial mining experiments. We wish to thank these individuals and companies and the many others who assisted.

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APPENDIX A

A BRIEF DESCRIPTION OF THE CORRTEX SYSTEM

The CORRTEX system consists of a CORRTEX digital recorder, a sensing element (a length of 50 ohm coaxial cable selected for its electrical and physical properties), a coaxial transmission cable between the recorder and the installed sensing element, assorted trigger, communication, command-and-monitor hardware, and the data acquisition and retrieval software. A CORRTEX recorder is a microprocessor controlled Time Domain Reflectometry (TDR) unit with a selectable discrete pulse period (10 to 98 μs in 2 μs increments). Upon receipt of a trigger, the recorder stores in internal memory the two-way-transit times (TWTTs) of 4049 electrical pulses The TWTT is measured using a windowed, voltage-threshold detection circuit on the differentiated return pulse. Both the window time and the threshold level are selectable. The CORRTEX recorder has a dual cable capability. In this mode, the unit alternately pulses two attached sensing elements. The pulse period on each cable is double the selected pulse period and only 2024 TWTTs are stored for each sensing element.

The recorder can be triggered by several different methods. A positive five volt pulse with a rise time of less than 1 μs and width greater than 100 ns is the normal trigger. In those environments where a reliable trigger is not available, the recorder can be placed in a continuous pulsing mode and, upon detecting four successive 1 ns shortenings of the TWTT, begins recording data. After transfer of the stored pulse time and TWTT data into a computer, the raw data are converted to a time-dependent record of cable length or position along the cable. Only the precrush full cable length TWTT and the propagation velocity of a pulse in the sensing element are required.

The TWTT of the combined transmission cable and sensing element, plus a short processing time of 2 to 3 μs, determine the minimum pulse period that can be selected. The desired recording time can further restrict the selection of the pulse period since 4049 stored TWTTs limit the total recording interval, except when an optional store-on-change-only (SOCHO) function of the recorder is selected. With the SOCHO option, data are stored only when the measured TWTT differs from the preceding TWTT by an input difference. This option may extend the total recording time, permitting the use of a shorter pulse period, constrained only by the electrical length of the cable.

The sensing element is a key component of the CORRTEX system. While any 50 ohm coaxial cable can be used, the electrical quality of the cable, its physical characteristics for handling and installation in the predetonation environment, expected peak pressure of the detonation shock front, length of time required to record the shock propagation, and the experiment objectives all combine to determine the cable type. The sensing elements are cut to a planned length, marked in 1.0±0.002 m increments, and terminated with a connector at the recording end and in a short at the downhole or detonation end. The sensing elements are electrically checked and measured. (The physical length divided by the electrical length provides the initial velocity of propagation for the data reduction.)

During the installation, if possible, geometric signatures are placed in the sensing element at known locations so that a sequence of discrete signatures will appear in the cable length data reduced with an initial velocity of propagation. These signatures permit the determination of the actual velocity of propagation for the cable at the time of the experiment, a dynamic calibration. By effectively adjusting the velocity of propagation to require that the signatures appear in the data at the measured positions along the cable, and then removing any effect on the data due to these signatures, an adjusted data set is produced. The result is the time-dependent position of the shock front along the path of the sensing element. If appropriate, this adjusted data can be geometrically converted to a radial position as a function of time.