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A mining research contract report
AUGUST 1983

ULTRASONIC STRESS TRANSFER: A DIRECT TEST OF ROCK BOLT INTEGRITY

Contract J0295037
Energy & Minerals Research Company

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

0272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO.

2.

3. Recipient's Accession No.

4. Title and Subtitle
Ultrasonic Stress Transfer: A Direct Test of Rock Bolt Integrity

5. Report Date
August 1983

6.

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8. Performing Organization Rept. No.
BuM2/83

9. Performing Organization Name and Address
Energy & Minerals Research Company
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P.O. Box 389
Exton, PA 19341

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) J0295037
(G)

12. Sponsoring Organization Name and Address
United States Department of the Interior
Bureau of Mines
Denver, Colorado 80225

13. Type of Report & Period Covered
Final Report
May 25, 1979-May 25,1983

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Until now, state-of-the-art technology to determine grouted rock bolt integrity has been inadequate. A device was developed which measures dynamic stress (ultrasonic energy) transfer through installed rock bolts, a measure which is directly proportional to the degree of grout bonding of the bolt to the mine roof structure and thus the ability of the bolt to bear static stress. The Rock Bolt Bond Tester (RBBT) is a hand-held portable device which shows the operator three ranges of bolt bond condition, i.e., one-third (bad bond), two-thirds (marginal) or fully bonded. These are shown respectively by a red, yellow or green light which displays for four seconds. RBBT performance was verified with 2½ to 8 foot bolts installed in various types of mine roof structures (sandstone, shale and boney coal/mud), and is now being tested by the Bureau in mines across the U.S. The unit is about the size of a 5-battery flashlight and contains the transducer, electronics and battery pack. The RBBT is designed for extreme ease of operation, requiring only manual contact with the bolt and signal read-out. The batteries are rechargeable (the charge lasts for 8 hours, with normal duty for each bolt test about 30 seconds) and the package is designed for durability in the mine environment. The prototype device has received MSHA approval.

17. Document Analysis a. Descriptors

Ultrasonic Rock Bolt Bond Tester

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement

19. Security Class (This Report)
Unclassified

20. Security Class (This Page)
Unclassified

21. No. of Pages
82

22. Price

(See ANSI–Z39.18) *See Instructions on Reverse*

OPTIONAL FORM 272 (4–77)
(Formerly NTIS–35)
Department of Commerce

FOREWORD

This report was prepared by Energy & Minerals Research Company, Exton, Pennsylvania, under USBM Contract No. J0295037. The contract was initiated under the Mining Research Program. It was administered under the technical direction of the Denver Research Center, Ground Control Division, with Mr. Raymond M. Stateham acting as Technical Project Officer. Mr. David J. Askin was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period May 1979 through May 1983. This report was submitted by the authors in May 1983. The work of this contract was performed under U.S. Patent No. 4,198,865 (issued April 22, 1980), and there are no other patentable features.

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I. INTRODUCTION

American mines install over 90 million rock bolts annually to support very large loads in excavated walls and roofs, and to protect against rock falls which can cause equipment damage, injury and death. It is therefore essential to know if a rock bolt is properly installed and whether it continues to support its load. An increasing percentage of the bolts used are the newer untensioned resin grouted type. The resin released in bolting fills any cracks or fissures and may increase the anchoring strength of the bolt.

In order to insure that bolts are performing their function of transferring the stress concentrated at the mine roof back through the overlying strata, the Mine Safety and Health Administration (MSHA) requires that 25 percent of all roof bolts in coal mines be inspected immediately after the working place has been fully bolted and that 10 percent of the bolts from the outby corner of the last open crosscut to the working face be inspected daily.

Until now, state-of-the-art technology for the measurement of grouted rock bolt integrity has been inadequate. Most techniques measure secondary characteristics and lack sensitivity. That is, they can only measure "good" and "bad" bolts; no precise measurement of degree of strength is possible. They also require extensive record keeping. Torque testing is not effective for grouted bolts as any torsional movement is a sign of failure in such bolts. Newer experimental techniques are subject to variables (such as bolt length) which differ greatly bolt to bolt, also necessitate extensive record keeping, and also measure indirect effects. All these systems offer only "average" parametric measurements rather than direct measurement of individual bolt performance.

It appeared that, in contrast, measurement of ultrasonic energy transfer to and absorption by the roof structure offered a solution to rock bolt integrity testing, on the principle that if a grouted rock bolt is securely anchored, it will not only transfer static stress, it will also transfer dynamic stress (e.g., ultrasonic energy). Thus the ultrasonic energy delivered to a securely anchored bolt, which is transferring static stress to the surrounding strata, will also be transferred to the strata. If the bolt is poorly anchored, energy delivered to the bolt will not traverse the gap or poor bond, but will be reflected back to the ultrasonic transducer and be indicated as an electronic signal. Ultrasonic energy transfer, therefore, is a direct measure of bolt function.

Accordingly, under Bureau of Mines sponsorship a device was developed to be practical in the mine environment. The instrument is described in the Bureau Technology News document No. 128, which is included as Figure 1 (pages 9 and 10).

Technology News

From the Bureau of Mines, United States Department of the Interior

Technology News describes tested developments from the Bureau of Mines Research Programs. It is published to encourage the transfer of this information to the minerals industry and its application in commercial practice. Mention of company or product names is for documentation only and does not imply government endorsement of a specific firm or product.

Bureau of Mines research is performed and reported under mandate of the United States Congress.
For a free subscription to Technology News, write to: Technology Transfer Group, Bureau of Mines, 2401 E St., NW, Washington, D.C. 20241.

Figure 1

No. 128, January 1982

Roof Bolt Bond Tester

Objective

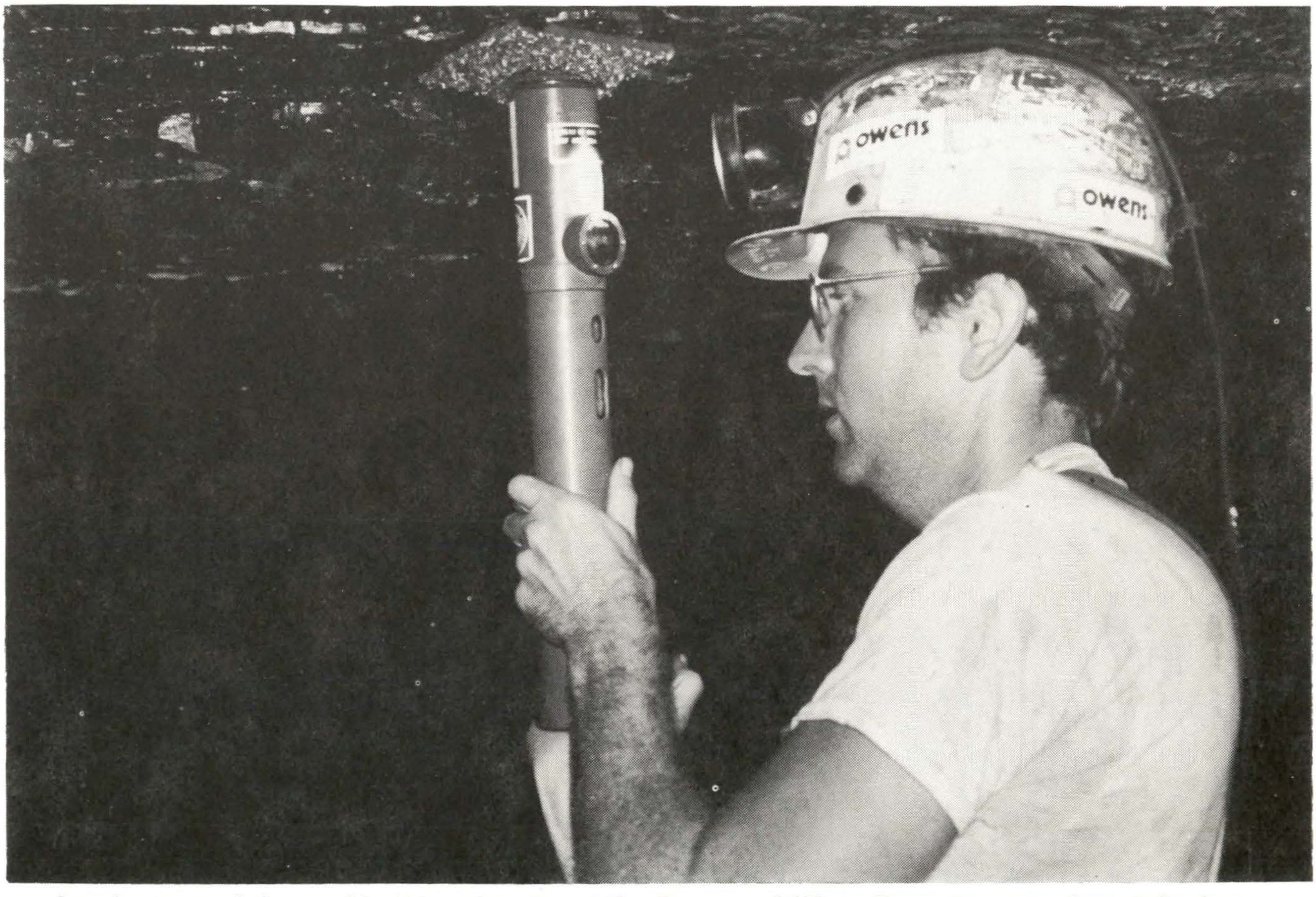
Develop a lightweight, portable device for use in mines for non- destructive testing of resin grouted roof bolt bond integrity.

Approach

A unique, intrinsically safe, electronic instrument has been developed that determines the holding quality of a fully grouted roof bolt by testing the integrity of the resin bond to both the bolt and to the surrounding rock.

How It Works

A measured pulse of energy is sent into the bolt by a piezoelectric transducer, and the instrument listens for reflected energy. Where the bolt is properly bonded, the energy passes from the bolt, through the resin, and out into the rock mass. Where proper bonding does not exist, a portion of the energy is reflected back along the bolt. The instrument measures the reflected energy and compares it to the original pulse. The amount



In-mine test of the roof bolt bond tester at the Bureau of Mines Bruceton experimental mine.

of energy reflected back is an indicator of the amount of the bolt surface that is not bonded, and the ratio of energy in the original pulse to the reflected energy can be used in evaluating bond integrity. This cycle of pulsing and listening is repeated about 200 times per second.

Operation of the tester is simple. The operator turns on the switch, and the instrument automatically initiates a 4-second, self-check procedure to verify proper operation. The operator then selects the proper bolt length range (2 1/2 to 4 feet, or 4 to 8 feet bolt length),and pushes the instrument firmly over the bolt head. When the coupling force is reached (about 5 pounds) the instrument automatically reads the bolt bond condition.

The instrument has three possible readings: red, yellow, or green, corresponding to "bad" (less than 1/2 bonded) marginal" (1/2 to 3/4 bonded) and "good" (more than 3/4 bonded). The reading is held for 4 seconds, then the instrument resets for the next test.

Operators normally become proficient with the instrument with about 1/2 hour of instruction and practice. The basic principle of the tester is well established in other industries.

Test Results

Laboratory tests were followed by underground tests in the Bureau's experimental mine in Bruceton, PA. In a statistically designed test, 182 bolts with varying degrees of bonding were installed with a roof bolter. Test results were confirmed by overcoring selected bolts. Tester accuracy was over 90%.

Additional tests are being conducted on a wide range of roof rock types and bolt lengths in mines across the U.S. to determine if calibration adjustment for the particular mine roof rock is needed, and to determine instrument durability.

The Bureau group supervisor heading this research is Raymond M. Stateham of the Denver Research Center.

For More Information

For more information contact the Technology Transfer Officer, U.S. Bureau of Mines, Denver Research Center, Bldg. 20, Denver Federal Center, Denver, Colorado 80225.

II. INITIAL DESIGN AND LABORATORY EXPERIMENTATION

A. Materials and Equipment for Simulated Installations

DuPont Fasloc-T^{R} 15-30 minute cure resin was selected as the bolt bonding material for laboratory testing instead of the similar resin (Fasloc-A^{R}) frequently used, which has a cure time in the mine of 24-30 seconds. The slow cure resin was chosen for the initial laboratory work to allow sufficient time for hand application. Since the laboratory ultrasonic absorption tests were conducted at least 24 hours after bolt grouting, the long cure time had no effect on measurements.

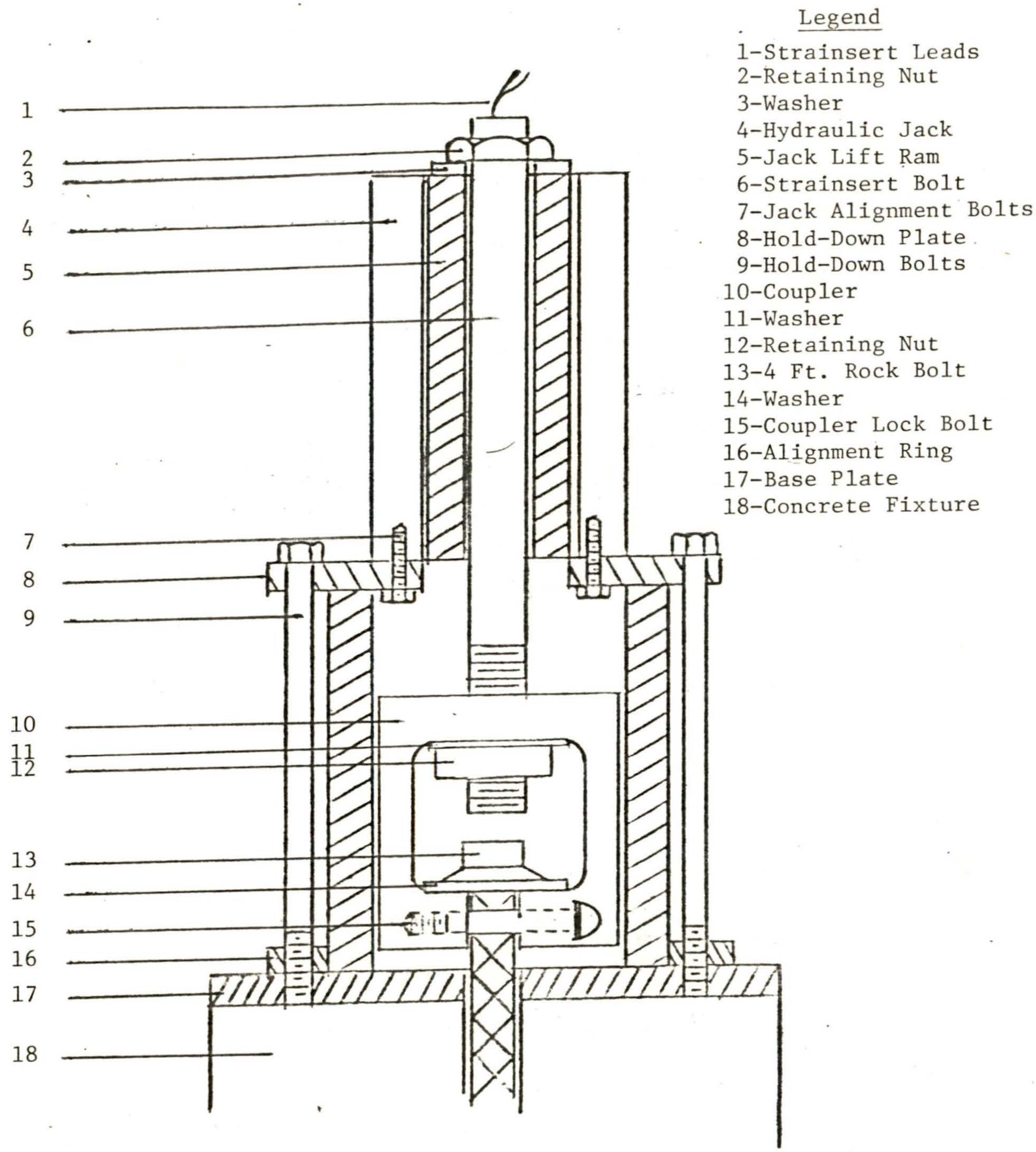
No. 6 rebar roof bolts, ten each of 48 inches and 72 inches in length (3/4-inch O.D.), were ordered from Bethlehem Steel. As reported in MESA Informational Report 1033, the combination of a 3/4 (#6) rebar and a 1-inch hole provides the optimum bolt-hole diameter differential for anchorage effect, and these resin bolt sizes are the most popular sold by Bethlehem Steel; also, 20 each of 6 inches x 6 inches x 1/4 inch flat and "donut" bearing plates were ordered. Although the flat plates are seldom used (for economic reasons) they allow improved accessibility to the bolt head and were more convenient for the initial laboratory tests. Later tests were planned with the more common "donut" design.

Molds were fabricated for casting concrete half-cylinders into which the rebars were bonded. Previous E&MR Co. experiments had shown that concrete is an acceptable laboratory simulant for roof rock in that it shows comparable energy attenuation. Half cylinders were chosen to permit easy manual application of resin and were joined to form a full cylinder with 10 inch outside diameter and a 1-inch central hole. The four-foot-long four-inch-radius cylinders were cast with concrete mixes which comply with ASTM Standard No. 270. The cured strength is 4000 lb/in^2. Molds were also designed to cast cylinders with the structural reinforcements necessary to permit exertion of extracting force against steel reinforcement plates rather than exposed concrete.

The design of a bench-scale device for measuring the extraction force needed to remove the bolts from the concrete was planned in order to corroborate experimental ultrasonic bond evaluation. A hydraulic jack was used to pull the bolt out of the concrete. The test equipment could simultaneously measure extraction force and extracted length, with a system powered by DC current suitable for field testing.

Several design configurations were developed, and Design 1 (Figure 2) was selected. It offers the advantage of requiring a minimum of exposed unbonded bolt above the cement cylinder surface, simulating in-mine bolt installation.

The Figure 2 configuration is composed of a solid, 10-inch diameter, concrete core (No. 18 on the figure) with a 1-inch central hole into which the test bolt is bonded. A base plate (17) is cast integrally with the concrete core to provide a mounting base for the extraction



Legend

1-Strainsert Leads
2-Retaining Nut
3-Washer
4-Hydraulic Jack
5-Jack Lift Ram
6-Strainsert Bolt
7-Jack Alignment Bolts
8-Hold-Down Plate
9-Hold-Down Bolts
10-Coupler
11-Washer
12-Retaining Nut
13-4 Ft. Rock Bolt
14-Washer
15-Coupler Lock Bolt
16-Alignment Ring
17-Base Plate
18-Concrete Fixture

Figure 2

ROCK BOLT EXTRACTION DESIGN 1

apparatus and to absorb the reactive load of extraction. A coupler (10) serves to interface the strain measuring bolt (6), to which the extraction load is applied, and the rock bolt under test (13). The extraction force is generated by a single-acting hollow plunger hydraulic cylinder (4) pressurized by a hand-operated hydraulic pump unit.

This arrangement provides up to 30 tons of extraction force and an extraction stroke of 2-1/2 inches. The spacer design was established to allow the coupler (10) to bottom-out against the hold-down plate (8) at less than 2-1/2 inches of stroke and thus protect the hydraulic jack (4) from damage in the event of bolt and/or bond failure with the attendant rapid extraction motion.

Measurement of the applied extraction force is provided by an electrical signal from the strain bridge in the strain monitoring bolt. Extraction distance is visually monitored using a scale measuring the separation distance between the bottom of the coupler (10) and the base plate (17).

B. Ultrasonic System Components

Prototype transducers for the generation of longitudinal and torsional ultrasonic waves were designed and ceramic components were fabricated by outside vendors. A 20-kHz transducer was used for early experiments to determine the optimum frequency of energy absorption for a longitudinal wave. A 50-kHz transducer showed an insufficient signal-to-noise ratio.

The bonded portion of the rebar is the critical factor in grouted bolts. The greater the bonded length, the greater the integrity of the bolt-roof interface. The test procedure was to generate multiple cycles of a fixed frequency ultrasonic wave and observe the amplitude reduction as the length of bonded rebar was increased.

C. Preliminary Test Procedures

As noted, initially a half-cylinder four feet long with a four-inch radius was cast from a mold fabricated to include a longitudinal channel 1-1/8" in diameter. In addition, five smaller half-cylinders were cast six inches in length and with the same four-inch radius and 1-1/8" inch channel as the base mold. The experimental procedure was to insert a four-foot rebar (1-inch diameter) into the channel in the base mold, which was mounted on a frame to expose the flat surface of the half-cylinder providing direct access to the rebar. Resin was applied to a six-inch section of the rebar to bond it to the base mold. The channel in one of the small half-cylinders was filled with grout and the flat surface of the half-cylinder joined to the base so as to completely enclose the bonded section of the rebar. This procedure insures that a measured section of the rebar has been securely bonded and surrounded by an absorptive medium eight inches in diameter. The measured length of bonded rebar can be incrementally increased by grouting further sections of the rebar to the base mold and bonding additional six-inch half-cylinders to the base. Fasloc-A resin, with a one-to-two minute cure time was used in this experiment. (In this case the small scale of application permitted use of the high speed resin.

The rebar had been tapped to accept a 1/2 inch x 20 national coarse thread center bolt. The similarly threaded transducer was mounted to the rebar by means of this bolt. A square wave pulse generator was used to produce an input signal 22 microseconds long and 17 volts amplitude. In the reflected pulse, peak-to-peak amplitude represents energy remaining in the bar after transfer of energy to the surrounding medium. The pulse is passed through an octave band pass filter to reduce noise interference and is displayed in the storage mode on an oscilloscope. The CRT of the oscilloscope is graduated so as to provide a direct readout of amplitude in millivolts.

The experiment was based on the premise that when the signal reaches the end and sides of the rebar, or the air interface, part of the energy is reflected and part is absorbed into the bonded concrete. Since the rebar serves as a waveguide, only that portion of the rebar which is bonded to the concrete will transfer energy to the surrounding medium. The lower the amplitude of the reflected pulse, the greater the amount of energy absorbed by the medium and hence the greater the length of the securely bonded rock bolt.

On this basis, the measurement of energy absorption was conducted in three steps. As noted, the rebar was bonded first to the four-foot concrete mold which served as a base. Resin was applied with a trowel until the 1-1/8 inch channel was filled. The bar was inserted into the channel and excess resin scraped away. In this experiment a 12-inch section of the bar was bonded to the base. Resin was then applied to the two six-inch sections bonded to the rebar and base mold and permitted to cure. At this point the transducer was activated and a measurement recorded. Two more sections were bonded and a second measurement taken. A fifth section was bonded and a final measurement recorded.

D. Experimental Data

Figure 3 is a graphic presentation of the test results. From this experiment it appeared that the loss in amplitude of the reflected pulse is in linear relationship to the length of bonded rebar. However, it also appeared that, because the amplitude of the reflected pulse decreases sharply as the bonded length increases, it is difficult with this apparatus to determine bonded length accurately for distances greater than about 40 inches. The power level was such that the reflected pulse had an amplitude of 100 millivolts for a rebar bonded for 30 inches of its length. Noise from other sources tends to produce signals with amplitude of about 50 millivolts. Given the linear relationship presented in Figure 3, it appears that measurement of bonded bolt length at the power level of 17 volts would not be straightforward for greater lengths, and further modification of the system would be necessary to measure bonding of complete four and six

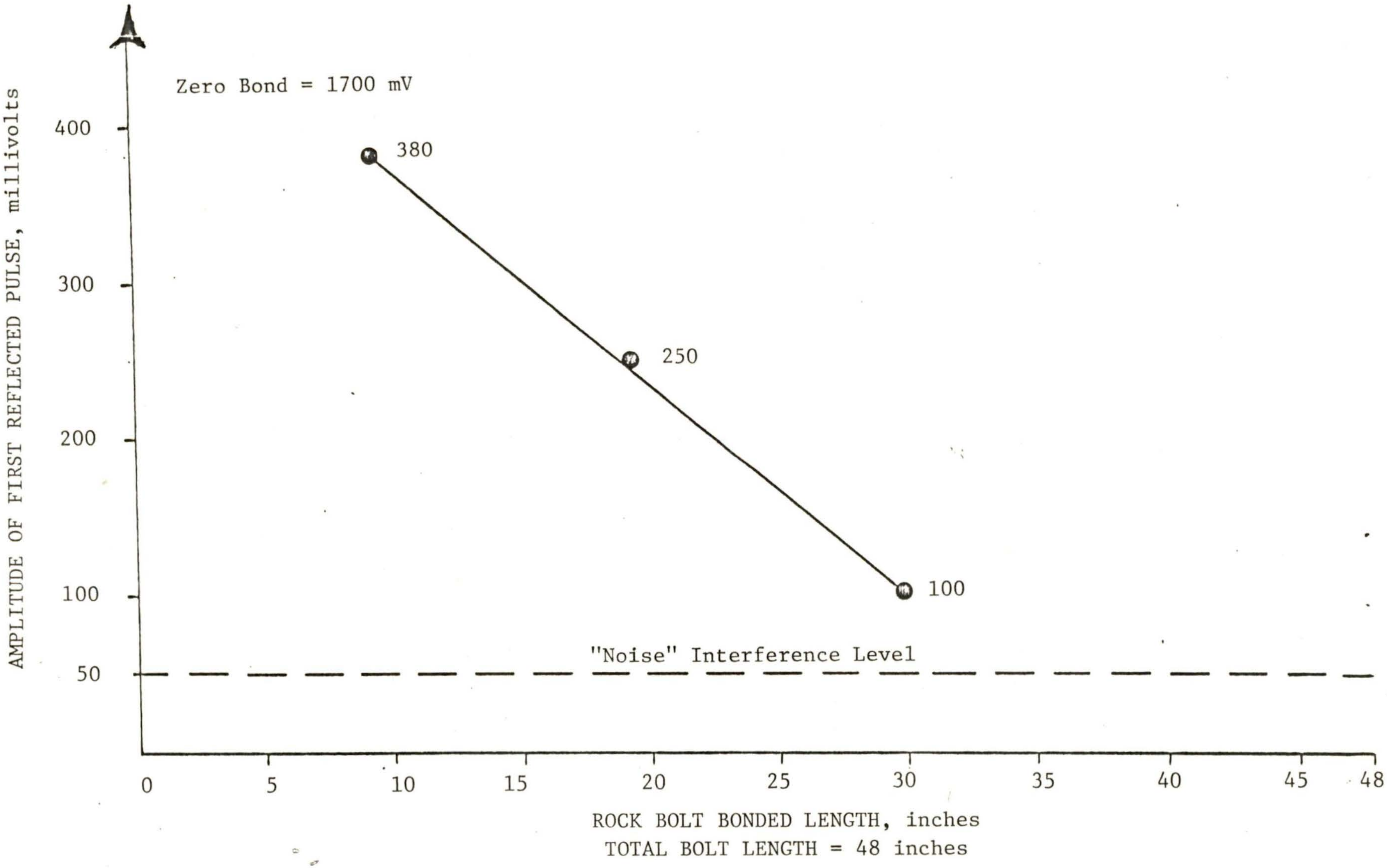


Figure 3

<u>ULTRASONIC MEASUREMENT OF ROCK BOLT BONDED LENGTH</u>

(Pulse Mode - Energy Absorption)

foot roof bolts. There was also the problem of discrimination between the significant reflected signal and irrelevant noise at the lowest amplitude levels.

A significant advantage of the current bench-scale bolt tester was its low voltage, pointing toward the capability of evolving an inherently safe apparatus.

III. CONTINUING WORK

Preliminary testing continued with the program matrix of pulse mode and continuous wave testing for both the axial and torsional modes of bolt excitation. These results indicated a somewhat broader range of signal sensitivity for the pulse mode than for the continuous wave mode. The pulse mode gave a 30-to-1 difference in signal amplitude between unbonded and fully bonded bolts, and a 10-to-1 difference in signal amplitude between unbonded bolts and bolts bonded for 1/3 of their length. The continuous wave mode showed a difference in signal decay-time constant (ring-down) of 2.6-to-1 between unbonded and fully bonded bolts.

Progress also included the adaptation of a standard E&MR electronic circuit to perform the pulse echo measurements. This approach gives easy translation from test equipment to field prototype design, with instrumentation of improved resolution and repeatability over the original laboratory instrumentation. Previous test data were acquired utilizing a commercial square wave pulse generator with data optically translated from the oscilloscope trace. The standard E&MR circuit has been designed to operate on 9-volt batteries and display the signal on an analog 15-volt scale meter. This circuit excites the 20-kHz transducer used for the testing with a 24-microsecond duration 22-volt pulse with less than 0.1 amp current. Thus, voltage and current characteristics fall well within the intrinsically safe power region as defined in BuMines Schedule 2G curve for methane (Figure 4). This curve indicates that 24 volts, 1 amp is the maximum acceptable limit.

A. Axial Mode Experiments

The bolt-cylinder combinations with donut-shape bearing plates were assembled in each of three configurations:

a) fully bonded the entire length of the bolt;

b) bonded over the middle 1/3 of the length of the bolt; and

c) unbonded.

1. Pulse Mode

Experimental data were acquired during this time for bolt testing in the axial excitation mode. The test samples and instrumentation previously described were used, and both the 50-kHz and 20-kHz systems were tested. Instrumentation was identical except for pulse duration. Results of the 50-kHz testing are given in Table I (page 19).

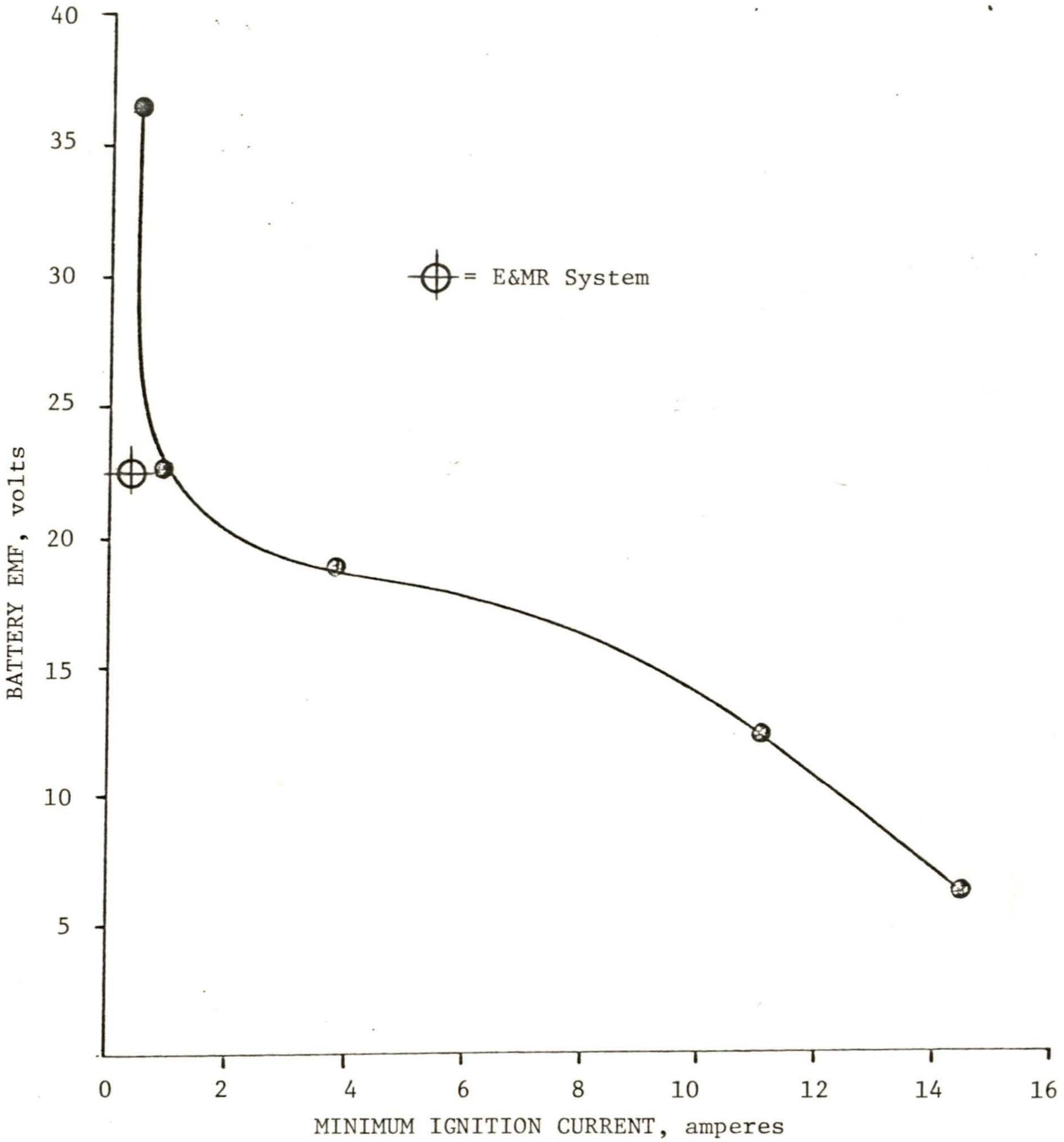


Figure 4

MINIMUM IGNITION CURRENT AS A FUNCTION OF VOLTAGE IN EXPLOSIVE METHANE-AIR MIXTURE

(8.1-8.6 percent CH_4 by volume)

Based on BuMines Schedule G in Wolf, R. A., "Design of Electrical Equipment for Intrinsic Safety", Reference (11), page 72.

Table I

50-kHz TEST WITH 48-INCH BOLTS

	Unbonded Rod & Cylinder Assembly	1/3-Bonded Rod & Cylinder Assembly	Fully Bonded Rod & Cylinder Assembly
Transducer Excitation Pulse	22-v/10μ sec.	22-v/10μ sec.	22-v/10μ sec.
Amplitude of first return echo (above background noise level)	Not Observable	Not Observable	Not Observable

Additional testing with direct application of the transducer to an unbonded length of rebar produced similar results. It was concluded that the 50-kHz system is not of sufficient sensitivity to warrant further testing in the axial mode.

The next series of tests used a 20-kHz transducer. These test results were repeatedly obtained with three baseline test cylinder, as shown in Table II.

Table II

20-kHz TEST WITH 48-INCH BOLTS

	Unbonded Bolt/Cylinder System	1/3-Bonded Bolt/Cylinder System	Fully Bonded Bolt/Cylinder System
Transducer Excitation Pulse	22-v/24 sec.	22-v/24 sec.	22-v/24 sec.
Amplitude of first echo pulse (above noise level)	15-v. (full scale)	5-v. (1/3 of full scale)	0.5-v. (1/30 of full scale)

These data corroborated the hypothesis of ultrasonic energy absorption and the feasibility of measuring energy absorption as a test of rock bolt integrity.

2. Continuous Wave Mode

Preliminary testing was also accomplished with standard laboratory instrumentation to determine sensitivity parameters in the continuous, or ring-down, mode of operation. This testing was accomplished for axial excitation using a 20-kHz system. For this experiment, a 4-inch radius concrete semi-cylinder was prepared and 5-inch length matching sections assembled and bonded onto a 48-inch long, 1-inch diameter rebar also bonded into the lower semi-cylinder. This allowed monitoring progressive lengths of bond area of the rebar into the assembled 8-inch diameter concrete cylinder. Here again, Fasloc-T resin was used for the test. The transducer was driven by a commercial power amplifier and function generator. In order to provide impedance matching, an E&MR designed transformer and multiple booster horns were used to provide maximum gain. Test procedure involved activating the 20-kHz transducer in continuous oscillation for a period of time. The output of the transducer was recorded in the storage mode on an oscilloscope, manual quick-disconnect of the driving power was performed, and the transducer decay oscillation signal was recorded. Analysis of this voltage decay trace using the formula which defines tau,

$$\tau = \frac{\Delta t}{\ell n \dfrac{x_1}{x_2}}, \qquad (1)$$

where x_1 = voltage amplitude at time 1,

x_2 = voltage amplitude at time 2,

Δt = time increment between time 1 and time 2,

τ = ring-down constant

was used to provide the numerical measure of the effect of bonding length on bolt damping of the residual 20-kHz ring-down signal. The data are summarized in Table III.

Table III
RING-DOWN SENSITIVITY WITH 48-INCH BOLTS

	Unbonded Bolt/Cylinder System	1/3-Bonded Bolt/Cylinder System	2/3-Bonded Bolt/Cylinder System	Fully Bonded Bolt/Cylinder System
Driving Signal Amplitude	200-v rms.	200-v rms.	200-v rms.	200-v rms.
Ring-Down Constant (tau)	22.5 μ sec.	12.2 μ sec.	8.9 μ sec.	8.5 μ sec.

When compared to 30-to-1 sensitivity as achieved in the pulse mode, it becomes apparent that the measurement of tau does not provide comparable measurement sensitivity of bond length.

B. Bolt Head/Transducer Adaptor Clamp Design

All experimental data acquired to this date were generated by direct coupling of the transducer to the bolt or rebar. The use of adaptor clamps applied to the bolt heads was required in order to move from the laboratory to later in-mine demonstration.

Accordingly, acoustical and fixture designs were initiated for clamping systems in longitudinal and torsional modes, with the constraint that fixtures for laboratory data acquisition be generally translatable to in-mine apparatus.

A simple commercial clamp was first modified and repeatedly applied to the heads of unbonded bolts. The signal attenuation attendant to the clamp interface was determined by measuring the acceleration level on the transducer side of the clamp interface and comparing it to that on the bolt side of the clamp interface. The results of these tests are tabulated below together with comparative measurements taken in the axial mode for the directly coupled transducer. These measurements (Table IV) indicated 13 to 14 db attenuation in signal attributable to the clamping interface. The signal-to-noise ratio did not deteriorate because of the clamping interface, indicating that the coupling loss could be accommodated by increasing the sensing circuit signal gain.

Table IV

COUPLING METHODS AND TRANSMISSION

Bolt Excitation Mode	Coupling	Transducer Signal Level at Input to Clamp (mv)	Measured Signal Levels Transmitted Through Clamp Interface (mv)	Attenuation (db)
Axial	Direct	825	725	-1.1
Axial	Adaptor Clamp	600	100	-15.6
Torsional	Adaptor Clamp	600	115	-14.3

A clamp assembly was breadboarded and used to determine clamp capability to discriminate between unbonded, 1/3-bonded and fully bonded bolt configurations. The fact that sufficient energy was transmitted through the clamp in both directions to permit bond integrity discrimination was established by attaching a separate sensor to the clamp assembly near the clamp-to-bolt head interface. The clamping arrangement was repeatedly removed and reclamped onto the bolt heads in order to determine both the bond discrimination sensitivity and the variation in measurement incurred by variability in the clamping interface to the bolt head. Table V summarizes these data and indicates comparable performance in both axial and torsional modes of adaptor clamp application.

Refinements in the breadboard design were indicated to reduce internal ultrasonic reflections in the clamp and enhance the reflected signal analysis.

C. Transducer Signal-Recovery Enhancement

A variation of our electronic switching circuit for transducer control resulted in an improvement of 40 db, or 100 to 1, in the recovered signal which indicates degree of bonding. The circuit change involved the addition of two semiconductor signal switches sequentially actuated by the control electronics. The first of these switches, in series between the pulse generating electronics and the transducer, electrically disconnected the transducer from the pulse generating electronics upon completion of the pulse generating phase. Since the pulse generating electronics are designed to have minimum output impedance, they will, if connected to the transducer, reduce output for the signal reflected from the bonded bolt. The addition of a semiconductor switch in the circuit can decouple the low impedance electronic circuit from the transducer during this receiving portion of its operation, resulting in a correspondingly greater transducer output for a given reflected signal.

A second semiconductor switch installed electrically across the transducer controls transducer ring-down and minimizes response to extraneous noise. When this switch is operated, a low value shunt impedance is momentarily placed across the transducer to load it and terminate ring-down. This momentary action effectively clears the transducer and prepares it for sensing of the reflected echo signal from the bolt.

The signal enhancing technique was used successfully with the bolthead adaptor clamp assembly. Figure 5 is a plot of reflected signal amplitude as a function of degree of bolt bonding for the first, second, third and fourth echo signals. The three curves yield values for the first reflected signal which establish a clearly satisfactory range of signal resolution for unbonded, 1/3-bonded, and fully bonded bolts. A signal spread of 17 db exists between zero bonding and full bonding and a 14 db spread in signal exists between a 1/3-bonded and a fully bonded bolt.

Table V

EVALUATION OF BREADBOARD CLAMPING APPARATUS
(Bolt Length 48 Inches)

A. Axial Mode Bolt Excitation

	Fully Bonded Bolt	1/3-Bonded Bolt	Unbonded Bolt
Average Reflection Signal Amplitude (mv)	5.6	5.2	19.5
Repeatability of Reflection Signal Amplitudes [Standard Deviation (mv) and (%)]	1 (18)	1.3 (25)	6 (30)

B. Torsional Mode Bolt Excitation

	Fully Bonded Bolt	1/3-Bonded Bolt	Unbonded Bolt
Average Reflection Signal Amplitude (mv)	4.8	6	25.9
Repeatability of Reflection Signal Amplitudes [Standard Deviation (mv) and (%)]	1.5 (30)	1.1 (18)	5.4 (21)

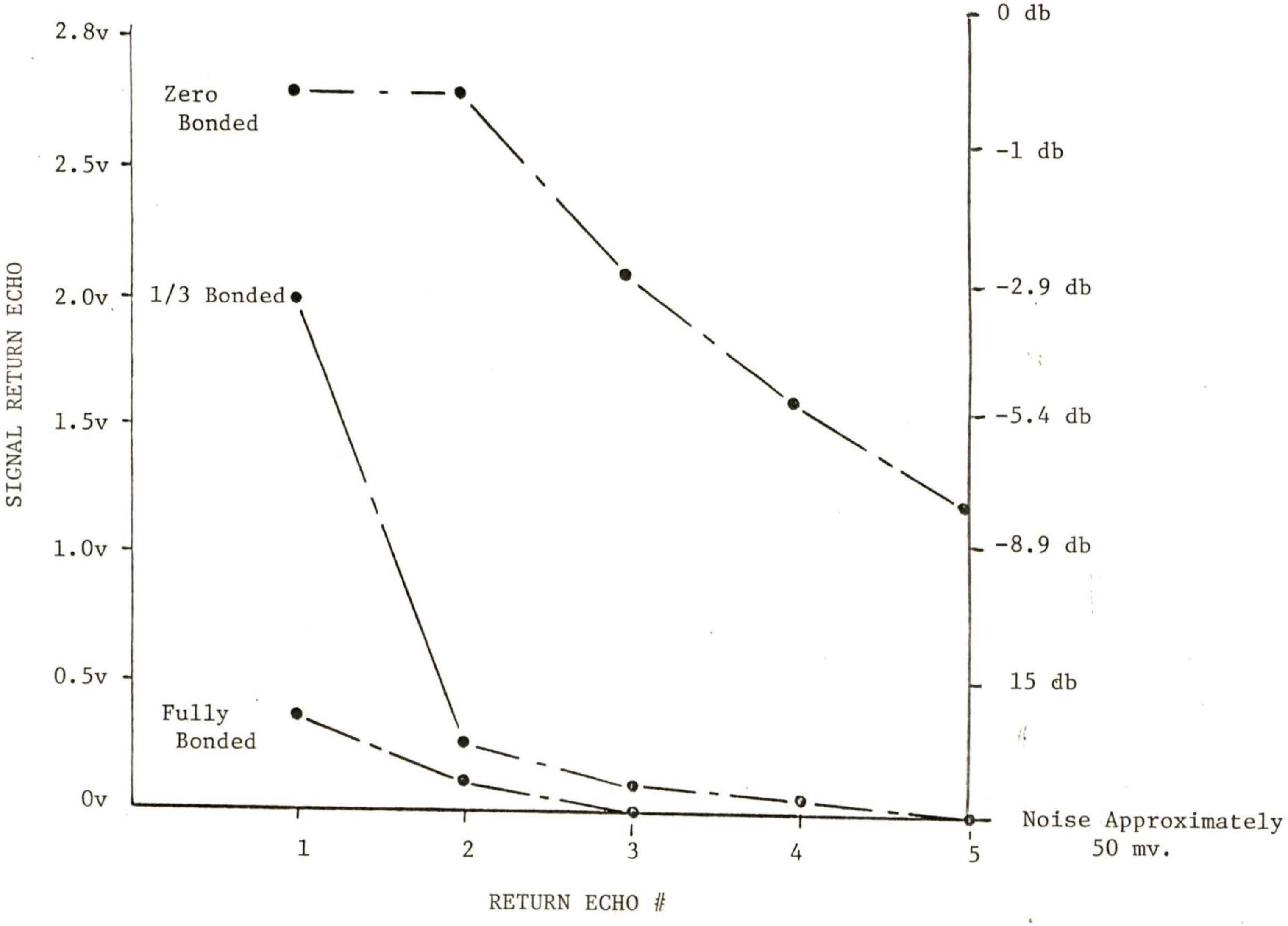


Figure 5
ENHANCED REFLECTION SIGNAL
FOR THREE DEGREES OF BOLT BONDING

IV. DESIGN MODIFICATIONS AND FIELD TESTING

A. Transducer Damping Mechanism

The electronic circuit described in Section III significantly improved signal sensitivity of the pulse echo system. Further reduction of internal reflections in the transducer-bolt head adaptor were desired to enhance the "echo signals" indicative of rock bolt bonding. To selectively attenuate transducer-to-bolt head reflections, a transducer damping mechanism (Figure 6) was designed and tested. The damping mechanism attenuates the ultrasonic wave traveling through the transducer adaptor section. Internal transducer/bolt head adaptor reflections travel through the adaptor section repeatedly while the echo pulse from the bonded bolt travels through the adaptor section only once. Each time a reflection passes the damper, ultrasonic energy is absorbed.

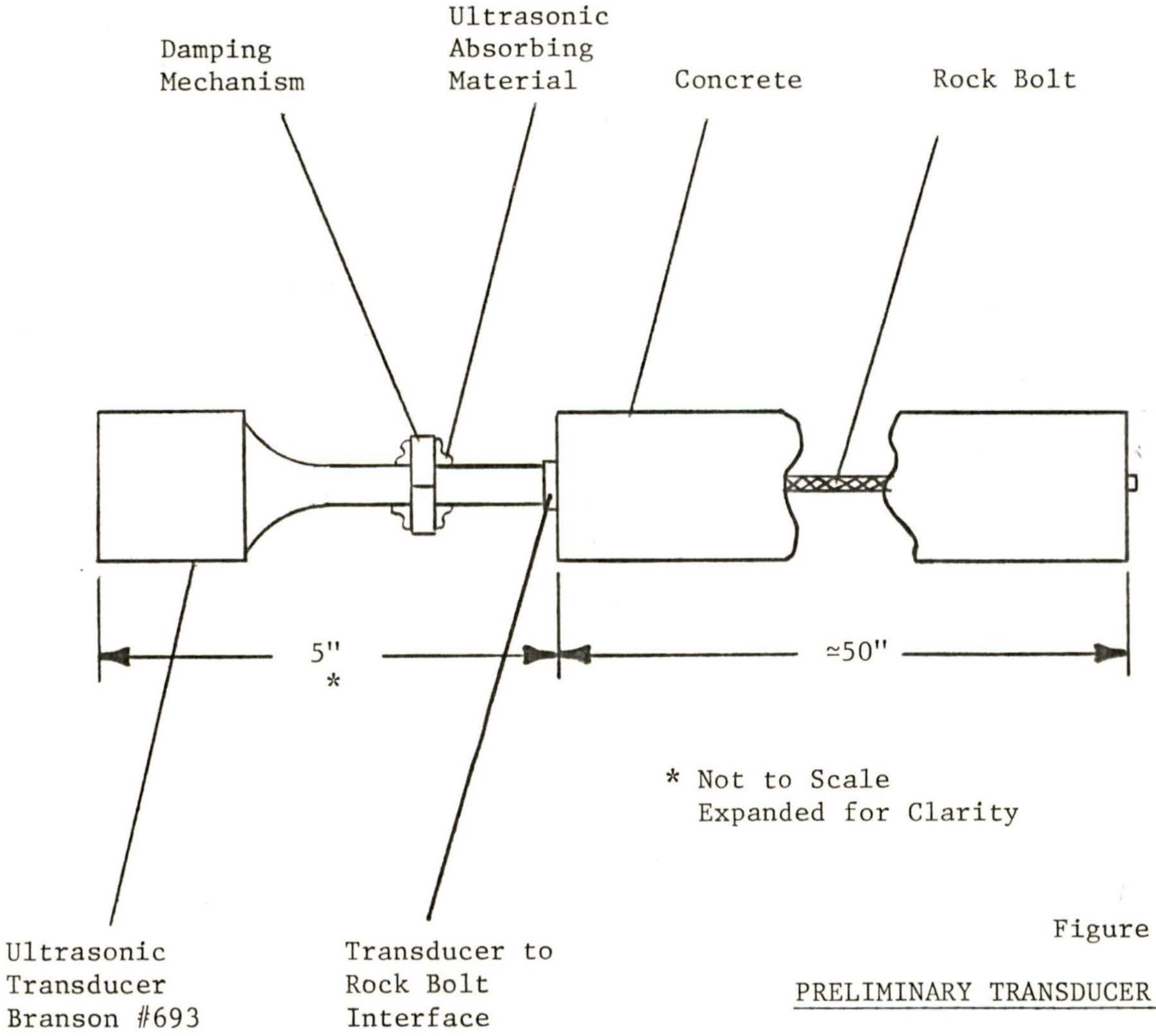
Table VI illustrates the attenuation of unwanted internal reflections achieved for unbonded, 1/3-bonded, and fully bonded bolts. These data show improvement in the ratio of echo signal to reflection and indicate the increased discrimination of the system.

B. Bolt Head Adaptor Clamp

Figure 7 shows a modified bolt head adaptor clamp designed for reduced size and weight, improved ultrasonic coupling, and ease of use. It contains an integrally mounted transducer and is designed to fit over the exposed bolt head. Axially threaded serrations on the interior surface of the adaptor section grip the corners of the bolt head, with solid contact assured by the clamping action of the taper nut on the outside of the adaptor clamp ring. Longitudinal slots are machined into the adaptor ring to allow the clamping force to be applied by the bolt head adaptor to the bolt head itself.

Test data on the fabricated assembly summarized in Table VII indicated good performance, but it had potential limits for successful in-mine use. Variation in bolt head size and bolt head conditions (e.g., rust) could affect the degree of ultrasonic energy coupling into the bolt for a given degree of clamping ring compression. Secondly, bond integrity was determined by measuring of the amplitude of the first echo signal, a direct function of main excitation pulse level actually coupled into the bolt. Hence any approach dependent on achieving a fixed degree of signal coupling has limited application in a mine environment, where variations in bolt-head size and condition exist.

As part of an ongoing E&MR-sponsored program in advanced transducer technology, a technique for measurement of an impressed main pulse amplitude as well as reflected pulse amplitudes had been developed. The technique employs integrally mounted sensing crystals within the transducer package for the purpose of providing transducer output monitoring and control. As originally developed, this technique, in conjunction with appropriate control circuitry, was intended to allow control of



* Not to Scale
Expanded for Clarity

Figure 6

PRELIMINARY TRANSDUCER DAMPING MECHANISM

Table VI

INTERFACE REFLECTION ATTENUATION

	Unbonded Bolt			1/3-Bonded Bolt			Fully-Bonded Bolt		
	Signal (mv)	Background Noise (mv)	Signal/Noise Ratio (db)	Signal (mv)	Background Noise (mv)	Signal/Noise Ratio (db)	Signal (mv)	Background Noise (mv)	Signal/Noise Ratio (db)
Without Reflection-Damping Device	800	600	2.5	300	350	-1.3	100	80	1.9
With Reflection-Damping Device	600	200	9.5	250	180	2.9	120	50	7.6
Improvement in Signal-to-Noise Ratio			7.1			4.2			5.7

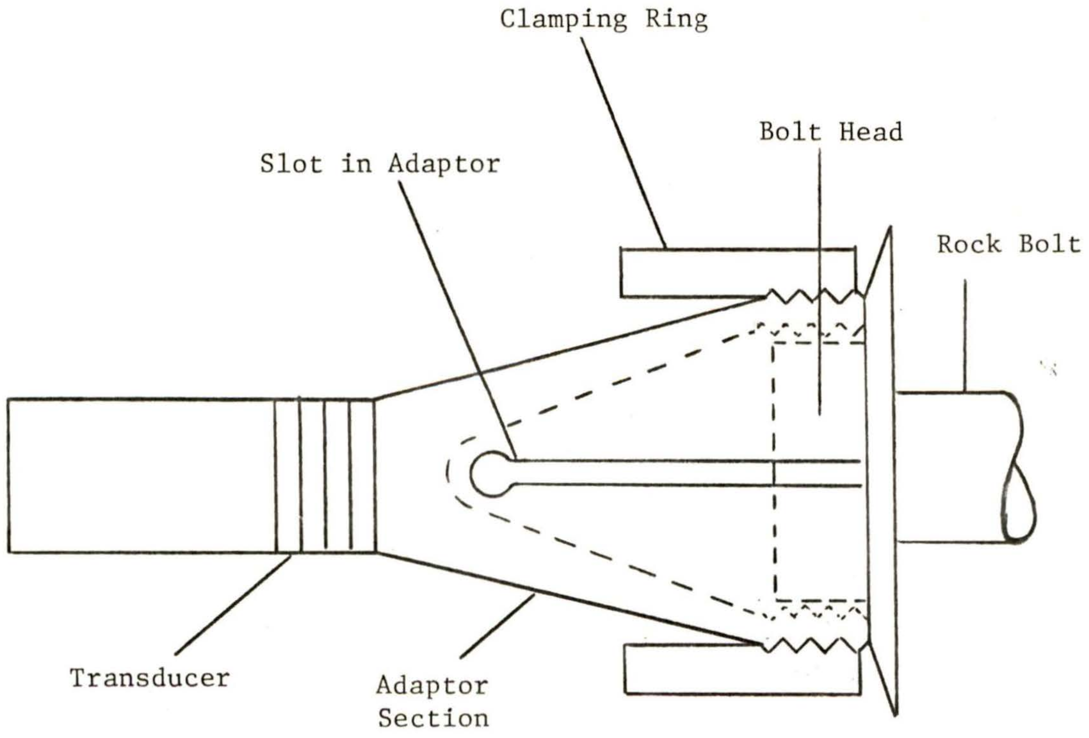


Figure 7

<u>PRELIMINARY TRANSDUCER - BOLT HEAD ADAPTOR CLAMP SCHEMATIC</u>

transducer pulse amplitude and wave form but was applicable to bolt bond monitoring. Since the actual bolt excitation pulse is constant and the echo pulse amplitude is analyzed relative to it, reliance on a constant degree of transducer-to-bolthead coupling should be obviated. It was thought that such modification could significantly increase the adaptability of the bond integrity measurement system to in-mine use.

This approach required relatively simple changes in transducer and circuit design, and in fact represented a simplification of the bolt head adaptor shown in Figure 7.

Table VII

EVALUATION OF BOLT HEAD CLAMP ADAPTOR

Bolt Bond Degree	Input Amplitude (mv)	Reflected Signal (mv)	Ratio
Unbonded	80	80	1
1/3-Bonded	80	29	0.36
Full-Bonded	100	16	0.16

C. Instrument Operation and Testing

At this point in the program, instrument operation was as follows: the transducer is pressed against the bolt head under test. The transducer incorporates a set of electrically driven crystals and a separate set of sensing crystals. These two sets of crystals are combined with control electronics in a closed loop servo configuration (designed on an E&MR Company-sponsored ultrasonic liquid level detection program and, because of its benefits, applied to the rock bolt bond integrity tester). The transducer servo control loop is operated in three modes controlled by built-in sequenced electronic switching. In the first mode, a single pulse command is generated by a timing unit and is used to gate the oscillation of the servo loop. This pulse signal activates a burst of mechanical energy within the transducer via re-generative feedback from the sensing crystals.

Sequential switching to a second control mode is then accomplished. In this mode any residual crystal ringing signal is sensed, and via degenerative feedback is used to counteract transducer mechanical ringing, thus electronically accomplishing a fast ringdown.

After a fixed delay time, the circuitry then switches into a signal-sensing configuration for a fixed time interval. In this sensing mode, the drive crystals are electronically switched out of use and the sensing crystal-set output is electronically switched into the signal processing and display circuit. The signal processing and display circuitry is activated by an electronic switch, which is controlled by an electronic signal indicating that a preset degree of input pulse strength to the bolt has been achieved.

The degree of input pulse strength is directly related to manually pressing the transducer against the bolthead (15 to 25 lbs. of force for the current prototype circuit). Once the preset signal strength is reached, the circuit operates automatically, in 1/100th of a second. Therefore, in order to achieve a reading, the operator is simply required to gently press the transducer against the bolthead flange until the measurement appears on the display. Once the input signal has been sensed, the signal processing and display circuit detects the return echo signal envelope, classifies this in the corresponding bolt bond percent category and displays the result. The display, once activated, is maintained for several seconds to allow the operator to read out the test result, and then resets to zero to permit the next test.

1. First Test Series

Preliminary tests were conducted to determine reading repeatability using unbonded, 2/3-bonded and 4/5-bonded bolt test specimens. A set of ten readings of the reflection signal envelope (indicative of degree of bonding) was taken on each specimen and later a second similar set of readings was taken. Two measures of repeatability were assessed from these data. First, the short term (variation within the ten-measurement set) and secondly, the average signal level of each of the two sets of readings were compared to determine set-to-set repeatability. Finally, the classifier outputs indicating the percent category of bolt bonding measured was noted. The classifier categories at this time were:

A - 0% - 25% Bonded
B - 25% - 50% Bonded
C - 50% - 75% Bonded
D - 75% - 100% Bonded

The results, shown in Table VIII, indicate that in a majority of cases, the classifier indicated the correct degree of bonding and that signal repeatability ranged from 1.5%, at best, to 17%.

Further testing was planned to verify these results and determine if improvement could be effected by additional comparator circuit improvement.

Table VIII

PRELIMINARY BOND MEASUREMENT REPEATABILITY DATA

	Unbonded (%)	2/3-Bonded (%)	4/5-Bonded (%)
1. Standard Deviation Within a Test Set	5	11	17
2. Difference in Average Reading Between Two Test Sets	5	1.5	11
3. Classifier Category Indicated	A (0-25) On eight out of ten tests	C (50-75) On seven out of ten tests	D (75-100) On seven out of ten tests

2. Second Test Series

Six specific levels of bolt bonding were tested, 0%, 33%, 50%, 66%, 80%, and 100%. Ten readings were taken on each bonded bolt sample and the average classification for each sample was determined. Figure 8 is a graph of the average classification vs. actual degree of bonding of the samples tested. The dots represent the average classification achieved for each sample. The dash above or beneath the dot indicates the center of the correct classification range for the bond sample being tested; the amount by which the dot is located above or below the center of the correct classification range is a measure of the percentage of the 10 sample readings taken which were outside of the correct classification. For example, on the 33%-bonded sample, seven readings indicated B classification and three readings indicated C classification. The dot therefore is located 3/10 of the way between the center of the B classification and the center of the C classification range. In general, the classification and bond degree correlate very well. The single exception is the 100% bolt bond sample for which the classification is below that which would be expected, and this sample was suspect.

After final packaging calibration, repeatability tests were conducted on three selected samples: 0%, 33% and 80% bonded. The results of these tests are shown as histograms in Figures 9, 10 and 11. In all cases the correct bonding level classification was indicated in at least 90% of all readings taken.

3. BuMines-Denver Tests

At Bureau of Mines Denver Research Center, testing was conducted on six bolts bonded into a concrete block 20'x10'x13', which was set into the ground at grade level. The bolts were installed in 1-inch-diameter holes

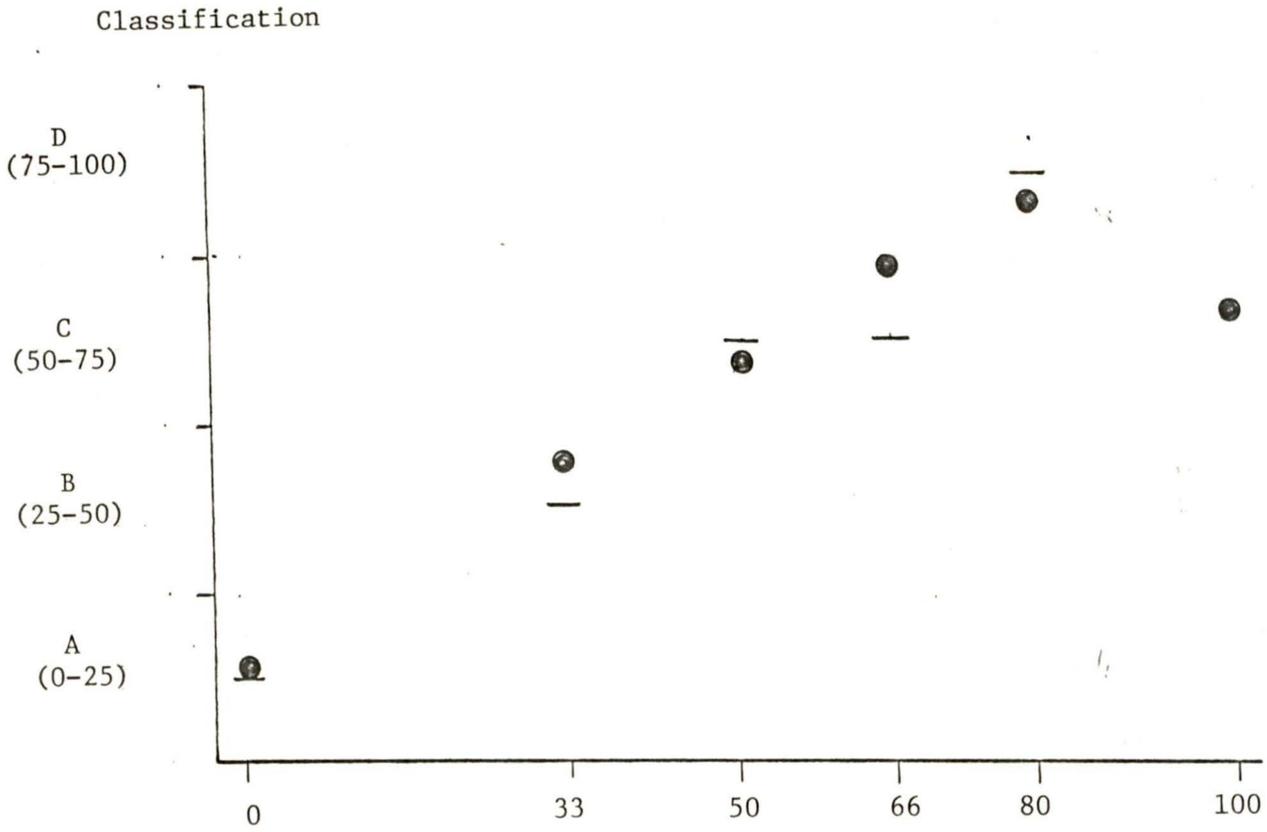


Figure 8

AVERAGE CLASSIFICATION
VERSUS DEGREE OF BONDING

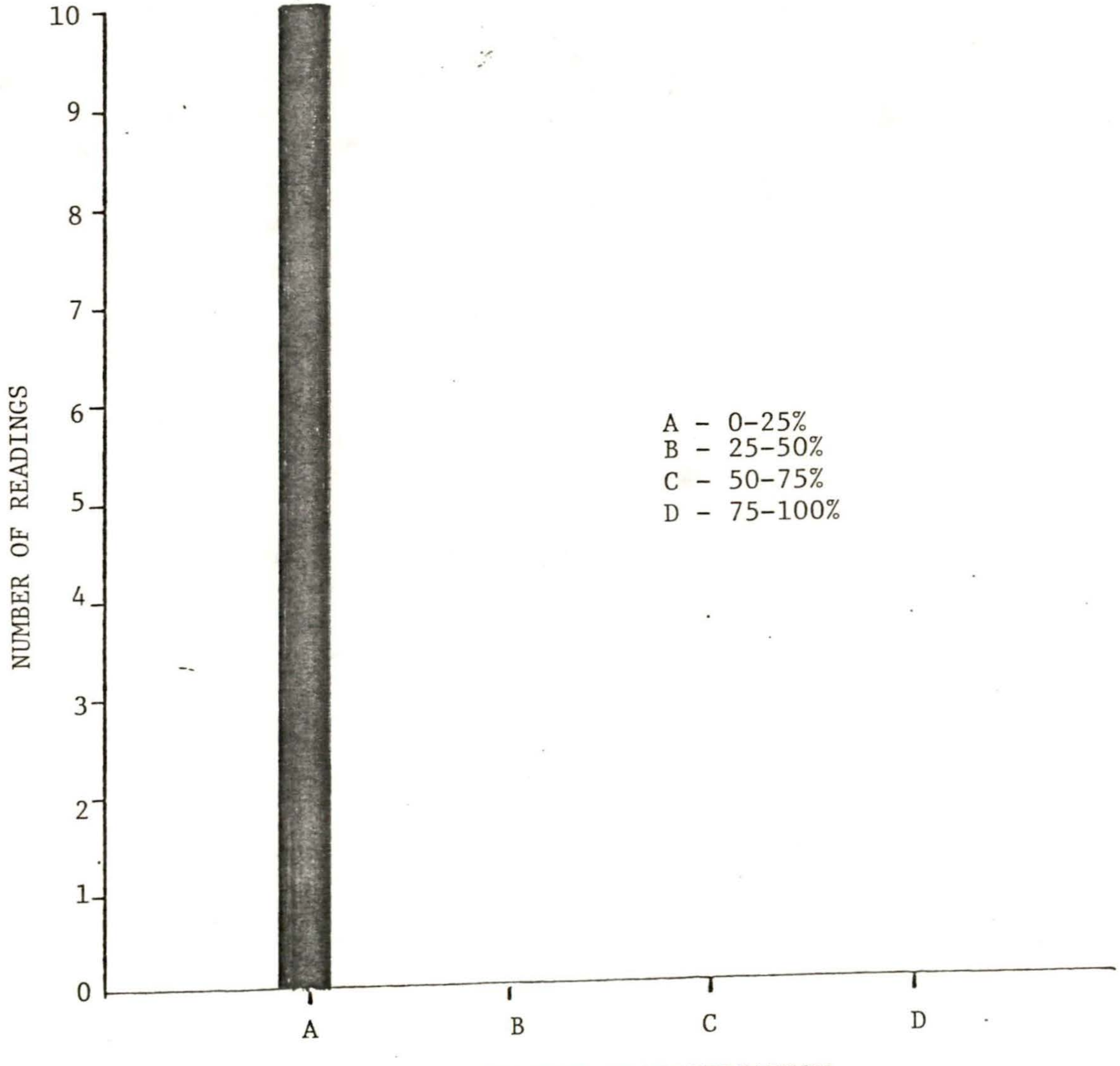


Figure 9
REPEATABILITY TEST WITH UNBONDED BOLTS

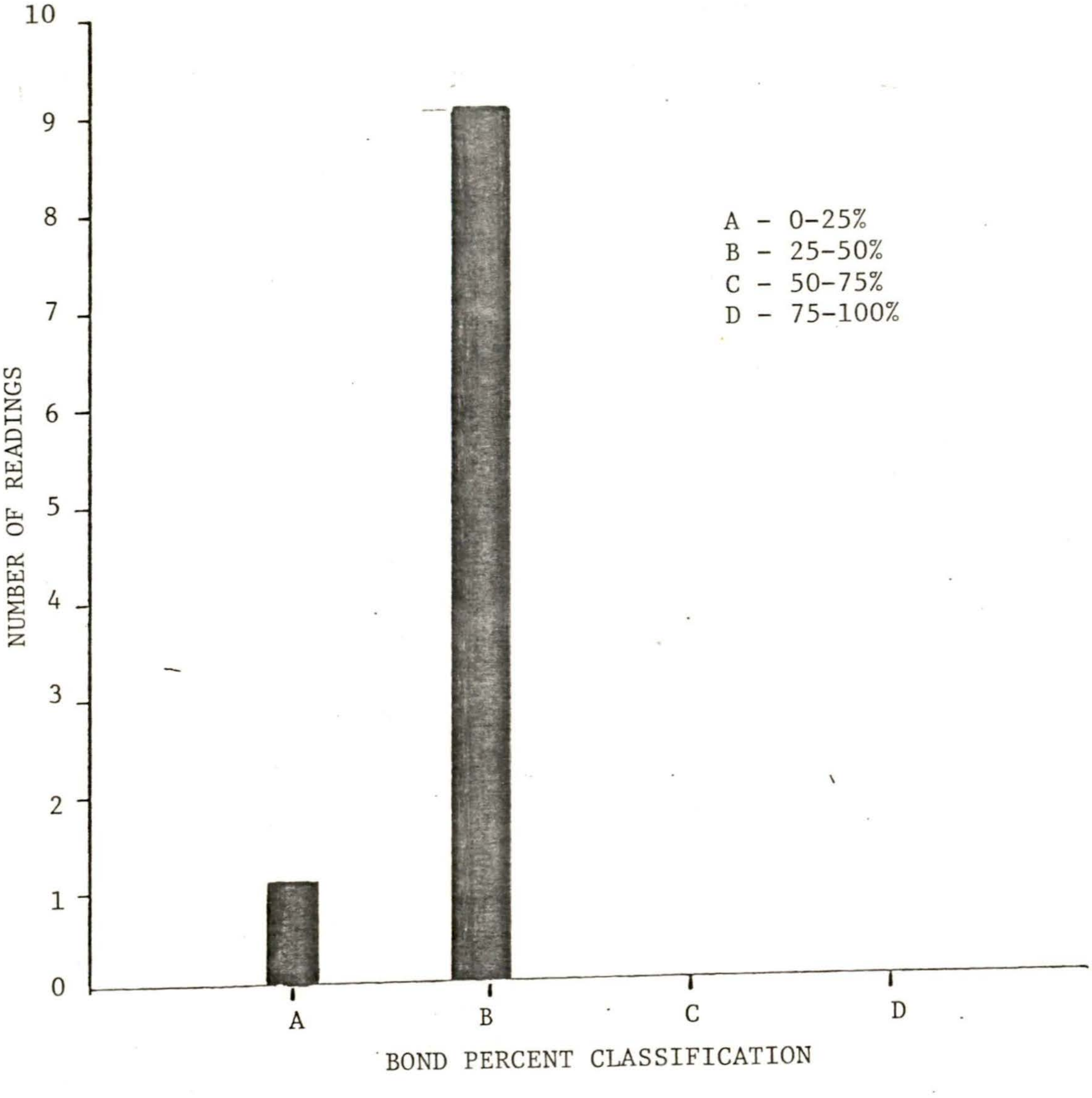


Figure 10
REPEATABILITY TEST WITH BOLTS BONDED
ON ONE-THIRD OF SURFACE

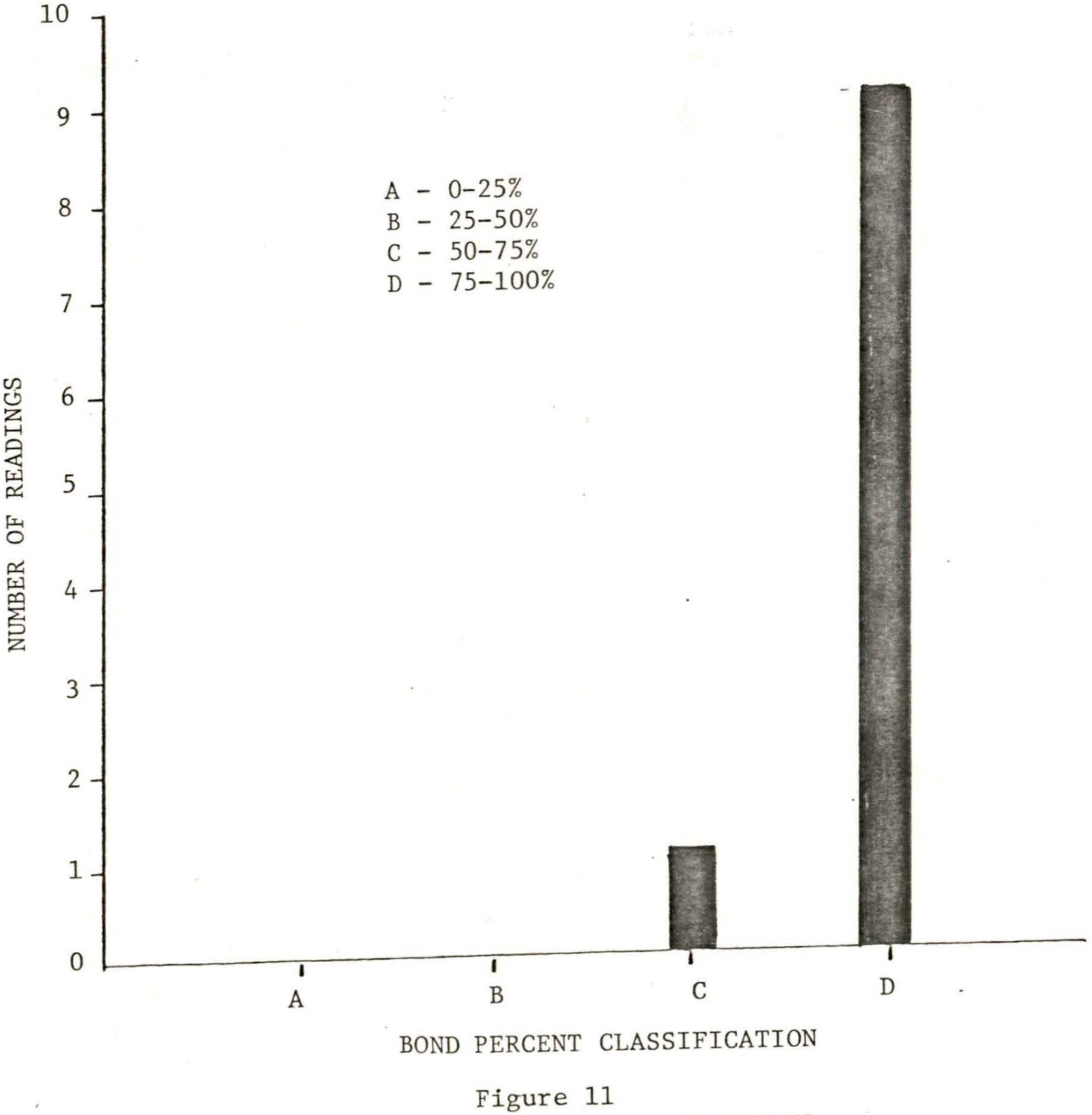


Figure 11

REPEATABILITY TEST WITH BOLTS BONDED ON 80% OF SURFACE drilled vertically downward into the block. Table IX indicates bolt identification number, degree of bonding specified for each bolt sample, and the average bolt bond tester readings. The tester reading on bolt #5 reflects doubt on the integrity of the bond actually achieved. The results of torque testing on similarly installed bolt #6 tend to confirm this doubt, since it easily broke loose with a torque wrench at much less than the specified holding torque.

D. Correction for Temperature Sensitivity

During testing at low ambient temperatures at BuMines, the integrity tester was observed to have a temperature-associated drift. While this was compensated for electronically during the Denver testing, a more suitable correction was clearly needed. After analysis, the source of this performance change was determined to be the damping material utilized in the probe to aid in promoting rapid signal ring-down. Removal of this material corrected the temperature effect while retaining measurement performance of the unit. A series of 20 readings was taken on each of three bolt bond samples: 0% bonded, 33% bonded, and 80% bonded. The results of these tests are summarized in Table X and indicate that satisfactory measurement performance was achieved without the use of the damping material and its attendant temperature effects.

E. Repeatability Testing

Tests were conducted on the breadboard roof bolt bond tester using the bonded bolts prepared previously. The 0%, 33% and 80% bonded samples were selected as the candidates for long-term repeatability testing of the breadboard unit. Testing began in March, and was designed to establish the repeatability of bolt bond measurement, both on a short-term and longer, 3-month, basis in order to provide design verification data of the breadboard configuration.

Table XI summarizes the results of testing conducted on 21 April, when 25 readings were taken on each bolt bond sample, and for comparison, repeats data acquired on 20 March with the same samples.

The classifications and distribution of the readings compare quite well between the two sets of tests conducted one month apart. The 0% (non-bonded) and 80% bond sample classification readings are nearly identical to initial results; the 33% bonded is somewhat more definitely in the "B" (25-50%-bonded) category, with 92% of the readings indicating "B", than previously when 75% of the readings indicated "B". The consistency of bond degree classification over this time interval was encouraging.

F. Quarry Test Program

A rock face was selected at Compass Quarries, Paradise, Pennsylvania, for the installation of rock bolts to be tested. This face contained a large monolithic block of limestone, easily accessible for drilling and

Table IX

DEGREE OF BONDING VS. ULTRASONIC CLASSIFICATION

Bolt Number	Degree of Bonding	Average Bolt Bond Tester Readings
1	1/3	C (50-75%) several B (25-50%)
2	1/2	A (50-75%)
3	1/8	A (0-25%), and B (25-50%) (a few readings)
4	100% with resin only (no hardener)	C (50-75%)
5	100% with cured resin	C (50-75%)*
6	2-1/2' long bolt with full bonding	C (50-75%)**

*The actual degree of bonding achieved on this bolt is in doubt because of the low ambient temperature at installation.

**The 2-1/2' bolt, while installed with the cured epoxy resin, easily broke loose with a torque wrench at much less than the specified holding torque. Since this bolt was installed at the same time as bolt #5, this result casts doubt on the integrity of the bonding achieved in bolt #5.

Table X

ULTRASONIC CLASSIFICATION VS. ACTUAL DEGREE OF BONDING

Sample Percent Bond	Tester Bond-Extent Classification Percentage
0%	A (0-25%) - 100% of readings
33%	B (25-50%) - 75% of readings A (0-25%) - 25% of readings
80%	D (75-100%) - 70% of readings C (50-75%) - 30% of readings

Table XI

BOND MEASUREMENT REPEATABILITY TESTING OF BREADBOARD CLASSIFIER

	Tester Bond-Extent Classification Percentage* (Percent of Readings)	
Sample Percent Bond	20 March Test	21 April Test
0	A 100	A 96
		B 4
33	B 75	B 92
	A 25	C 8
80	D 70	D 72
	C 30	C 28

*Bolt Classification:

A. 0-25% bonding
B. 25-50% bonding
C. 50-75% bonding
D. 75-100% bonding

installing rock bolts, which would better simulate an actual mine roof than the laboratory cylinders, and could thus serve to confirm the evaluation conducted in March at BuMines Denver.

Four holes slightly over 1¼-inch were drilled into the limestone wall. Drilling holes at a convenient working height with the apparatus available resulted in the hole axis being inclined slightly downward. Four-foot bolts were installed and bonded to four different extents; 90, 75, 50 and 25 percent of the bolt surface. The bolts were spun to mix the resin in a manner simulating an actual mine roof installation.

After waiting for the period required for adequate resin cure, constraints of time and weather permitted testing only three of the four installed bolts. The results are shown in Table XII.

Additional bolts were installed in the quarry wall using modified equipment and procedures. Holes of one-inch diameter, a smaller diameter than on previous installations and one which better simulates the resin annulus in actual mine installations, were drilled with their axes inclined slightly below horizontal to prohibit water drainage into the hole. Three levels of bonding were used in the new installations; full, 3/4 and 1/4. The extent of bonding tests produced results comparable to those attained in the laboratory. Table XIII summarizes the testing. Classification accuracy and repeatability of 100% was achieved on the full and 1/4-bond cases and 90% accuracy on the 3/4-bonded case.

Based on this testing, the breadboard unit showed itself useful to verify performance of the prototype unit.

G. Bolt Extraction Testing

Four concrete cylinders were prepared with support plates and one-inch through holes. Bonding measurements were made using the bolt bond tester for several consecutive days before the extraction tests.

Bond levels of 25-30%, 50-60%, 80-90% and full (100%) were planned. During installation and rotation of the bolt for the 100% bonded case, a seal plug was ejected from the cylinder end. Subsequent bolt rotation would have resulted in loss of resin. Rotation was terminated and the incompletely mixed bond allowed to set up. Readings taken with the breadboard bolt bond tester were in the 0-25% category. Several days later, bond tester readings remained in the 0-25% category and bolt extraction showed axial motion at 400 lbs. force, indicating that virtually no integrity had been achieved in the partially mixed resin and that the condition had been correctly diagnosed by the breadboard bond tester unit.

Extraction testing was completed on the three remaining bolt specimens; 25-30%, 50-60%, and 80-90%. Bond degree was measured with the bolt bond tester, in ten reading samples, shortly after bolt installation and periodically thereafter over a 15-day period to obtain additional measures of tester repeatability.

Table XII

BOLT BOND INTEGRITY TESTER READING

Bolt Number	Est. Bond Degree	Category: Same Day as Installation	Category: Three Days After Installation
1	90%	(75-100%) 10 Readings	(0-25%) 5 Readings
2	75%	(50-75%) 3 Readings (75-100%) 7 Readings	(0-25%) 5 Readings (25-50%) 4 Readings
3	50-60%	(0-25%) 1 Reading (25-50%) 3 Readings	(0-25%) 7 Readings (25-50%) 3 Readings
4	25%	Not Tested	Not Tested

Table XIII

ULTRASONIC ROCK BOLT BOND TESTER
JUNE READINGS

Test Number	Quarry Installation Bonding Levels: 1/4	3/4	Full
	Tester Readings		
1	0-25	50-75	75-100
2	0-25	50-75	75-100
3	0-25	50-75	75-100
4	0-25	50-75	75-100
5	0-25	50-75	75-100
6	0-25	25-50	75-100
7	0-25	50-75	75-100
8	0-25	50-75	75-100
9	0-25	50-75	75-100
10	0-25	50-75	75-100

A significant trend was noted in the readings of both the 90% and 30% (nominal) bonded specimens. The readings on the 90% specimen, for example, start in the 35% region and in an approximately exponential manner approach an average reading of about 90%. The time to reach final value is approximately four to five days.

The nominally 30% bonded specimen appeared to decrease in average measured bond strength from about 50%, to a final value near the nominal level of 30%, in a period of two to three days.

Both of these variations, viewed from the perspective of past test experience, indicate unsatisfactory bond curing and/or deterioration. During extraction, slow bolt creep was evident and was initiated at the

24,000 and 28,000 lb. levels. After the bonds yielded, tester measurements consistently read in the 0-25% category on both specimens, indicating additionally the capability of the tester to detect bond failures as well as bond quality at installation.

The 60% nominal bond specimen was measured to be consistently 65-77% (average readings) from installation until extraction. The bond appeared to have solid integrity on this specimen, with bolt failure only upon extraction.

The bolt extraction test program thus served to confirm the capability of the breadboard bolt bond tester to: detect actual bond quality at installation; track trends in bond integrity; and detect bond failure.

V. PROTOTYPE DESIGN AND TESTING

A. Circuit Design

Initial design was completed on prototype tester circuitry. The circuitry was functionally similar to the breadboard unit, but with 30% fewer parts.

A single data window, one millisecond wide and commencing 2.5 milliseconds after the main burst, was selected for all bolt lengths to be tested, 2½ to 8 feet. Tests on unbonded specimens of 2½ ft. and 8 ft. bolts confirmed an adequate reflected signal (used for bond extent classification) for this bolt length range.

The data sample rate was increased from 100 samples per second in the breadboard unit to 200 samples per second in the prototype to permit better signal averaging and the use of a minimum parts count sample and hold-signal analysis.

A three-level classification circuit for bonding degree was designed and tested, with bond levels indicated by LED lights, red for 0-50%, yellow for 50-75%, and green for 75-100%.

The bond level percentage ranges can be adjusted to other values if desired.

1. Electronic Design

The Roof Bolt Bond Tester electronic design is shown functionally in Figure 12; the block diagram illustrates how the basic functions of transducer drive control, signal processing and display, and power conditioning are accomplished.

The transducer is composed of a drive section and a signal sensing section. Using the signal sensor as a feedback element, the servo loop electronics operate the transducer in three modes.

Initially the transducer servo drive electronics and the transducer are connected in a regenerative mode by the servo loop mode switch as controlled by the sequencer. In this mode the transducer is driven at a fixed amplitude and oscillates at its resonant frequency. The servo loop remains in the drive mode for 1.5 milliseconds. At the end of this period the sequencer switches the servo loop to a degenerative mode by bypassing an inverter. In the degenerative mode the servo rapidly damps the transducer oscillation (typically in 0.1 millisecond). The servo loop remains in this mode for 0.35 millisecond; the sequencer then opens the servo loop mode switches, permitting the transducer to function as a sensor of the reflected energy from the bolt under test. This mode, the return echo sensing mode, lasts 3.15 milliseconds; the sequencer then again places the servo loop in the regenerative mode and the cycle repeats. The sequencer cycles at a rate of 200 times per second. The signal processing and display function utilize the majority of the circuitry of the instrument. Two separate data monitoring and signal processing functions are performed. The output of the transducer signal sensing section is sampled during the regenerative mode and again during the return echo sensing mode by two separate data channels, each composed of an envelope detector and a sample and hold circuit.

The signal amplitude during the regenerative mode acts as a measure of ultrasonic energy coupling into the bolt under test. The amplitude of the signal decreases with increased coupling of ultrasonic energy into the bolt; the increase in coupling is achieved by pressing the transducer coupler more firmly against the bolt head flange. This signal envelope is compared to a preset reference level; when it equals that level, an electronic comparator state changes, initiating a four-second echo signal classification and display sequence.

The signal amplitude is also sampled during the return echo sensing mode, during a 1-millisecond "data window" corresponding to the sequencer generated "read" pulse. The echo signal amplitude is compared to two preset references at the start of the four-second echo classification and display period. One reference level represents a 75-percent bond condition and the other represents a 50-percent bond condition, enabling one of three classification conditions to exist:

1. Echo signal equivalent to less than both reference levels indicating under 50 percent bond;

2. Echo signal equivalent to more than the 50 percent level but less than the 75 percent level; and

3. Echo signal equivalent to more than both reference levels, indicating greater than 75-percent bond level.

The echo signal level is classified by comparators and the resultant classification stored for four seconds in an electronic latch circuit. The latch circuit drives a red, yellow or green light-emitting diode to visually indicate the classification.

At the conclusion of the four-second period, the latches are reset and the light-emitting diode excitation power removed by the termination of the echo signal classification and display sequence.

In addition to the signal processing function, circuitry is provided for two self-test and monitoring functions.

First, the signal amplitude during the regenerative mode is compared to a second preset level. If the signal amplitude is smaller than this level, it indicates that an improper drive or a transducer malfunction exists. The result of a "low signal" comparison is an output from the electronic comparator which causes the red light-emitting diode to flash two or three times per second as a self-test failure indication.

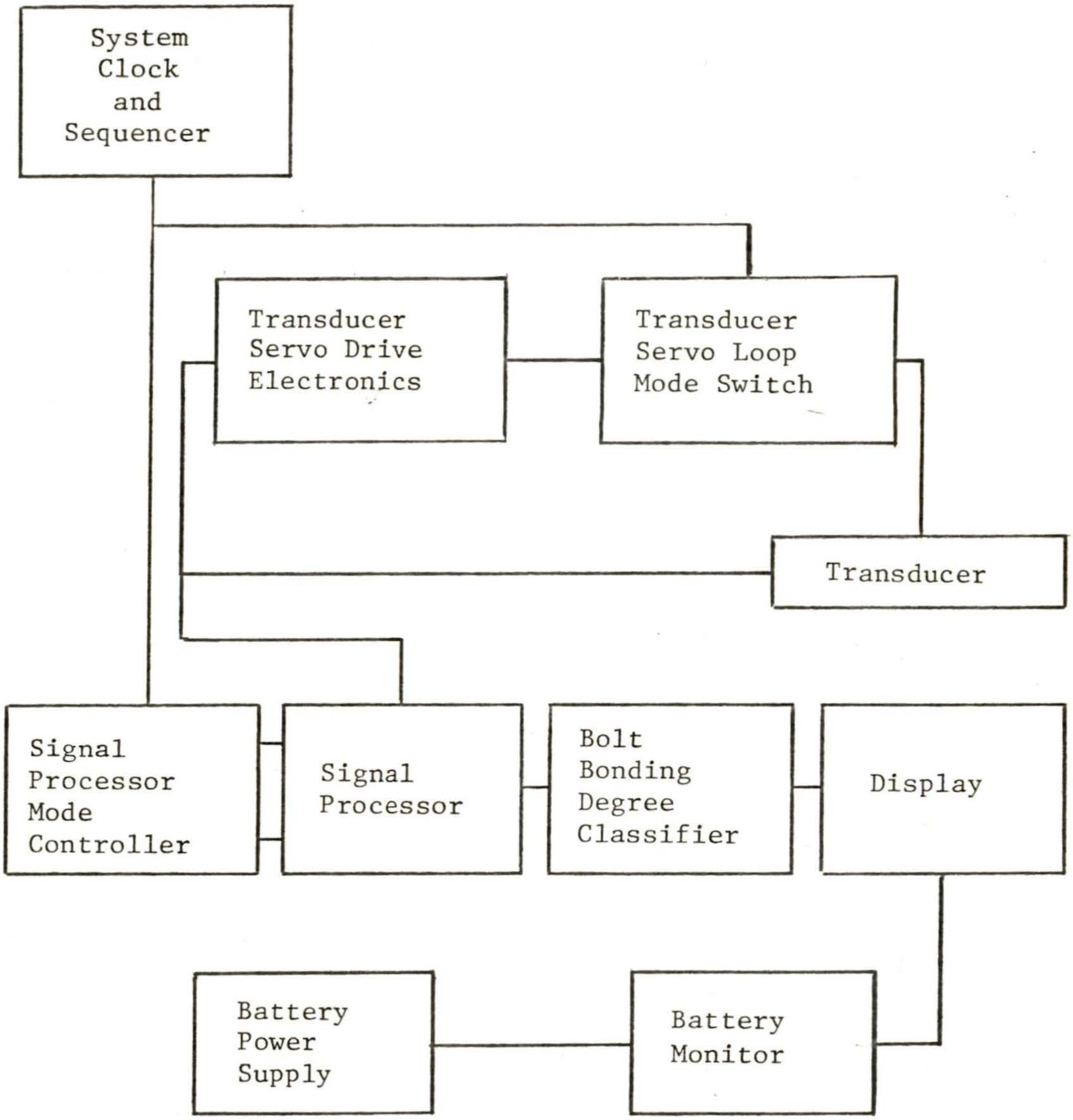


Figure 12

<u>ROOF BOLT BOND TESTER</u>
<u>BLOCK DIAGRAM</u>

Additionally, a circuit is included which monitors battery voltage for the unit. Battery voltage is compared to a reference level equivalent to the minimum acceptable value for operation of the Bolt Tester electronics. The electronic comparator circuit drives a dual polarity light-emitting diode. Battery voltage above the reference limit is indicated by the diode emitting a green light. Battery voltage below the reference level is indicated by emission of a red light, which shows that battery charging is needed.

To insure accurate circuit operation over the range of battery voltage levels during discharge, an integrated circuit voltage regulator provides a constant level of regulated voltage. The regulator is current-limited to assure safe operation in the event of a short circuit failure in the electronics. The current limit, 100 ma, is 100 times less than the value required to ignite a critical methane/air mixture.

Primary power for the electronics is provided by 16 AA-size (500 MaH capacity) Nicad rechargeable batteries which are electrically connected into four sets with four batteries in series in each set. The positive and negative terminals for each of the sets are brought out to a connector at the rear of the battery pack. This arrangement was selected to avoid recharging more than four Nicad batteries in series, which could result in uneven charge and shortened battery life. A plug in the connector socket contains the jumpers to interconnect the four sets of batteries. This plug also houses a fusible resistor which is electrically in series with the battery positive output. The resistor limits battery current in a short circuit condition to a maximum of 1 ampere for 2-3 milliseconds until the fuse opens.

2. Electronic Packaging

The electronic functions described are performed by seven integrated circuit chips and associated components. Four quad bifet operational amplifier chips, one quad bilateral switch chip, one hex inverter chip and one voltage regulator chip are employed. Four LEDs are used; one dual polarity (red/green) for battery condition monitoring and three single color LEDs to display bolt bond condition (red, yellow and green).

The electronics are packaged on two single-sided circuit boards each measuring 1½ inches by 5¼ inches. The circuit functions are divided between the two circuit boards to minimize the number of board-to-board interconnections. One board is mounted on top of the other to provide a compact electronics module. The upper board contains the voltage regulation, battery and drive signal self-test and monitor functions, and the bolt bond classification and display light functions. The lower board contains the sequencer and servo mode switch ing functions, the servo loop electronics and the dual-channel signal processing electronics.

The electronics module connects to the transducer and the on/off switch through a miniature connector mounted on one end of the electronics module, and to the battery pack through a two-pin connector on the opposite end.

B. Transducer

The transducer is an adaptation of a standard Energy & Minerals Research Company design and has a bolt head coupler built in. This transducer coupler has a thin rubber ring which adapts to the roof bolt head flange and allows coupling of both ultrasonic energy into the bolt and echo energy from the bolt into the transducer signal sensing section. Behind the coupler, two pairs of crystals are arranged with the forward pair generating the ultrasonic excitation to be coupled into the bolt head and the rear pair acting as a signal sensor. The transducer is designed to operate at its resonant frequency of 20 kHz during the regenerative mode of instrument operation.

The transducer is mounted to the internal structure of the case by bolting through the transducer flange and into the mounting structure within the case.

C. Packaging

At this point in development of the Tester, the transducer was protected by a shroud bonded to the case. A protective switch guard and rubber diaphragm seal the on/off switch assembly to protect it from moisture and minimize the risk of switch damage if the unit is dropped. Immediately behind the switch is the connector and mounting plate, to interconnect the electronics, transducer, and on/off switch. The electronics module, supported in a slot in the case internal wall, if oriented so that the indicator LEDs for battery and bolt bond condition are located under windows in the outer case. The battery pack connects to the electronics module through a two-pin connector at the rear of the electronics module. The safety fuse plug connects into the rear of the battery pack, held in place by a spring cushion mounted in the end cap. Two pins internally mounted into an iron plate were spring-loaded to engage two holes in the case to prohibit unscrewing the cap. A cap lock actuator was developed to grip the cap and, when energized, disengage the pins from the tester case, allowing access to the instrument interior.

The prototype was 16½ inches long, 2¼ inches diameter where gripped, and weighed 4½ pounds.

The battery power supply was designed to operate for 6 to 8 hours continuously for much longer intermittently.

Readings are made by placing the instrument coupler against the bolt head and pressing with about five pounds of force. The display presents a red indication for a bond extent under 50 percent, a yellow indication for a bond extent of 50 to 75 percent, and a green indication for a bond extent of 75 to 100 percent. The display will persist for four seconds and then reset for the next reading.

The first prototype was designed for four-foot bolts. Design of a dual-range modification of bolt bond lengths of 2½-foot or 4-foot (Low Range), and 6-foot or 8-foot (High Range) was next undertaken. A transducer coupler modification to permit testing of flat as well as crown flange bolts was also designed.

D. Battery Charger Development

The E&MR 4 X 4 battery charger utilizes a constant current voltage limited design. For extremely low battery voltage and charge state, a constant current is introduced into the battery set. As the charge state and battery voltage approach their full charge value, the charger current tapers off and the charger goes into a voltage limit mode of operation. This charging circuit operation is designed to provide the charge current profile deemed by the battery manufacturer to result in longest battery life. A battery test to determine adequate charge level was built in, with a test switch and green light signal.

E. Prototype Testing

During the development of the prototype configuration several kinds of tests were performed to verify or demonstrate unit performance.

1. Bond Measurement Stability Testing

Reading stability testing was conducted over a 1½-month period. The readings were taken on four-foot long bolts which were bonded into 10-inch diameter concrete cylinders with approximately 1/3, 2/3 and full bonding. Additionally, a totally unbonded four-foot bolt was tested. The results of these tests are shown in Table XIV-XVII. Table XIV presents the initial set of 25 readings on each of four bolt conditions shortly after bonding. Table XV presents comparable readings taken 24 hours later. Tables XVI and XVII present comparable readings taken 45 days later at the conclusion of the test.

The unbonded and 1/3-bonded samples consistently indicated a "red" or faulty bond condition. The other two samples (2/3-bonded and fully-bonded) both indicated a very slight change in readings toward a lower percentage bond condition.

Previous and subsequent experience with similar bonds indicates that a deterioration in the resin to cement bond occurs, often within a few hours of the bonding operation. This may be an explanation for the slight but distinct trend in both of these samples toward an indication of a lower integrity bond; that is, the 100 percent bond readings after the first set contained one or two "yellow" readings and the readings on the 2/3-bonded sample progressed from 44 to 92 percent "yellow" during the course of the test. These readings may represent tracking of a deteriorating bond condition.

Table XIV

PROTOTYPE BOLT BOND TESTER: Test Date 12/16/80

Preliminary Test
4-Foot Bolt Samples

Reading Number	No Bond	1/3-Bond	2/3(+) Bond	Full Bond
1	R	R	Y	G
2	R	R	Y	G
3	R	R	G	G
4	R	R	G	G
5	R	R	G	G
6	R	R	Y	G
7	R	R	G	G
8	R	R	Y	G
9	R	R	Y	G
10	R	R	G	G
11	R	R	G	G
12	R	R	Y	G
13	R	R	G	G
14	R	R	Y	G
15	R	R	G	G
16	R	R	Y	G
17	R	R	G	G
18	R	R	G	G
19	R	R	Y	G
20	R	R	G	G
21	R	R	G	G
22	R	R	G	G
23	R	R	G	G
24	R	R	Y	G
25	R	R	Y	G

R = less than 50% = Red
Y = 50-75% = Yellow
G = 75-100% = Green

(11 yellow)
(14 green)

Table XV

PROTOTYPE BOLT BOND TESTER: Test Date 12/17/80

Preliminary Test
4-Foot Bolt Samples

Reading Number	No Bond	1/3-Bond	2/3(+) Bond	Full Bond
1	R	R	Y	G
2	R	R	Y	G
3	R	R	Y	G
4	R	R	Y	G
5	R	R	G	G
6	R	R	G	G
7	R	R	G	G
8	R	R	Y	G
9	R	R	Y	G
10	R	R	Y	G
11	R	R	G	G
12	R	R	Y	G
13	R	R	Y	G
14	R	R	Y	G
15	R	R	Y	Y
16	R	R	Y	G
17	R	R	G	G
18	R	R	Y	G
19	R	R	Y	G
20	R	R	Y	G
21	R	R	G	Y
22	R	R	G	G
23	R	R	Y	G
24	R	R	Y	G
25	R	R	Y	G
			(18 yellow) (7 green)	(23 green) (2 yellow)

R = less than 50% = Red
Y = 50–75% = Yellow
G = 75–100% = Green

Table XVI

PROTOTYPE BOLT BOND TESTER: Test Date 1/30/81

Evaluation of S/N-A001

Test Set No. 1

Test No.	Unbonded	1/3 Bonded	2/3 Bonded	Fully Bonded
1	R	R	Y	G
2	R	R	Y	G
3	R	R	G	Y
4	R	R	Y	G
5	R	R	Y	G
6	R	R	Y	G
7	R	R	Y	G
8	R	R	Y	G
9	R	R	Y	G
10	R	R	Y	G
11	R	R	Y	G
12	R	R	Y	G
13	R	R	Y	G
14	R	R	Y	G
15	R	R	Y	G
16	R	R	Y	Y
17	R	R	Y	G
18	R	R	Y	G
19	R	R	Y	G
20	R	R	Y	G
21	R	R	Y	G
22	R	R	Y	G
23	R	R	Y	G
24	R	R	Y	G
25	R	R	Y	G
	(25 Red)	(25 Red)	(24 Yellow)	(23 Green)
			(1 Green)	(2 Yellow)

Table XVII

PROTOTYPE BOLT BOND TESTER: Test Date 1/30/81

Evaluation of S/N-A001

Test Set No. 2

Test No.	Unbonded	1/3 Bonded	2/3 Bonded	Fully Bonded
1	R	R	Y	G
2	R	R	Y	G
3	R	R	Y	G
4	R	R	Y	G
5	R	R	Y	G
6	R	R	Y	Y
7	R	R	Y	G
8	R	R	Y	G
9	R	R	Y	Y
10	R	R	Y	G
11	R	R	Y	G
12	R	R	Y	G
13	R	R	G	G
14	R	R	Y	G
15	R	R	G	G
16	R	R	Y	G
17	R	R	Y	G
18	R	R	Y	G
19	R	R	Y	Y
20	R	R	Y	G
21	R	R	Y	G
22	R	R	Y	G
23	R	R	Y	G
24	R	R	Y	G
25	R	R	Y	G
	(25 Red)	(25 Red)	(23 Yellow) (2 Green)	(22 Green) (3 Yellow)

2. In-Mine Demonstration Test

In-mine tests were conducted at the Bureau of Mines Bruceton Test Facility, to observe reading consistency with several people making the measurements, and to indicate the ability of the unit to function in a mine environment. Four bolts having four different bond conditions were set in the Bruceton mine roof. One bolt was set with only a 1/3 quantity of resin which was unmixed (uncured), a second bolt was set with properly mixed resin but only enough to be 1/3-bonded, a third bolt was 2/3-bonded, and the fourth bolt was fully bonded. Five operators who had no previous experience took several readings on each of the four test bolts. Reading agreement was excellent among the five operators, especially on the 1/3-bonded and 1/3-uncured resin bolts. Three of the five operators had consistent and full reading agreement on all four bolts. One salient observation in this test was the ease with which previously untrained operators learned the tester operation and were able rapidly to get consistent and correct readings.

3. Case Mechanical Integrity Test

In preparation for planned MSHA testing for experimental permissibility for the prototype testers, a series of drop tests was conducted to assure case capability to survive being dropped in the mine without opening and exposing the battery pack. A weighted dummy unit was constructed to closely simulate an actual unit. The unit contained an actual battery pack and safety end cap. The unit was dropped onto a cement floor from heights of 2, 4, and 6 feet with impact on each of eight axes for each height. Table XVIII illustrates the axes and shows the results of each drop test. Visual and mechanical damage was determined after each of the 24 tests. Although some impact denting was noticed on the combined axis (+X, -Y, etc.) drops, the case remained intact and neither the safety cap nor the battery pack was ever ejected.

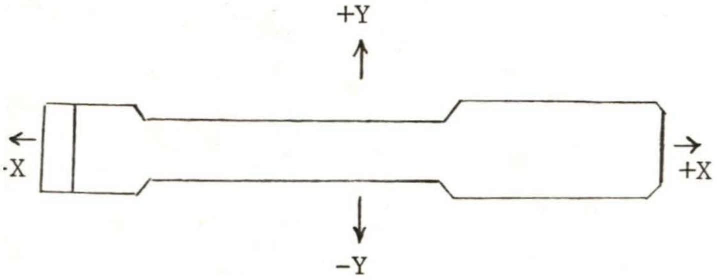
4. MSHA Review

A full drawing set describing the Roof Bolt Bond Tester in detail was reviewed by MSHA for design compliance with intrinsic safety guidelines. Additionally, a complete tester, a spare battery pack and extra fuse plugs and components were supplied for MSHA tests.

Tests were conducted to determine the time required for the fusible resistor to open electrically under a battery short-circuit condition. Typical response time for the fuse plugs to open was 2 milliseconds, which is quite suitable. Overvoltage battery tests were conducted in which 25% above nominal battery voltage was placed in series with the battery pack current-limiting resistor and the circuit closed through an MSHA standard methane detonation spark test unit. The standard detonation test, 1000 short-circuit contact occurrences, was performed with no methane detonation. Hence the battery pack and associated fuse plug were proven safe at the nominal design level and with at least a 25% safety margin.

Table XVIII

BOLT BOND TESTER DROP TEST



Unit wt. 1883 gms. (4.15 lbs.)

(Free fall drop onto cement floor using weighted drop-test sample.)

Drop (impact axis)	Height, ft. 2 feet	4 feet	6 feet
+ X	no case damage	no case damage	no case damage
- X	"	"	"
+ Y	"	"	"
- Y	"	"	"
+ X, + Y	case impact dent	case impact dent	case impact dent
- X, + Y	"	"	"
- X, - Y	"	"	"
- Y, + X	"	"	"

Notes:

1) No structural failure of case occurred.

2) Cap remained intact.

3) Battery pack was not ejected or exposed on any test.

The results of drop testing performed by E&MR were reviewed by and found acceptable to MSHA, confirming the mechanical integrity of the tester.

5. Bruceton Tests

After extensive testing by MSHA (Appendix B) and a change in one capacitor of the electronics system, the prototype ultrasonic roof bolt bond tester has received an experimental permissibility certificate, Permit No. 459. This issuance allows testing of the prototype units in operating mines. Roof Bolt Bond Tester SN-A01 was modified and prepared for the long-term stability test of 180 bolts in the Bruceton test mine, with test initiation scheduled for August 1981. The unit was delivered to Mr. Raymond Stateham, Technical Project Officer, and calibrated for use.

The 180 bolts were installed with amounts of resin calculated to achieve 1/3rd, 2/3rd or full-bonded conditions. The roof, however, is in extremely poor condition, with 3 to 12 inches of crumbling coal under delaminated, channel-filled shale, and therefore the testing was necessarily limited to tracking changes from an initially measured set of baseline readings. The baselines were taken with five readings per bolt, and are summarized in Table XIX for all measurable bolts (i.e., some of the bolt heads were sunk into the roof to an inaccessible depth).

The "red" readings of the supposedly full-column bolts occurred in clusters; bolt overcore was planned to determine the actual extent of bonding. Long-term stability testing of the measurable bolts was continued.

Flat and crown flange bolts were tested with equal ease.

6. Tests in Operating Coal Mines

Following the initiation of long-term stability tests with the SN-A01 ultrasonic roof bolt bond tester in the Bruceton test mine, five additional prototype bond testers (SN-A02 through 6) were fabricated for evaluation in operating coal mines.

Additionally, since the devices were to be evaluated in various separate mines, ancillary equipment cap lock actuators and battery chargers, described previously in Section V, were fabricated for each unit.

Evaluation of the units was conducted in two operating Colorado mines, McClain Canyon on December 2 through 5, and Bear Coal Company on December 6 through 8, 1981. These mines provided the opportunity to test in sandstone and shale roofs respectively. The data are tabulated in Tables XX through XXIII and plotted in Figure 13. They are compared in Figure 14 with subsequent tests in the Bruceton test mine with a boney coal/mudshale structure. The data from these Bruceton readings, a continuation of the long-term stability tests, are tabulated in Table XXIV.

Table XIX

ROOF BOLT BOND TESTER
LONG-TERM STABILITY TEST

Unit - SN-A01
R Scale - 47K

Date: August 7, 1981
Initial Reading Set
180 Bolt Test
BuMines, Bruceton

	Reading Summary	
Resin Amount	Flat Flange (No. of Bolts)	Crown Flange (No. of Bolts)
1/3 Column	13 R 2 Y 1 G 3-G/Y/R 2-3G/2R 2-3Y/3R	30 R 0 Y 0 G 1-3R/2Y 1-2G/2R/Y
2/3 Column	13 R 2 Y 6 G 1-3Y/2R 1-2Y/2R/G	19 R 3 Y 3 G 2-2R/3G 1-2Y/3G
Full	11 R 1 Y 11 G 1-3G/2Y	12 R 1 Y 12 G 1-3R/2G

R = Red, = less than 50%
Y = Yellow, = 50 to 75%
G = Green, = 75 to 100%

Table XX

READINGS TAKEN ON 15 BOLTS IN MCCLAIN CANYON MINE
(Sandstone Roof)

	Reading Number										Extra
	1	2	3	4	5	6	7	8	9	10	11
Row 1A	2.32	3.69	5.20	4.90	4.59	4.60	4.50	3.20	2.80	3.20	4.60
B	3.40	3.50	3.00	3.60	3.70	3.05	4.10	3.10	3.80	3.90	3.80
C	3.10	2.80	3.50	2.70	3.10	2.80	2.90	2.50	3.12	2.96	
D	0.42	0.38	0.42	0.405	0.41	0.43	0.38	0.42	0.38	0.42	
E	0.61	0.24	1.11	1.40	1.05	1.00	1.00	1.00	1.10	1.20	
Row 2A	5.20	5.62	5.62	5.60	5.90	5.60	4.89	4.92	5.69	5.69	
B	2.89	1.85	1.56	2.50	2.15	1.98	1.60	1.40	1.40	0.79	
C	0.60	1.30	1.56	1.70	2.10	2.20	2.20	2.20	2.30	2.90	
D	0.80	0.70	0.40	0.62	0.46	0.50	0.76	0.35	0.42	0.47	
E	0.73	0.68	0.80	1.60	1.50	1.60	0.95	0.50	0.69	0.58	
Row 3A	5.62	5.69	5.62	5.69	5.69	4.94	5.57	5.69	5.69	5.69	
B	3.15	5.41	5.46	5.42	5.32	5.30	5.50	5.14	5.40	5.51	
C	4.60	4.50	5.20	5.10	5.10	5.10	5.20	4.80	4.89	5.10	
D	1.90	1.58	2.50	2.50	1.90	2.20	2.60	2.70	2.50	2.60	
E	0.60	0.50	0.38	0.37	0.29	0.28	0.29	0.29	0.27	0.28	0.28
Normal 4-ft. mine-installed bolt	--	0.21	0.21	0.29	0.31	0.27	0.31	0.39	0.39	0.39	0.32

Notes:

1. Reading (in volts) at output of amplifier A4C (echo signal envelope)
2. 4-foot, flat flange bolts, Celtite resin
3. Bolt tester serial number A-07
4. Hi/Lo range switch in Lo position
5. Initial Bonding Amounts:
   A. 6-inch bond (12%) C. 24-inch bond (50%) E. 48-inch bond (100%)
   B. 12-inch bond (25%) D. 30-inch bond (62%)

Table XXI-(A)

READINGS TAKEN ON 14 BOLTS IN BEAR MINE, JUST AFTER INSTALLATION (10 AM)

(Shale Roof)

	Reading Number										
	1	2	3	4	5	6	7	8	9	10	11
Row 1A	5.67	5.68	3.89	5.60	4.90	4.90	4.78	4.90	5.67	5.70	
B	3.20	3.40	3.10	3.40	4.30	2.80	3.20	3.20	3.70	3.50	
C	1.60	1.30	0.80	2.10	1.70	1.80	1.40	2.00	1.50	1.80	
D	3.20	3.40	3.30	3.20	3.10	3.20	3.70	3.20	2.60	3.30	
E	0.37	0.33	0.36	0.34	0.41	0.43	0.33	0.42	0.34	0.39	
Row 2A	5.70	5.69	5.70	5.70	5.70	5.70	5.70	5.70	5.70	5.69	
B	3.90	4.20	4.80	3.80	4.10	4.70	4.10	4.20	4.10	4.20	
C	3.60	4.10	3.80	3.80	3.60	2.80	3.40	3.60	3.60	3.40	
D	1.80	2.30	0.80	1.60	0.80	0.60	0.80	1.20	0.80	1.80	1.70
E	0.30	0.28	0.36	0.32	0.24	0.32	0.28	0.28	0.30	0.28	
Row 3B	3.80	3.90	5.70	3.90	3.70	3.60	3.70	3.70	3.50	3.70	
C	1.80	2.20	2.80	2.70	1.90	2.10	2.50	2.60	2.40	2.30	
D	1.40	3.20	1.60	1.70	1.40	1.80	1.90	1.10	2.10	2.10	1.30
E	0.28	0.80	0.78	0.777	0.80	0.80	0.75	1.50	0.86	0.90	0.90

Notes:

1. Reading (in volts) at output of amplifier A4C (echo signal envelope)
2. 4-foot, flat flange bolts, Celtite resin
3. Bolt tester serial number A-07
4. Hi/Lo range switch in Lo position
5. Initial Bonding Amounts:
   A. 6-inch bond (12%) C. 24-inch bond (50%) E. 48-inch bond (100%)
   B. 12-inch bond (25%) D. 30-inch bond (62%)

Table XXI-(B)

READINGS TAKEN ON 14 BOLTS IN BEAR MINE, JUST AFTER INSTALLATION (4:15 to 5 PM)

(Shale Roof)

	Reading Number										
	1	2	3	4	5	6	7	8	9	10	11
Row 1A	5.60	3.90	5.6	5.60	5.60	5.60	4.80	4.90	5.40	4.90	
B	2.80	3.40	1.80	4.00	4.80	3.90	4.20	3.90	3.90	3.90	3.80
C	0.90	1.80	1.60	1.60	0.90	1.80	0.90	0.90	1.20	1.20	
D	1.00	0.90	1.20	1.00	1.00	0.90	1.00	0.90	1.10	1.10	
E	0.70	0.35	0.42	0.45	0.32	0.48	0.52	0.32	0.34	0.32	0.90
Row 2A	5.70	5.70	5.70	5.70	5.70	5.70	5.60	5.60	5.70	5.70	
B	3.90	3.40	2.90	3.80	3.20	4.10	4.10	2.90	3.40	2.80	
C	3.30	3.60	3.60	3.50	3.80	3.40	3.50	3.60	3.40	3.20	4.90/ 1.80
D	0.90	2.80	1.80	0.90	0.90	0.60	0.80	1.00	0.70	0.80	
E	0.28	0.29	0.28	0.24	0.23	0.29	0.21	0.29	0.30	0.28	
Row 3B	3.70	3.90	3.90	4.60	4.20	3.90	3.80	3.80	3.80	5.40	5.70
C	1.70	1.60	1.80	1.70	1.90	1.80	2.10	1.40	1.80	2.20	
D	0.90	1.00	1.00	1.90	1.40	1.40	1.00	1.50	1.20	1.90	
E	0.40	0.40	0.90	0.70	0.80	0.90	0.40	0.70	0.70	0.90	0.40

Notes:

1. Reading (in volts) at output of amplifier A4C (echo signal envelope)
2. 4-foot, flat flange bolts, Celtite resin
3. Bolt tester serial number A-07
4. Hi/Lo range switch in Lo position
5. Initial Bonding Amounts:
   A. 6-inch bond (12%)　C. 24-inch bond (50%)　E. 48-inch bond (100%)
   B. 12-inch bond (25%)　D. 30-inch bond (62%)

Table XXII

TIME SPREAD SANDSTONE ROOF TESTS IN MCCLAIN CANYON MINE:

First/Second Reading Spread
(approximately 24 hours between readings)

$\frac{\Delta}{\sigma\ \text{max}} > 1$	Sample	Average First Reading	σ	Average Second Reading	σ	(1st-2nd) Δ Avg.
--	1A	2.9	1.6	4.0	1.00	-1.1
1.6	1B	2.1	0.9	3.5	0.36	-1.4
--	1C	2.0	1.0	3.0	0.28	-1.0
--	2B	2.1	0.8	1.9	0.60	+0.2
1.3	2C	1.1	0.4	1.9	0.60	-0.8
4.5	3C	3.2	0.4	5.0	0.25	-1.8
3.6	3D	0.66	0.45	2.3	0.40	-1.64

+ Δ = Improved Bond

- Δ = Degraded Bond

Table XXIII

SHALE ROOF TESTS IN BEAR MINE

First/Second Reading Spread
(approximately 6½ hours between readings)

$\frac{\Delta}{\sigma_{max}} > 1$	Sample	Average First Reading	σ	Average Second Reading	σ	(1st-2nd) Δ Avg.
--	1B	3.4	0.4	3.7	0.8	-0.3
--	1C	1.6	0.4	1.3	0.4	+0.3
7.0	1D	3.2	0.3	1.0	0.1	+2.2
1.4	2B	4.2	0.3	3.5	0.5	+0.7
1.7	3C	2.3	0.3	1.8	0.2	+0.5
--	3D	1.8	0.6	1.3	0.4	+0.5

$+ \Delta$ = Improved Bond

$- \Delta$ = Degraded Bond

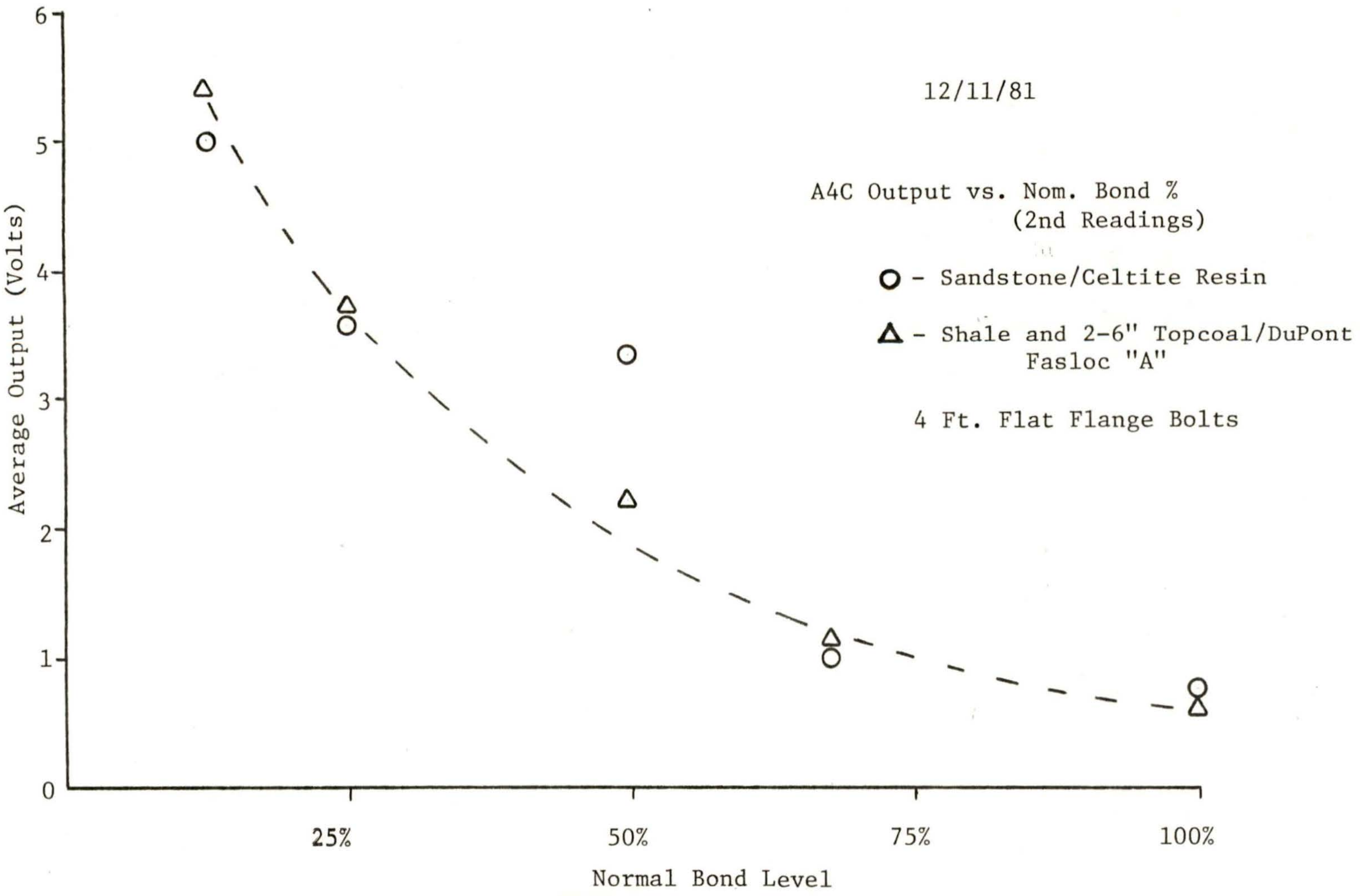


Figure 13

<u>IN-MINE TEST DATA</u>

12/11/81

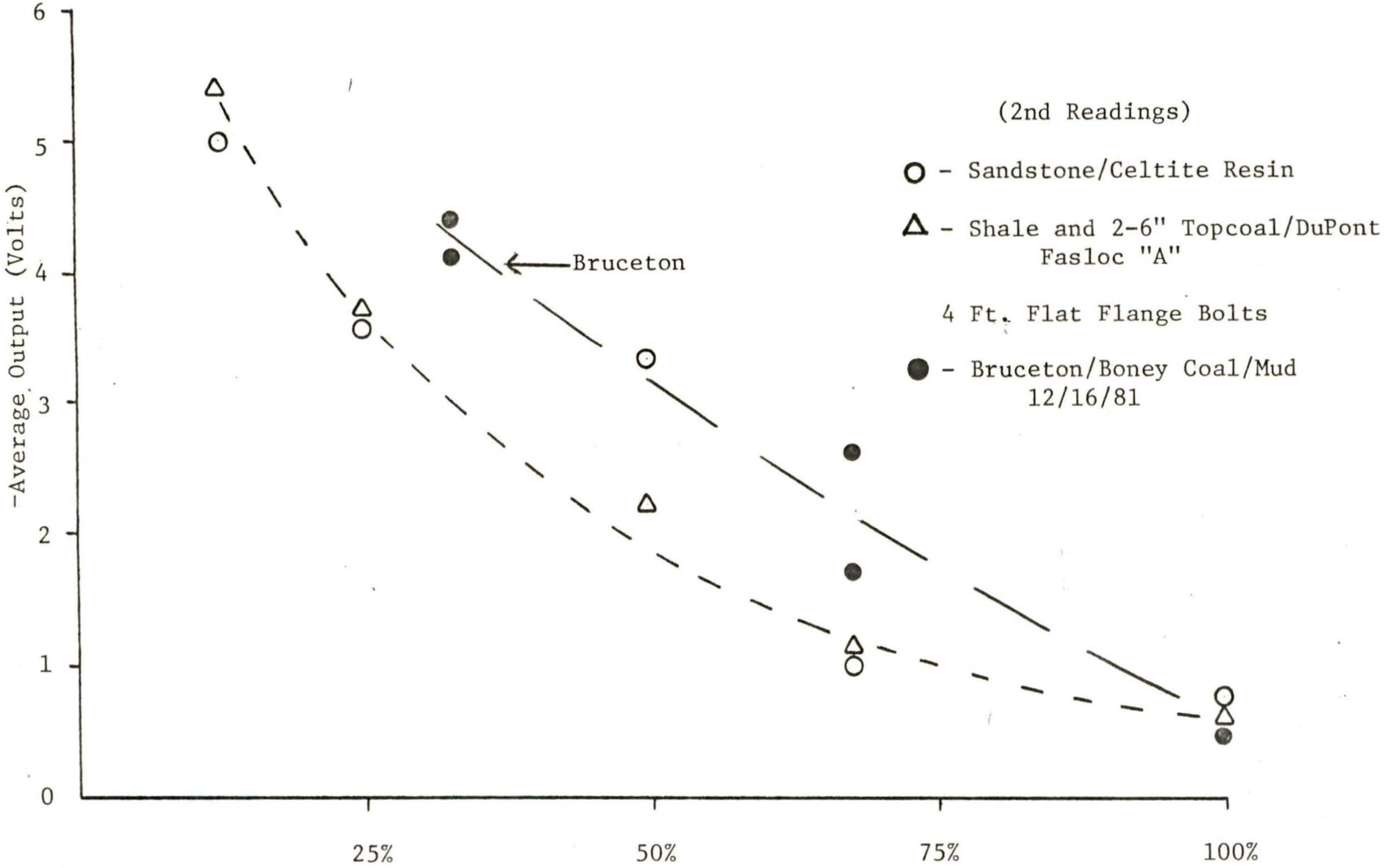


Figure 14

<u>IN-MINE TESTS COMPARED WITH BRUCETON READINGS</u>

A4C Output vs. Nom. Bond %

Table XXIV-(A)

READINGS TAKEN IN BRUCETON TEST MINE

(Boney Coal/Mudshale Roof)

	Reading Number									
	1	2	3	4	5	6	7	8	9	10
12E (Red)	4.20	4.01	4.56	4.13	4.12	4.47	3.86	4.06	4.02	3.60
12A (Red)	4.20	4.22	4.24	4.34	4.11	4.62	3.91	4.51	4.48	4.45
28D (Yel)	2.50	2.75	1.49	2.90	2.84	2.83	2.52	2.57	3.21	2.56
32C (Yel)	4.36	1.73	0.86	1.01	1.35	1.55	1.72	1.82	1.01	1.47
30C (Grn)	0.24	0.55	0.57	0.71	0.62	0.29	0.54	0.23	0.43	0.35
30F (Grn)	0.74	0.25	0.40	0.26	0.42	0.47	1.16	0.27	0.14	0.21

Notes:

1. Reading (in volts) at output of amplifier A4C (echo signal envelope)
2. Quiescent Level: 230-780 millivolts
3. Hi/Lo range switch in Lo position
4. Readings from 180-Bolt group in A Butt

Table XXIV-(B)

READINGS TAKEN IN BRUCETON TEST MINE
(12 room)

	Reading Number									
	1	2	3	4	5	6	7	8	9	10
A (1st time)	3.34	0.98	1.19	2.62	3.16	3.65	0.50	1.41		
A (2nd time)	0.50	2.83	2.47	0.93	0.57	2.54	2.73	3.08	1.33	1.40
B	0.39	0.25	0.28	0.24	0.27	0.33	0.28	0.52	0.33	0.56
C	1.67	1.12	1.01	0.91	1.11	0.97	1.14	0.61	2.51	0.97
D	--	--	--	--	--	--	--	--	--	--

Notes:

1. Reading (in volts) at output of amplifier A4C (echo signal envelope).
2. Readings taken on 4 flat-flange bolts with washers (wet and rusty).
3. The A (2nd time) readings were taken after moving a board over to stand on.
4. The plate for the D bolt was offset sideways, which prevented taking any readings.

In general, all of the data showed comparable results for the sandstone and shale roofs and demonstrated tester accuracy.

F. Tester Calibration; Unit Design

A calibrator unit was developed to allow the tester to be used in differing roof conditions. Ideally, the calibrator should be a passive energy absorber as is the mine roof. A calibrator "breadboard" was assembled and tested to determine if all types of bolt length, roof condition and degree of bonding could be simulated with a passive system. The first series of tests utilized a transducer constructed with a single pair of crystals. In this configuration, resistive loading of the crystal pair would not absorb sufficient energy to simulate a well-bonded condition.

The second series of tests was performed using a transducer constructed with two pairs of crystals (like the bolt tester). Tests indicated that a passive system can in fact absorb sufficient energy to simulate a well-bonded 4-foot bolt. Further tests were scheduled to determine whether a well-bonded 8-foot bolt also could be simulated with a passive system.

A redesigned four-crystal transducer was bench-checked and showed fully adequate energy absorption. Circuitry was then designed based on the data collected in the McClain Canyon and Bear Mines, to permit calibration of the tester for use with two distinctly different mine roofs, sandstone and shale.

The circuitry involves a passive resistive network which electrically loads the crystals to simulate energy absorption of the bolt at the three conditions of bond integrity. The circuitry, which is capable of use with 4-foot and 8-foot bolts, tested out as fully adequate.

The final calibrator is a transducer similar to the one used in the Roof Bolt Bond Tester. It uses four piezoelectric crystals and a passive resistor network to absorb the signals from the bolt detector. The amount of energy absorbed depends on the resistive loading applied to the crystals. One of six resistors is switched into the loading network, whose values correspond with a Red, Yellow or Green indication for high to low ranges. The calibrator will be usable with both the resin grout and the inorganic grout without re-calibration.

Figure 15 is a sketch of the calibrator, with the calibration procedure following.

The calibrator response is based on readings taken in three different mines with differing mine roof compositions. They are the McClain Canyon Mine with sandstone roof, the Bear Coal Company Mine with shale roof, and the Bruceton test mine with boney coal/mudshale structure. Thus, the calibrator was designed to tune the roof bolt bond tester to all three mine roof compositions with one procedure.

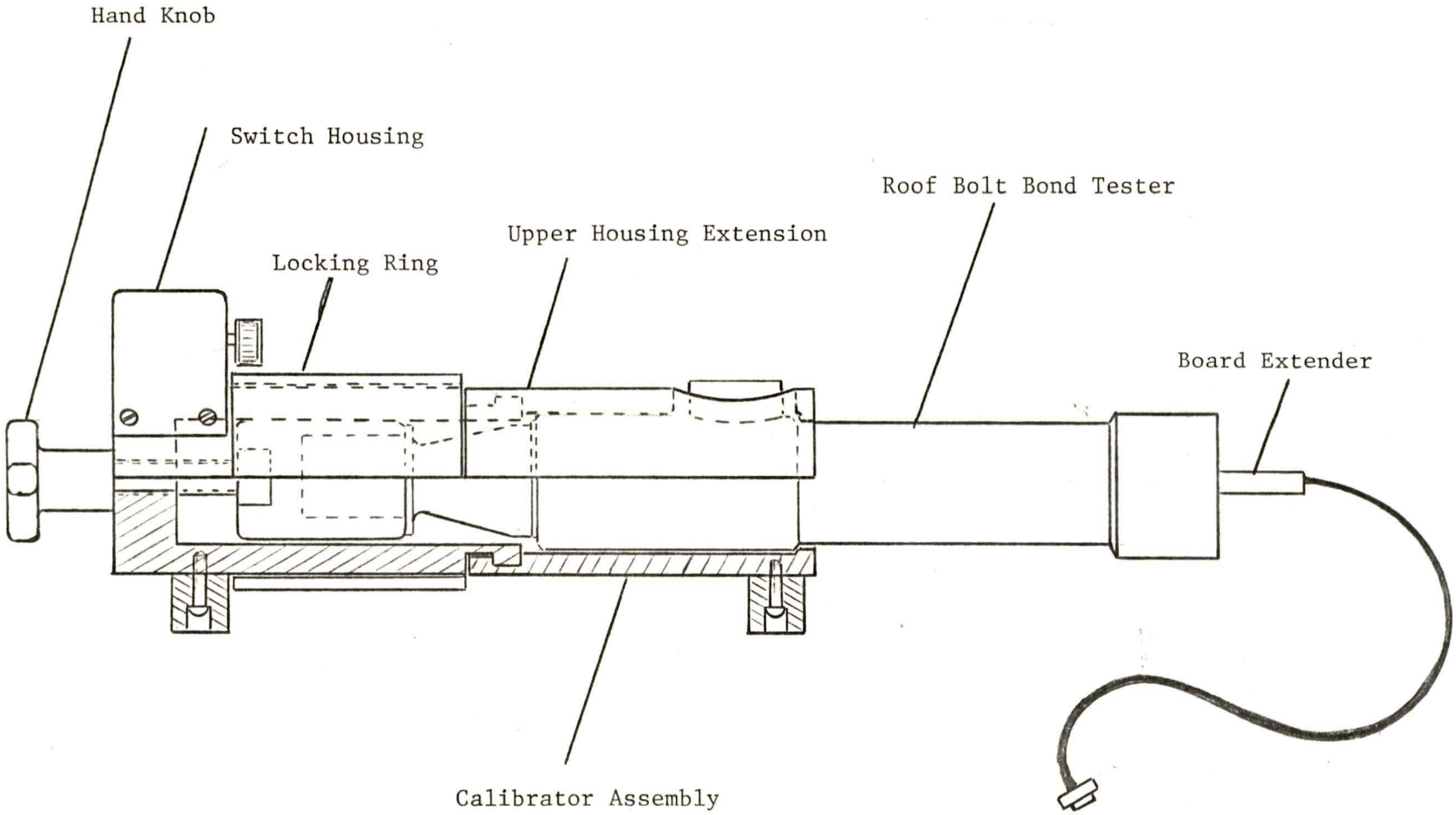


Figure 15

ROOF BOLT BOND TESTER CALIBRATOR

Calibration Procedure - E&MR Co. Roof Bolt Bond Tester

Equipment Needed:

- E&MR Calibrator Assembly
- E&MR Board-Extender Cable
- DC Voltmeter
- Dual Trace Oscilloscope
- 14-Pin and 16-Pin DIP Test Clips

Before starting ensure that:

- Battery pack is fully charged.
- Transducer rubber coupler is securely bonded to transducer. Use cyanoacrylate glue (Super Glue), to mend any de-bonds.

Calibration:

Install Bolt Tester Into Calibrator

- Slide locking ring toward switch housing.
- Remove upper housing extension.
- Place tester into calibrator.
- Replace housing and secure with lock ring.

Adjust Regulated Voltage

- Adjust R-16 for 13.50 volts, between pins 3 & 7 of VR-1 (uA 723).

Adjust Trip Point

- Start with R-85 fully clockwise, and calibrator hand knob fully counterclockwise.
- Connect scope ground to A-1 pin 13.
- Connect scope channel 1 to S-1 pin 2 (100 mV/Div.).
- Connect scope channel 2 to A-4 pin 7 (5 V/Div.).
- Turn calibrator hand knob until channel 1 scope trace drops 150 mV.
- Without moving calibrator hand knob, adjust R-85 counterclockwise until scope trace jumps about 6 volts.
- Tool is now adjusted for correct push pressure.
- Switch instrument into low range,
  Set calibrator on low red, adjust R-22 for red display
  Set calibrator on yellow, adjust R-23 for yellow display
  Set calibrator on green; if display is not green, re-adjust R-23 for proper yellow, green indication.
- Switch instrument into high range,
  Adjust R-21 for proper display indications.

VI. ALTERNATE GROUT TESTING

With the emergence of organic and inorganic grouts as bolt bonding materials, it was considered desirable to evaluate tester utility with some representative grouts supplied by the Bureau.

Concrete forms were poured to simulate mine roofs for installation of bolts bonded with these alternate grouts. The first installations were bolts of 4- and 8-foot lengths at the three bond integrity conditions (33, 66 and 100%) using the Amicon epoxy grout supplied. The grout was allowed two weeks to cure before testing. Preliminary results then indicated no return-signal response at the highest sensitivity of the Roof Bolt Bond Tester.

An inorganic grout was next received and found to give similar results to the standard resin grout now in use; the results of Table XXV agree quite well with the previously reported results obtained in the mine.

The Amicon epoxy grout was retested. No measurable signal returns were encountered even with only 1/3 bonded bolts. More epoxy grout was to be sent from Spokane in order to bond bolts 1/3 from the back end, in order to give a comparison of results obtained by the Technical Project Officer.

Table XXV

INORGANIC GROUTED BOLTS
(4 ft. Flatheads)

33% Bond (v)	66% Bond (v)	100% Bond (v)
5.704	.740	.076
4.248	.500	.060
4.780	.836	.060
6.356	.436	.096
4.484	.572	.064
5.560	.500	.044
5.388	1.488	.040
5.160	2.308	.052

VII. FINAL DATA COLLECTION AND CALIBRATION

In operating mines, the type of ceiling (shale, limestone, etc.) encountered is important in determining the calibration of the Roof Bolt Bond Tester. A unit calibrated for a shale roof will not necessarily give the proper response when used in a mine with, for instance, a limestone roof. When the first units are delivered, E&MR plans to send a technician with each instrument. The instrument will be for sale with and without a calibrator. The technician will have the mine owner install bolts of known condition in various degrees of bonding. He will then calibrate the RBBT and the calibrator to that particular mine. Data will be collected during the calibration procedure and matched to the particular roof type. After the sale of between 50 and 100 RBBTs, the data collected should enable E&MR to calibrate the units before they are shipped, thus reducing their cost.

Another problem that will be encountered in operating mines is the rested condition of the boltheads of older installations. The rust will inhibit the transmission of the ultrasonic signal into the bolt. The bolt will have to be scraped clean and to a consistent degree. Therefore, E&MR may have to come up with a device which is feasible within our existing technology which would clean the bolts properly and all to the same degree for consistent results.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

As grouted bolts are installed in increasing numbers in the mines, a reliable device to test the integrity of their installation becomes more important. The Rock Bolt Bond Tester--RBBT--was developed to answer this previously unmet need. In addition to the successful technical performance achieved, the tester further satisfies the obvious requirement of practical operation in the difficult mine environment:

1. The RBBT instantly reads the bond strength of a grouted bolt to one of three conditions, 1/3, 2/3 or fully bonded. These conditions are readily apparent to the untrained operator by the use of a "traffic light" read-out, i.e., red, yellow or green.
2. The unit is easily portable, about the size of a 5-battery flashlight.
3. The transducer, electronics and battery pack are contained in the same package.
4. The batteries are rechargeable, with the charge lasting for 8 hours continuous operation; normal duty for each bolt test is about 30 seconds.
5. The RBBT is designed for extreme ease of operation, requiring only manual contact with the bolt head and signal read-out, and thus operator training is minimal.

The prototype tester has been approved by MSHA for the Bureau of Mines; approval re-assignment to E&MR is in process. When this is received, E&MR plans to manufacture and market the RBBT for coal mine use.

B. Recommendations

Since the RBBT principally offers safety rather than operating efficiency, it presents a different marketing problem than the usual item of capital equipment. E&MR hopes that the Bureau will continue to use its good offices in encouraging use of the RBBT.

An additional spur to speeding introduction of the tester in significant numbers to operating mines would be that of The Bureau aiding in the final data collection and prototype "de-bugging".

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(3) Kinsler, L. and A. Frey, Fundamentals of Acoustics, John Wiley & Sons, Inc., New York (1962).

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(8) Maropis, N., et al., "Methods and Apparatus Empolying Torsional Vibratory Energy for Wrenching", U.S. Patent No. 3,521,348 (July 21, 1970).

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(10) Tarpley, W. B., Jr. and D. R. Culp (Energy & Minerals Research Company), "Apparatus and Method of Monitoring Anchored Bolts", U.S. Patent No. 4,198,865 (April 22, 1980).

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APPENDIX A

Ultrasonic Energy Transfer Through a Variable Quality Juncture

APPENDIX A

ULTRASONIC ENERGY TRANSFER
THROUGH A
VARIABLE QUALITY JUNCTURE

III. Derivation of Appropriate Equations

The symbol system used in this section is as follows:

Z_m: Mechanical Impedance

A: Area of Waveguide

ρ: Medium Density

c: Medium Wave Velocity

W: Pulse Energy

W_o: Initial Pulse Energy

k: Energy Proportionality Constant

U: Pulse Amplitude

U_o: Initial Pulse Amplitude

α_s: Spatial Attenuation (in Neper/unit length)

α_t: Energy Transfer Constant (in Neper/unit length)

x: Distance from Introduction of Wave Pulse

A. Ultrasonic Energy Reflection at an Interface

The parameter that determines the reaction of a wave to a boundary or interface (as in an air gap in an unbonded grouted bolt or in a loose sleeve bolt) is the mechanical impedance Z_m at the juncture where:

[1] $Z_m = A\rho c$

A area of waveguide,
ρ medium density,
c velocity.

B. Ultrasonic Energy Transmission

Because particle motion is imparted to the medium by the stress change and because the resulting wave propagates away from the source, waves may be used effectively to transmit energy. For many ultrasonic applications, especially non-destructive testing, this energy is transmitted in the form of a pulse. The energy of the pulse would be given as (3):

[2] $W = kU^2$,

where k depends both on the characteristics of the medium and the wave shape. Note that the pulse energy varies as the square of the instantaneous pulse amplitude U. Waveguides may be used advantageously to channel ultrasonic energy into a particular region. For a wave confined exclusively to an ideal waveguide with no internal losses, the energy of the wave will remain undiminished regardless of the distance traveled.

So long as the mechanical impedance Z_m does not change (regardless of the individual values of A, ρ, and c) the wave will continue to propagate undisturbed. If the impedance of the medium changes, part of the incident energy will be reflected at the transition while the remaining energy will continue in its original direction. This concept is commonly used for flaw detection in ultrasonic non-destructive testing.

C. Ultrasonic Energy Absorption

As already indicated, a wave traveling in an ideal waveguide would continue forever with undiminished energy W. This is obviously not the case for real materials. Hence an additional factor must be introduced to account for the irreversible conversion and loss of ultrasonic energy into heat. Since the amount of energy lost is proportional to the wave energy available, Equation [2] may be modified to yield:

$$[3] \qquad W = k[U_o \exp(-\alpha_s x)]^2$$
$$= kU_o{}^2 \exp(-2\alpha_s x)$$
$$= W_o \exp(-2\alpha_s x) \quad .$$

The factor in brackets in Equation [3] is the instantaneous pulse amplitude, which decreases exponentially with distance x by the factor α_s. U_o and W_o are, respectively, the amplitude and energy of the pulse at the beginning of the material in question. The exponential factor α_s is called the spatial attenuation constant and has been found to increase with the first power of frequency for many materials, so long as the wave length is greater than the grain size (4,5).

Equation [3] describes a wave whose energy W is decreasing exponentially with distance. The larger the value of α_s, the greater the pulse energy decrease for a given distance of x.

Certain structural engineering materials very closely approximate an ideal non-dissipative medium. For instance, steel has an α_s of approximately 9×10^{-3} Neper/meter at 20 kHz. This means that a wave will have lost only 2% of its energy after having traveled 4 feet.

Most geologic materials, on the other hand, readily absorb ultrasonic energy. Measurements of a sandstone core sample in our laboratory have shown an α_s of 322×10^{-3} Neper/meter at 20 kHz. Thus, an ultrasonic wave propagating through this sandstone loses energy 190 times faster than steel. Other geologic materials have similarly high energy absorption characteristics, as shown in Appendix C.

D. Ultrasonic Energy Behavior in Anchored Section of Grouted Bolt

As ultrasonic waves are delivered through a section of bolt that is unanchored, they are constrained to travel through the bolt alone. When they reach the grouted section(s) of a bolt, they will continue to travel through the bolt but at diminished energy level, since a portion of the energy will transmit through the grout. This behavior is shown in the equation:

$$\begin{aligned} [4] \qquad W &= k\{U_0 \exp[-(\alpha_s+\alpha_t)x]\}^2 \\ &= kU_0{}^2 \exp[-2(\alpha_s+\alpha_t)x] \\ &= W_0 \exp[-2(\alpha_s+\alpha_t)x] \quad . \end{aligned}$$

The factor α_t is the energy transfer constant.

Appendix A References

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10. Tarpley, W. B., Jr., and D. R. Culp, "Apparatus and Method of Monitoring Anchored Bolts", U. S. Patent Application No. 927,712 (July 24, 1978). All claims allowed July 11, 1979.

APPENDIX B

MSHA Review

Date: 7-10-81
By: R.T. Miller

Investigation EP-459

PAR NO. 0037952

SUBJECT:

Bureau of Mines
Roof Bolt Bond Tester
Permit No. 459

INTRODUCTION:

The U.S. Bureau of Mines through Mr. Ray Stateham's letter dated April 9, 1981 requested a permit for the subject Roof Bolt Bond Tester.

GENERAL DESCRIPTION:

The Roof Bolt Bond Tester was developed for the U.S. Bureau of Mines by the Energy & Minerals Research Company under contract no. J0295037.

This Roof Bolt Bond Tester uses an ultrasonic transducer for generating, transmitting and receiving the test signal. The transducer has an integral piezoelectric crystal oscillating at a rate of 20,000 C.P.S. to generate the test signal which is transmitted into the bolt being tested by placing the transducer end of the bolt tester firmly against the roof bolt flange. The transducer will transmit for a period of 1.5 millisecond after which it will be automatically switched to the receive mode. In the receive mode the transducer picks up the echoing signal through the bolt and feeds it into a signal processing circuit. Once processed the signal is basically a D.C. level that's fed into a classifier circuit. This classifier circuit will analyze the signals amplitude and switch on the appropriate LED. When their is little or no signal echo in the bolt the green LED will light indicating that the bolt is bonded securely to the roof. If the yellow LED lights this will indicate a questionable amount of signal echo and similarly a questionable bond. A questionable bond will occur if an insufficient amount of resin was installed in the bolt hole or if the resin didn't harden properly. When the red LED lights there is a large amount of signal echo present indicating that the bolt is not bonded securely to the roof.

The roof bolt tester also has a battery monitoring circuit which gives a continuous visual display of the battery pack charge condition by means of a dual red/green LED. The LED will light green if the batteries have a sufficient charge and will switch to red when the battery pack voltage falls below a preset voltage.

INTRINSIC SAFETY EVALUATION:

After reviewing the Energy & Minerals Research Company schematic drawing C10032 sheets 1 and 2 the following items were judged to affect the intrinsic safety of the instrument:

1) Rechargeable nickel- cadmium battery pack, drawing C10025

2) 20 Ω current-limiting resistor, R43 on drawing C10032 sheet 1.

3) 4.7 uf capacitor, C2 on drawing C10032 sheet 1.

The battery pack, consisting of sixteen (16) AA size, 500 mAH, nicad batteries was first tested to determine its maximum short circuit current without the 20 Ω fusible current limiting-resistor (Edison, part number R2414) in the battery pack circuit. As indicated on test sheet number 1 this battery pack was found capable of producing a maximum short circuit current of 12.22 amperes. Next the current limiting resistor was reinstalled in the battery pack and further testing was performed. With the resistor in the battery pack the current is limited to 900 mA as indicated by the red curve on test sheet number 1. Comparing the fully charged battery pack voltage of 16 X 1.4 = 22.4 volts to UL913 figure 23.1 it was found that the minimum igniting current at 22.4 volts in methane is 1.90 amps. To further ensure the safety of this battery pack it was tested using the standard I.E.C. spark test apparatus as shown on test sheet numbers 3 and 4. Test Sheet number 3 shows the results of the test with a safety factor of 1.25 times the normal battery compliment (4 additional cells) added in series with the battery pack. As indicated the test gas was not ignited during this test. Test sheet number 4 shows the results of the spark ignition test conducted with two battery packs in parallel increasing the short circuit current to 1.8 amperes. This test was stopped after 500 cycles to recharge the battery packs and reverse the polarity of the leads to the I.E.C. spark test apparatus for the remaining 500 cycles of the test. As indicated the test gas was not ignited during this test either, thus, the battery pack is judged not to be an ignition hazard in a methane-air atmosphere.

Test sheet numbers 2 and 5 show the results of the tests conducted on the 20 Ω current limiting resistor (Edison, part number R2414). Test sheet number 2 is a record of the time duration required to open the resistor when the battery pack is short circuited. As indicated it took 1.6 milliseconds to open the resistor while limiting the short circuit current to 900 mA. Test sheet number 5 shows the results of the test conducted to determine the maximum surface temperature of the resistor while dissipating approximately 1 watt. Sample number 1 was first subjected to a power level of 950 mW until the surface temperature stabilized, this was recorded at 59.4°C. This same resistor was then subjected to a power level of 1.1 watts and it opened instantly before any measurements could be taken. Sample number 2 was then subjected to 1.1 watts, it opened in 15 seconds reaching a maximum surface temperature of only 48.2°C. This resistor is judged to be suitable for its intended use as a current limiting resistor when installed in series with the battery pack. This current limiting resistor will be mounted on a 14 pin D.I.P. plug which plugs into the end of the battery pack to tie the four (4) circuits (4 cells each) of the battery pack together in series.

Capacitor C2 (Ref. Drawing C10032 sheet 1) is specified on Bill of Materials BM10032 sheet 4 to be 4.7 micro-farads, ± 20% tolerance, with an operating voltage of 35 volts. This capacitor was tested (test sheet no. 6) using the standard I.E.C. spark test apparatus with a safety factor of greater than + 20% added to the capacitors specified value. No ignition of the test gas was observed, thus, this capacitor is judged incapable of storing sufficient electrical energy to ignite a methane-air mixture either alone or if a short should occur in VR-1 from pin 11 or 12 to pin 3 placing the capacitor in parallel across the battery pack.

After this test was conducted an additional margin of safety was discovered. The compressed air used in the methane-air mixture was found to contain 27% oxygen making this methane-air mixture more ignitable than a standard methane-air mixture with 21% oxygen in the compressed air.

All other components, assemblies and combinations of components are judged not to be potential ignition hazards.

CONCLUSION:

The subject Roof Bolt Bond Tester meets all applicable requirements of 30 CFR Part 18.

A permit letter granting Permit No. 459 and dated July, 1981 was issued to the U.S. Bureau of Mines covering the subject Roof Bolt Bond Tester.

A copy of this letter is filed as Data Sheet 9.

A copy of the drawing list applying to this permit is filed as Data Sheet 6.

Data Sheet 10, are photographs showing the Roof Bolt Bond Tester.

FEES:

The total charge for the investigation was $00.00.