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# Evaluation of Nondestructive Test Instruments for Wire Rope

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UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| cm | centimeter | lb | pound |
| ft | foot | m | meter |
| ft/min | foot per minute | mm | millimeter |
| hp | horsepower | m/min | meter per minute |
| in | inch | mm/s | millimeter per second |
| kg | kilogram | m/s | meter per second |

# EVALUATION OF NONDESTRUCTIVE TEST INSTRUMENTS FOR WIRE ROPE

By G. L. Anderson,[1] T. M. Ruff,[2] and P. F. Sands[3]

## ABSTRACT

The critical importance of wire rope integrity to the mining industry has led to the creation of standards for the retirement of wire rope as well as to the development of electromagnetic devices and procedures that would allow wire ropes to be tested against these standards without destroying them. The U.S. Bureau of Mines (USBM) conducted research to evaluate these devices by measuring loss of metallic cross-sectional area and the number of wire breaks, or local faults. The intent was to define the extent to which the technique can identify degradation within the rope, e.g., broken wires, corrosion, and wear.

Experimental results showed that instrument sensitivity depended on a number of factors, including rope diameter, placement of sensors, location and characteristics of flaws, rope speed, and tension on the rope. The experiments also demonstrated the importance of having an elongated recorder trace and a properly trained and experienced operator to interpret overall results.

A design of a rope and test procedures for use in laboratory evaluation of instruments have been recommended by the American Society for Testing and Materials Committee E07.07.10, Wire Rope Applications. The USBM is working through this committee to develop standards for an electromagnetic method of wire rope inspection.

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# INTRODUCTION

The widespread use of wire rope throughout the mining industry, especially for critical functions such as personnel hoisting, has prompted the U.S. Bureau of Mines (USBM) to investigate methods of assuring that such ropes are safe. Visual methods of inspection have been found to be unreliable. Routine retirement without inspection is too costly because some ropes are retired before they are worn or corroded. However, nondestructive testing (NDT) devices have shown considerable promise for ensuring safety while extending usable rope life. These devices saturate a rope with a magnetic field, then sense any disruptions in this field caused by structural anomalies in the rope.

Standards for conducting the inspection, as well as judging the accuracy and reliability of nondestructive test results, are needed before these tests can be used reliably in the mining industry. Thus, the USBM initiated an experimental program that would provide the foundation for developing test standards for these devices. Experiments were run on eight commercially available instruments to determine each instrument's sensitivity to a number of factors, including rope diameter, location of sensors within the test instrument, flaw characteristics, rope speed, chart speed, and rope tension. This work follows other studies comparing electromagnetic NDT instruments (Corden, 1980).

# BACKGROUND

Locating broken wires and other anomalies is difficult in a rope that may be thousands of meters long. Before the advent of electromagnetic testing, only the exterior of the rope could be inspected, and then only visually. Visual inspections could be enhanced by wrapping a rag around the rope and snagging broken wires protruding from the surface. Besides being hazardous to the inspector, this method is deficient because not all broken wires protrude from the surface, and internal corrosion, no matter how severe, can go unnoticed.

The electromagnetic method enhances the thoroughness of an inspection by detecting broken wires or other local faults (LF) and losses in metallic cross-sectional area (LMA). The method can detect LF and LMA that occur on a rope surface and within the interior of a rope, and can do this at rope speeds up to 122 m/min (400 ft/min).

Even though electromagnetic NDT is the best available method for determining the overall condition of a rope, there is uncertainty as to the method's reliability. This is because test instruments differ from one another to some degree, as do the procedures and capabilities of different operators. Reliability is imperative, particularly when deciding when a rope should be replaced because enough metallic cross-sectional area has been lost or enough wire breaks are present to make the rope unsafe.

Replacing a rope is known as rope retirement. Retiring a rope at the proper time requires retirement criteria. Effective criteria depend on, among other things, an accurate understanding of the capabilities of the instruments and good inspection procedures. Also, both the instruments and the procedures require standardization.

Of major concern is the Code of Federal Regulation 30 CFR 57.19024, which requires that a rope be retired when it has lost 10 pct or more of its strength. Determining this figure requires correlating LF and LMA with strength loss; this correlation has been difficult to define because, while LMA relates to strength loss, the relationship is not linear. For example, corrosion weakens a wire rope, but the exact degree of weakening cannot be estimated simply from LMA.

Another concern with electromagnetic NDT is the difficulty in interpreting the results. Results are displayed as a trace on a continuous strip chart. An experienced interpreter usually can explain the trace more accurately than can a less experienced interpreter. Sometimes even two experienced interpreters may provide different perceptions of the same trace, because the type and quality of their experiences may vary.

# TEST PROGRAM

## DESCRIPTION OF ELECTROMAGNETIC NDT INSTRUMENTS

Various electromagnetic NDT instruments for wire rope have been built in the United States and abroad, and some are commercially available. The variety of the instruments stems, in part, from the variety of sizes and uses of wire rope, i.e., ropes for cranes and elevators, stationary support ropes, anchor ropes, mine hoist ropes, and larger diameter cables used as draglines in surface mining.

Differences are also a result of the unique design and capabilities of each manufacturer's instrument, including various methods of magnetization, differing sensors for measuring the magnetic field, and differing processing electronics. However, all instruments include the same basic equipment: a sensor head, an electronics console, and a data-recording unit. Figure 1 illustrates the basic components of an NDT instrument.

The sensor head of an instrument is hinged and clamps around the wire rope (figure 2). All instruments introduce a magnetic field in the wire rope as the rope passes through the sensor head. The magnetic field is then measured (sensed) from within the head. Methods of magnetizing the wire rope vary from instrument to instrument. The newer instruments use rare-earth permanent magnets to saturate the rope with a magnetic field; one older instrument uses electromagnetism. Most instruments have a means of testing different rope sizes by placing inserts in the sensor head. Others have a different sensor head for different ranges of rope diameter. The sensor heads may vary from 15 cm (6 in) long and 2.3 kg (5 lb) in weight to over 46 cm (18 in) long and 45.4 kg (100 lb) in weight.

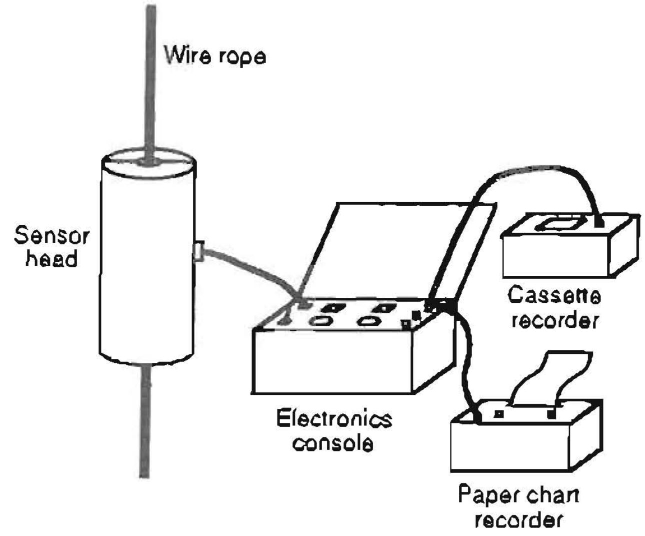

Figure 1.—Typical components of NDT instrument.

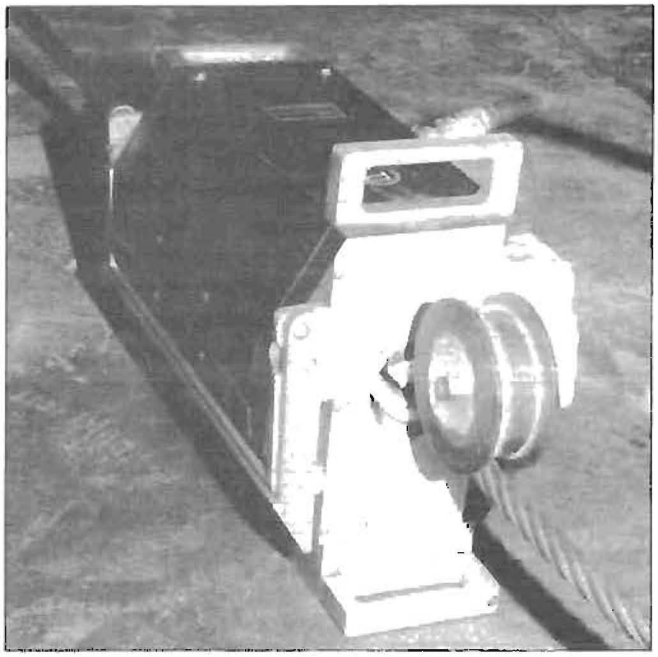

Figure 2.—Head of typical test instrument.

Some instruments test for either LF or LMA and others test for both. Instruments that record LF and LMA simultaneously have become more popular than those measuring only one or the other. The LF signal from a magnetized broken wire can be detected as a fringing magnetic field that extends beyond the surface of the wire rope (Rotesco, Ltd., 1988). Most instruments use sensors mounted within the sensor head to detect these fringing fields as the LF signal. To detect changes in the wire rope's LMA, sensors measure the total flux contained in the rope as it passes through the magnets of the sensor head. This measurement is based on the principle that, at magnetic saturation, the magnetic flux within the rope is proportional to its metallic cross-sectional area. Different instruments use different sensors at different locations within the sensor head to measure LF and LMA.

There are various types of sensors used to detect LF and LMA. For instance, pairs of differential coils are used to detect the fringing magnetic field of a broken wire (figure 3). The coils encircle the wire rope as the sensor head is closed. Each coil scans 180° of the rope's circumference. Voltage is induced across the leads of the coil if a changing magnetic flux passes through it (shaded

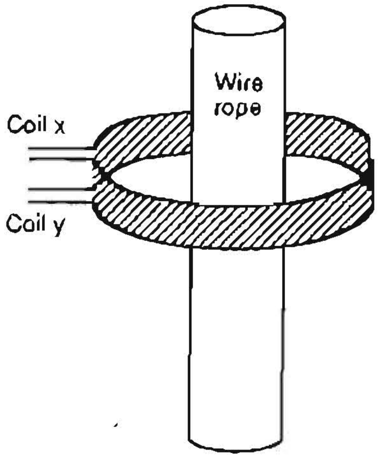

Figure 3.—Differential coils.

area of figure 3). The changing magnetic flux is accomplished by the movement of a steady flux relative to the coil. As the fringing flux lines of a broken wire pass through the coils, voltage is induced across their leads, providing a raw LF signal.

Flux gate sensors measure total magnetic flux. A flux gate sensor consists of a core of magnetic material surrounded by a pickup coil. When the sensor is placed in a varying magnetic field along the core-coil axis, a varying magnetic flux is produced in the core, changing the core's permeability and inducing a voltage in the pickup coil proportional to the changing magnetic flux (figure 4) (Primdahl, 1973). These sensors are placed in the path of the magnetic flux as it returns to the magnet, as shown in figure 5. As the wire rope is magnetized and passed through the sensor head, the magnetic flux passes from the north pole of the magnet to the wire rope. It then passes along the wire rope and back to the south pole of the magnet. Since magnetic flux prefers steel to air, the flux passes directly from the rope, through the flux gate sensor, and to the south pole of the magnet, completing the magnetic circuit. The total flux measured by the sensor is then recorded as the raw LMA signal.

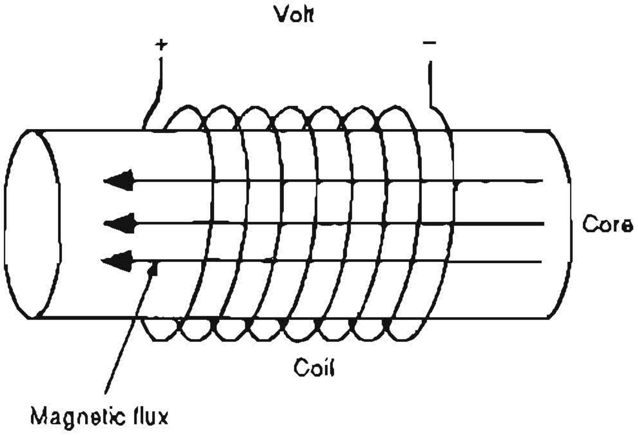

Figure 4.—Flux gate sensor.

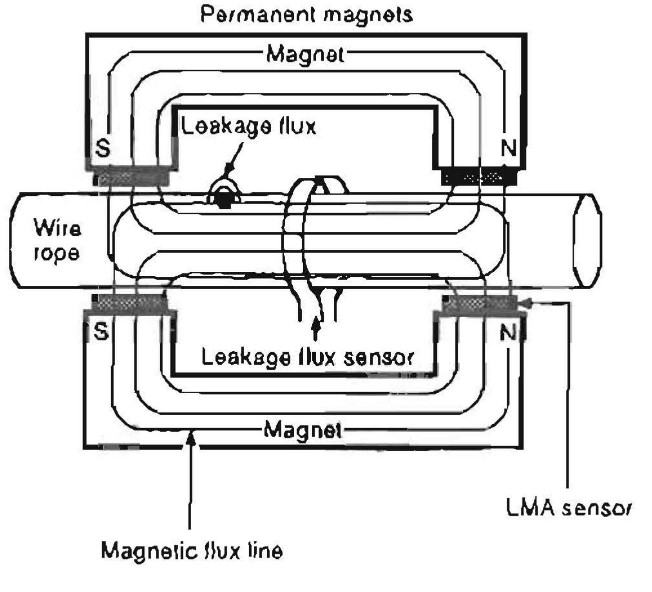

Figure 5.—Sensor configuration of Rotescograph test instrument. Instrument A.

Hall sensors are also used to measure LMA and LF. Hall sensors are semiconductor devices utilizing the Hall effect, described as follows: If a conductive material is placed in a magnetic field parallel to its y-axis and a current is allowed to flow through the material along its x-axis, then an electric field will be induced along the z-axis. This electric field will be proportional to the magnetic flux flowing through the device and is measured as output voltage (Hayt, 1981). Figure 6 illustrates this effect. Hall sensors are placed in the center of the sensor head to measure the fringing fields of broken wires. They are also placed at the poles of the magnets and the wire rope to measure the return flux for LMA measurements (see figure 7). Unlike sensors that measure the output voltage of coils in magnetic fields, Hall sensors do not rely on a time-varying field to produce output voltage. Hence they are not sensitive to the speed at which a rope is traveling through the sensor head, and an instrument using these sensors does not require speed compensation (Kitzinger and Naud, 1979).

Another type of sensor measures LMA by measuring the total flux within the wire rope directly (figures 8 and 9*B*). This sensor uses a hinged coil that wraps completely around the rope being tested to create a voltage proportional to the time-varying magnetic flux within the rope and, therefore, within the coil. The flux within the rope is proportional to the rope's cross-sectional area. This sensor differs from the other LMA sensors in that it measures magnetic flux directly, not the return flux as it passes through the gap between the wire rope and the magnet (Weischedel and Ramsey, 1989).

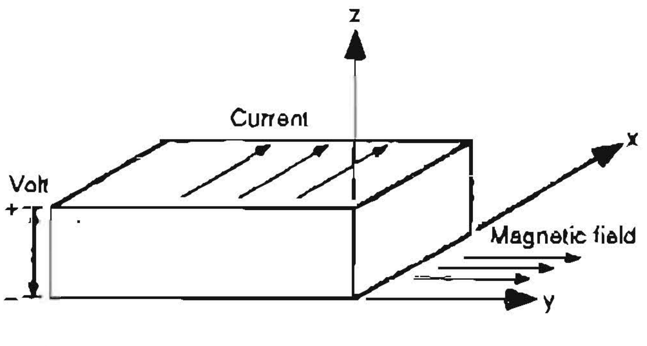

Figure 6.—Relationship between magnetic field and current using Hall device.

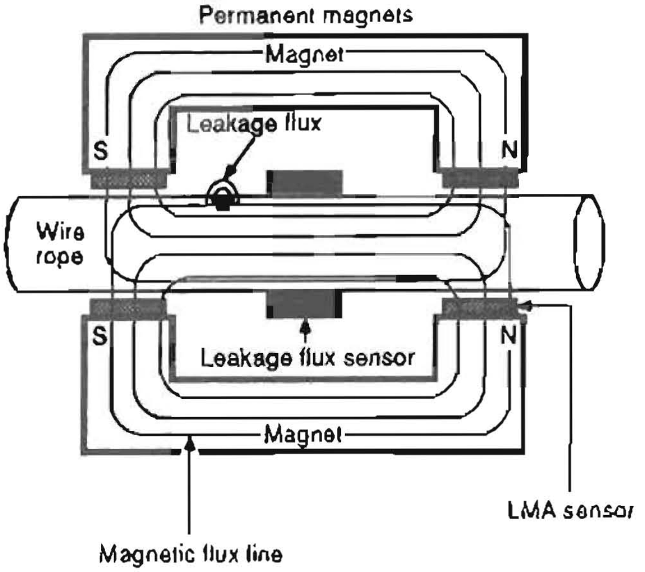

Figure 7.—Hall sensor configuration of Magnograph NDT instrument. Instrument B.

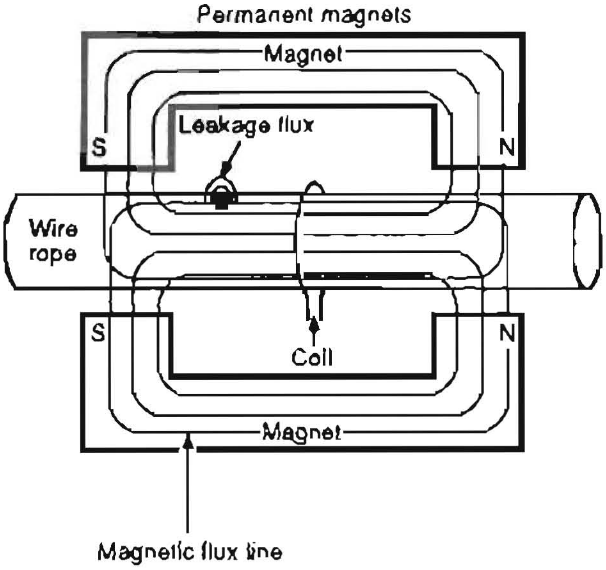

Figure 8.—Sensor configuration of LMA 250 and LMA 75 NDT instruments. Instruments C and D.

The raw signal data obtained from all sensors are processed and enhanced in the electronic console of the instrument for recording on a strip chart for analysis. Most recording devices use a pen and ink or thermal trace on a paper chart recorder, while others indicate anomalies in the rope with an audible signal transmitted through headphones. Some instruments even sound an alarm and automatically mark the wire rope with paint at the location of the anomaly (these types of instruments were not studied). Most of the instruments allow the signal to be recorded on

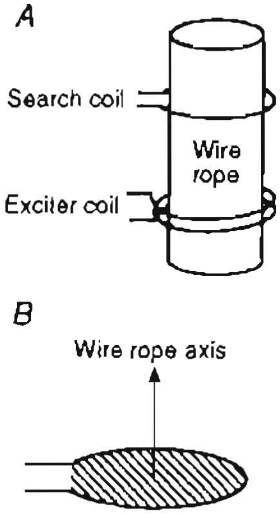

Figure 9.—Configuration of alternating current-type instrument. A, Coil configuration; B, search coil active plane.

a tape recorder so the results can be analyzed later or transferred to a computer.

The paper chart recorder is the most familiar and popular means of displaying data. The horizontal centerline of the signal trace can be moved up and down to zero the instrument, and the trace can be elongated or heightened to aid in its study. While the height of a recorded spike from an LF anomaly has no quantifiable significance, its relative magnitude, when compared to rope noise, indicates a break in a wire. The LMA signal can be quantified by calibrating the instrument on a new section of the rope and comparing the worn or corroded section to it. Variations in the LMA trace can then be quantified as a percentage of the decrease in cross-sectional area.

Figure 10 shows typical responses to common anomalies.[4] On the left, corrosion is the principal cause of the 2.8-pct loss in LMA. Missing wires of different lengths are shown, two being accompanied by a broken wire. Corrosion is depicted both as a loss in cross-sectional area on the LMA trace and as an increased height on the LF trace. Unfortunately, not all instances of LMA and LF are shown as clearly as on this trace.

## INSTRUMENTS INVESTIGATED BY U.S. BUREAU OF MINES

Seven different instruments built by three different American and Canadian companies were obtained for the tests. Together, these instruments could inspect ropes from 1.9 to 6.2 cm (3/4 to 2-1/2 in) in diameter. Four

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[4] Although the USBM now uses metric units, these tests were conducted using US customary units.

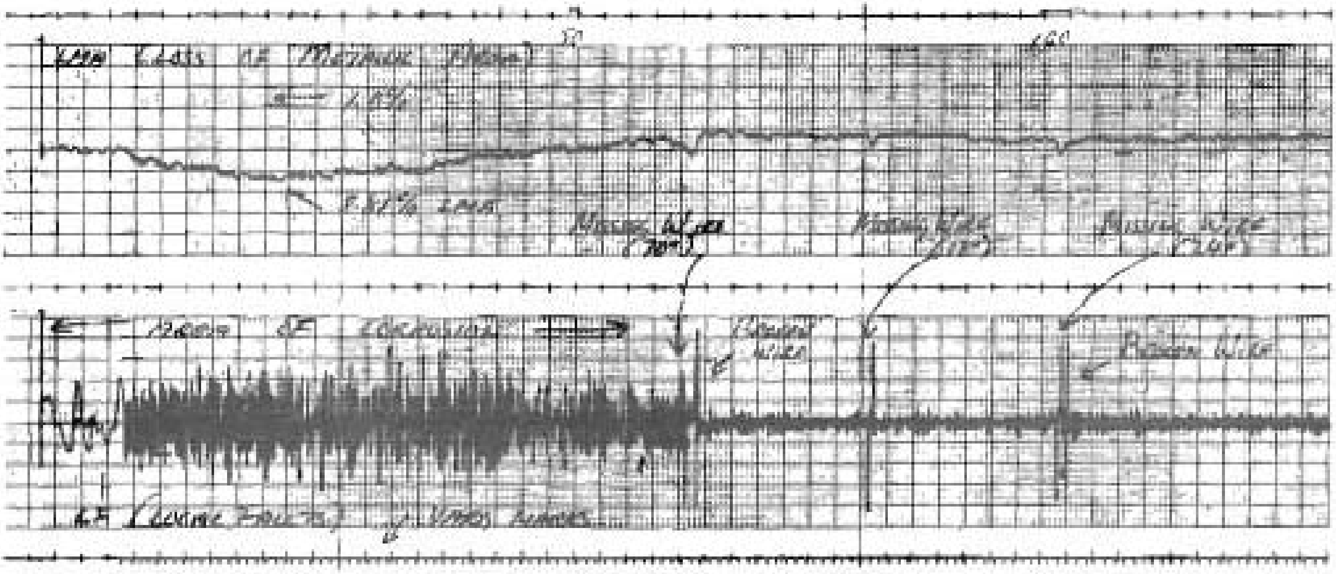

Figure 10.—Sample field trace.

detected LF and LMA, and three were designed for either LF or LMA only. Each instrument has been improved in later models; therefore, the instruments tested do not represent the latest technology. One instrument, which was designed for 1.9 cm (3/4 in) in diameter rope, would not fit around the 1.9-cm (3/4-in) test rope and was dropped from the program.

### Instruments A and B

These two instruments, built by Rotescograph[3] (instrument A) and Magnograph (instrument B), are similar in most respects (figures 5-7). They both use permanent magnets to magnetically saturate the wire rope, and they measure the return flux to obtain the LMA where it leaves the rope and enters the head of the magnet. Both instruments detect the LF signal using a separate sensor located between the poles of the magnets. The principal difference in the instruments is in the types of sensors used. Instrument A uses flux gate sensors to measure the return flux for LMA and differential coils to measure LF. Instrument B uses Hall sensors to measure LMA and LF (Kitzinger and Naud, 1979).

### Instruments C and D

As with instruments A and B, instruments C and D (LMA 250 and LMA 75) use permanent magnets to magnetize the wire rope. Instruments C and D differ from one another only in their size. They both differ from instruments A and B in that they use split sensor coils wrapped around the wire rope to measure the flux within the rope rather than the return flux at the gap between the rope and the poles (figure 8). The output from this coil is conditioned to provide the LF signal. This signal is then integrated to obtain the LMA signal (Weischedel and Ramsey, 1989). Instruments C and D inspect ropes up to 6.2 and 1.9 cm (2-1/2 and 3/4 in) in diameter, respectively.

### Instruments E and F

These two instruments measure LF only. Both instruments use differential coils placed around the wire rope to measure leakage flux resulting from broken wires (figure 3). The two instruments are similar in most respects to instrument A, but the flux gate sensors have been removed. Instrument E is compact and can be hand held. It is mainly used for inspecting small ropes such as those used on elevators. Instrument F is an early version of electromagnetic test instruments and is not used extensively.

### Instrument G

This instrument operates using a single, hinged search coil that measures magnetic flux directly. The configuration is different from other instruments in that magnetization involves an electromagnet rather than permanent magnets (figure 9). An alternating magnetic field is applied to the wire rope by a two-turn Helmholtz coil. The principle is that of a simple transformer. A hinged

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[3] Reference to specific equipment or trade names does not imply endorsement by the U.S. Bureau of Mines.

search coil wraps around the rope and acts as a secondary winding with the wire rope as the ferrous core. Changes in cross-sectional area of the wire rope from wear or corrosion cause changes in the magnetic flux, which induces voltage in the search coil that can be measured as LMA. The voltage signal has an amplitude component that corresponds to the LMA signal and a phase component that corresponds to the magnitude of the eddy currents. Eddy currents are electrical currents induced in the wire rope as a result of the rope's immersion in an alternating magnetic field. The eddy current measurement can be used by a trained eye to distinguish between corrosion and wear (Poffenroth, 1983).

## TEST DESIGN

### Test Fixture

The fixture shown in figure 11 and described in table 1 was built and operated at the USBM to evaluate the accuracy of test instruments. Test ropes were made by adding artificial anomalies to 17.4-m (57-ft) lengths of rope, and then joining the ends together with hooks to make a continuous loop. Rope speeds from 24 to 122 m/min (80 to 400 ft/min) were obtained by placing the loop over three sheaves, one of which was driven by a motor with a speed control. The sheaves were arranged to provide areas for both vertical and horizontal orientation of the instruments, and one sheave could be adjusted to provide the tension needed to hold the rope on the sheaves. As the rope traveled over the sheaves, it rotated about its longitudinal axis, duplicating the different rope-to-pickup coil orientations characteristic of actual field inspections.

Table 1.—Test fixture specifications

| Description | Specifications |
|---|---|
| Power system | 3/4-hp motor, reducer, clutch-brake, tachometer. |
| Structure | 4.1 by 8 cm (1-5/8 by 3-1/8 in) slotted angle. |
| Sheaves | 1 m (42 in) in diameter cartwheels; 3-cm (1-3/16-in), self-aligning, pillow-block bearings. |
| Sheave liners | 60 durometer rubber, 3.8 cm (1-1/2 in) thick, bonded to cartwheel tread, grooved to 3.5 cm (1-3/8 in) in diameter. |
| Control | Controller with on-off, run-jog, forward-reverse, start-stop speed regulation and emergency stop buttons. |
| Speed regulation | 24- to 122-m/min (80- to 400-ft/min) rope speed. |
| Rope tension | Screw jack with load indicator. |

In addition, a straight, 11-m (35-ft) length of rope was mounted in a large tensile testing machine (figure 12). The rope was placed under tensions similar to those found in the field, and the instruments were moved along the stationary rope, as opposed to the rope moving through the instrument.

### Design and Preparation of Test Ropes

To study the instruments under controlled conditions, test ropes were made by adding simulated anomalies to new ropes. The purpose was to simulate broken wires and reductions in cross-sectional area, and then to locate and measure these anomalies using the electromagnetic instruments.

The length of a discernible gap is important because the smaller the gap that a NDT instrument can detect, the sooner this rope-weakening condition can be identified. In a production installation, the adjoining ends of a broken wire separate from one another as the rope flexes over the sheave while under load. The more the separation, the more the electromagnetic field of an electromagnetic test device is disrupted by the gap and the ends of the wire, until the disruption is discernible above the characteristic noise on the trace. The ideal method of simulating these gaps is to actually remove short pieces of wire by grinding or cutting. This is difficult and time consuming, especially if the piece is removed from the interior of the rope.

It was reasoned that the NDT instrument would react in the same manner to any abrupt change in cross section, whether it was an addition or a subtraction of wire. Given this, short lengths of wire could be simply added to the interior and exterior of a rope and results similar to those of an actual gap obtained. However, after various configurations of rope and methods of simulation were tested, it was found that simply adding wire did not accurately simulate a gap. Therefore, new test ropes were constructed with short sections of the rope's wires removed to simulate actual anomalies more accurately. Considerable data have been obtained using the added wires and are reported here where valid. The wires were added either to the surface of the rope in the valleys between the strands, or inside the rope under the outer strand. Gaps were either produced in the outside of the rope using the crown wires or in the inside of the rope using the wires under the strand. Crown wires are the outer wires of the outer strands.

When the hooked ends of the rope passed through the instrument, the magnetic field was violently distorted. For this reason, anomalies were placed at least 1.2 m (4 ft) from the ends. For similar reasons, the anomalies were placed at least 46 cm (18 in) apart.

Figure 13 shows the length and location of the simulated anomalies and table 2 shows the test rope diameters and constructions. Some of the test-rope characteristics result from recommendations made by the E07.07.10, Wire Rope Applications Section, of the American Society for Testing and Materials.

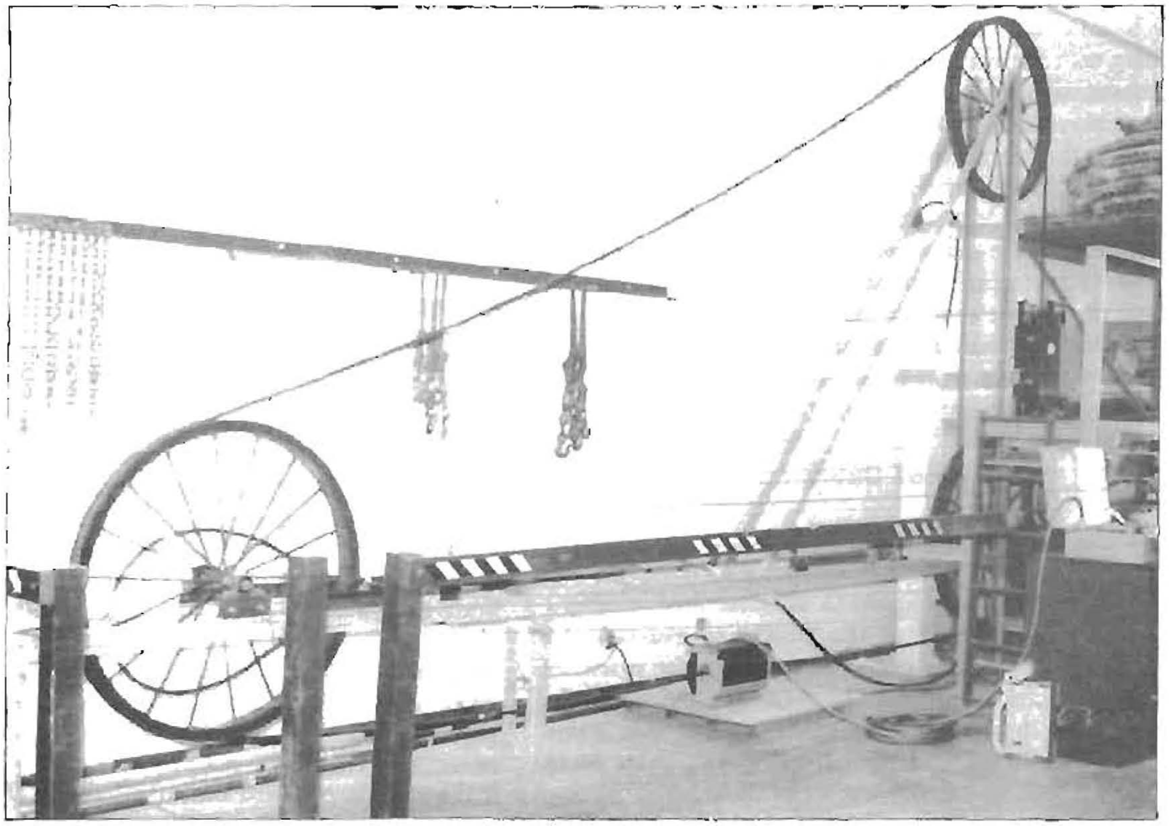


Figure 11.—NDT instrument fixture.

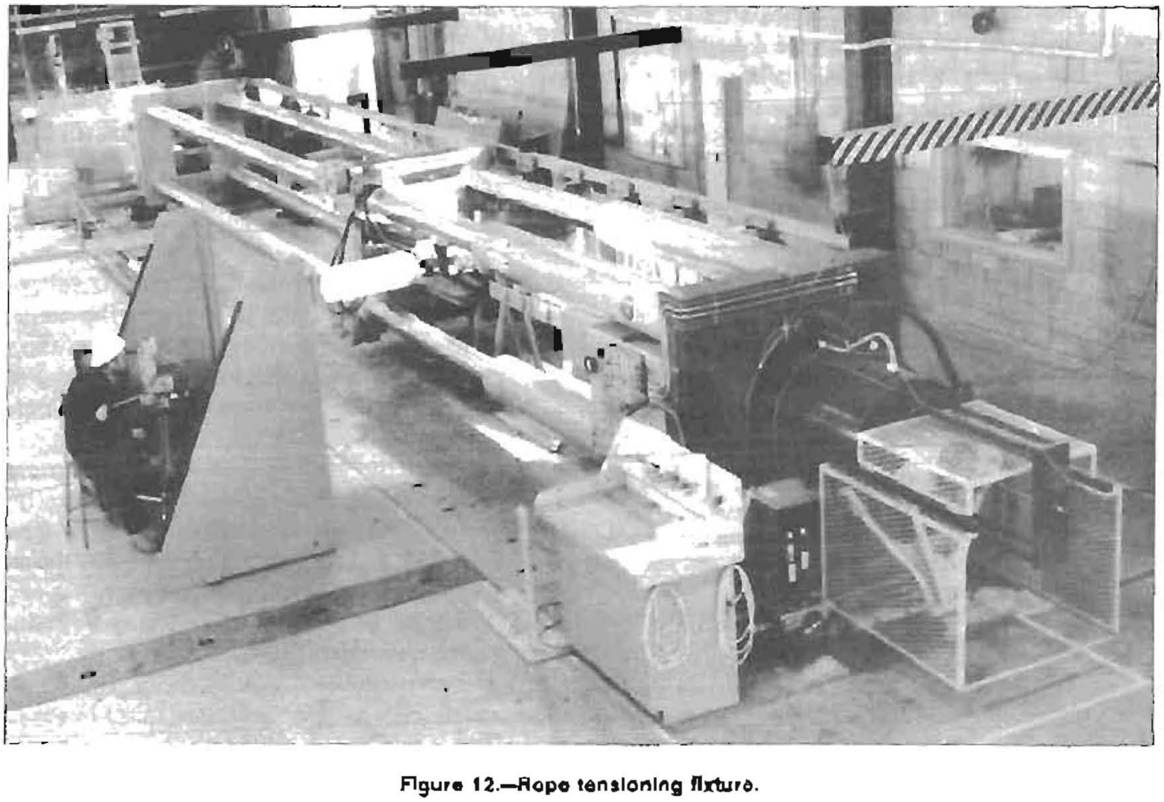
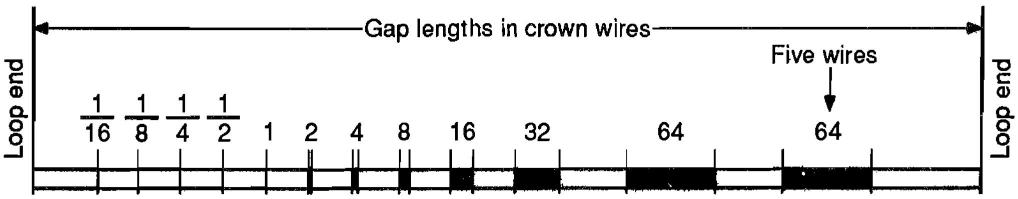
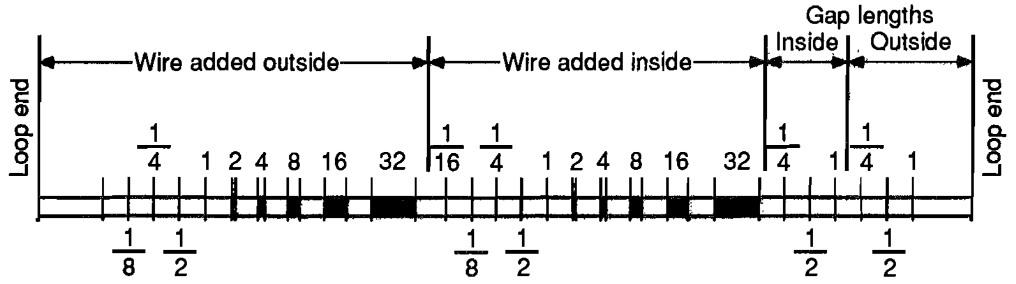


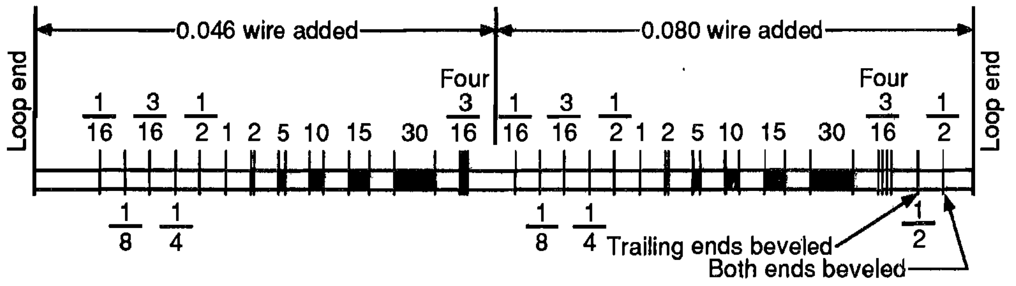
Figure 12.—Rope tensioning fixture.



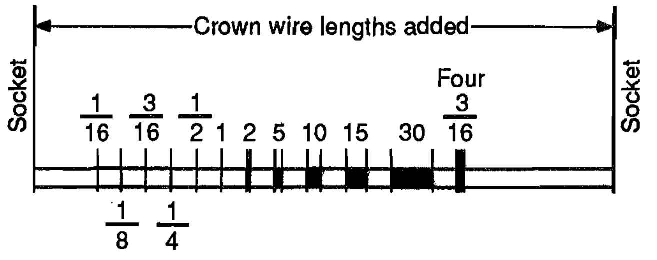
Rope no. 5: 3/4–in–diam 6x25 FW, RRL
Rope no. 6: 1–1/2–in–diam 6x19 Seale, IWRC, RRL



Rope no. 3: 3/4–in–diam 6x25 FW, RRL
Rope no. 4: 1–1/2–in–diam Seale, IWRC, RRL



Rope no. 2: 3/4–in–diam 6x25 FW, RRL



Rope no. 1: 1–1/2–in–diam 6x25 FW, FC, RLL
2–in–diam 6x25 FW, FC, RRL

**Figure 13.—Test rope descriptions and location of artificial anomalies, inches.** ***A*****, Rope 1, added pieces of crown wire;** ***B*****, rope 2, added wires;** ***C*****, ropes 3 and 4, added 1.2 mm (0.048 in) in diameter wires and gaps;** ***D*****, ropes 5 and 6, gaps in crown wires. Terms: FW = filler wire; RRL = right regular lay; IWRC = independent wire rope core; FC = fiber core; RLL = right lang lay.**

Table 2.—Diameter and construction of test ropes

| Rope | Diameter |  | Construction |  |
|---|---|---|---|---|
|  | cm | in | 6 × 19 IWRC | 6 × 25 FW FC |
| 1 ...... | 3.8 | 1-1/2 | Seale | X |
| 2 ...... | 1.9 | 3/4 |  | X |
| 3 ...... | 1.9 | 3/4 |  | X |
| 4 ...... | 3.8 | 1-1/2 | X |  |
| 5 ...... | 1.9 | 3/4 |  | X |
| 6 ...... | 3.8 | 1-1/2 | X | X |

IWRC = independent wire rope core. FW = filler wire. FC = fiber core.

NOTE.—All test ropes are right regular lay except rope 1, which is right lang lay.

Some tests were made in search of procedures and equipment that would increase the efficiency of the testing. For example, it was thought that by inserting a wire rope inside a metal pipe, the combined metallic cross section would simulate the cross section of a larger diameter rope. If so, one test rope and various steel pipes could be used to simulate different diameters of rope. A rope with artificial anomalies was inserted through a 2.5 cm (1 in) in diameter pipe in an attempt to simulate a 3.2 cm (1-1/4 in) in diameter rope, but the method was not successful; stray magnetic fields were created and, in some cases, even the polarity changed. Underbakke and Haynes (1982) reported that beveled wire ends create a larger effect than do square-end wires. In rope 2, two 1.3-cm-(1/2-in-) long wires, 2 mm (0.08 in) in diameter, were added to the rope surface. One was tapered on one end, the other tapered on both ends. The results of several tests showed that the shape of the wire break had no effect on the signals.

## Test Procedures

A rope was mounted on the sheaves, the instrument test head was clamped around the rope in either a horizontal or vertical position, and the motor control was set to the desired rope speed. As the simulated anomalies passed through the instrument, the speed of the recorder strip chart and the height of the trace were calibrated and set. Instruments were operated according to the manufacturer's instructions. Tests were done at 24, 61, and 122 m/min (80, 200, 400 ft/min).

Evaluation of NDT traces involves judgment on the part of the evaluator. For this reason, during earlier test programs (Corden, 1980; Geller and Udd, 1991), qualified commercial operators were employed to operate the instruments and to interpret the traces. However, these operators were not always available throughout the total test program and changing operators confused the results. The long-term nature of the USBM's program further exacerbated the problem. In addition, a goal was to determine whether relatively inexperienced operators, such as mine personnel, could evaluate NDT results. Therefore, the tests were done and the results evaluated by inexperienced USBM project personnel.

The results were organized using computer spreadsheets. The percentages of change in metallic cross-sectional area as measured on the strip chart were entered into tables. Because the actual change in cross-sectional area could be calculated knowing the cross sections of both the rope and the added wire or gap, the accuracy of the measured LMA was calculated as a percentage of actual cross-sectional area removed from the rope. Two different investigators made independent evaluations of the traces.

Inaccuracies in measuring LMA are inherent in the physical dimensions of the trace. As is customary, LMA was obtained from measuring the drop from the highest part of the trace, which is usually recorded at a section of the rope having no wear or corrosion. A small difference in this peak measurement can represent a large LMA because of the narrow width of the chart paper. This limits the extent that the signal can be expanded vertically to increase the sensitivity. All LMA traces in this study were run at a scale where one major division of 0.5 cm (0.2 in) was equal to 1 pct LMA, or a maximum chart range of ±5 pct LMA. Therefore, the smallest readable difference in LMA was one-half of a small division, or 0.1 pct LMA. This is important when interpreting figures 14 through 18. In figure 18, an apparently large 12-pct difference in LMA accuracy actually represents only a minimum readable value of 0.1 pct LMA.

LMA accuracy is defined here as the percentage of actual physical loss that the instrument was able to detect. However, an outer wire of a 1.9 cm (3/4 in) in diameter rope (a portion of which was removed for the tests) represents only 0.79 pct of the metallic cross-sectional area of a 6 × 25 FW rope, or four small divisions on the chart. Given that the minimum readable division is one-half of one small division, or one-eighth of the cross-sectional area of the outside wire, the minimum readable difference in LMA accuracy is one in eight, or 12 pct.

The traces presented here were all obtained using different instruments. However, the conclusions are generally true for all instruments tested. Also, to aid the reader in studying the traces, the simulated anomalies were aligned directly above the trace. Wherever practical, the LMA trace was included along with the LF trace because viewing both together often aids in interpretation.

For the tests done in the tensile machine, the instrument was moved along the rope by hand at about 64 m/min (210 ft/min).

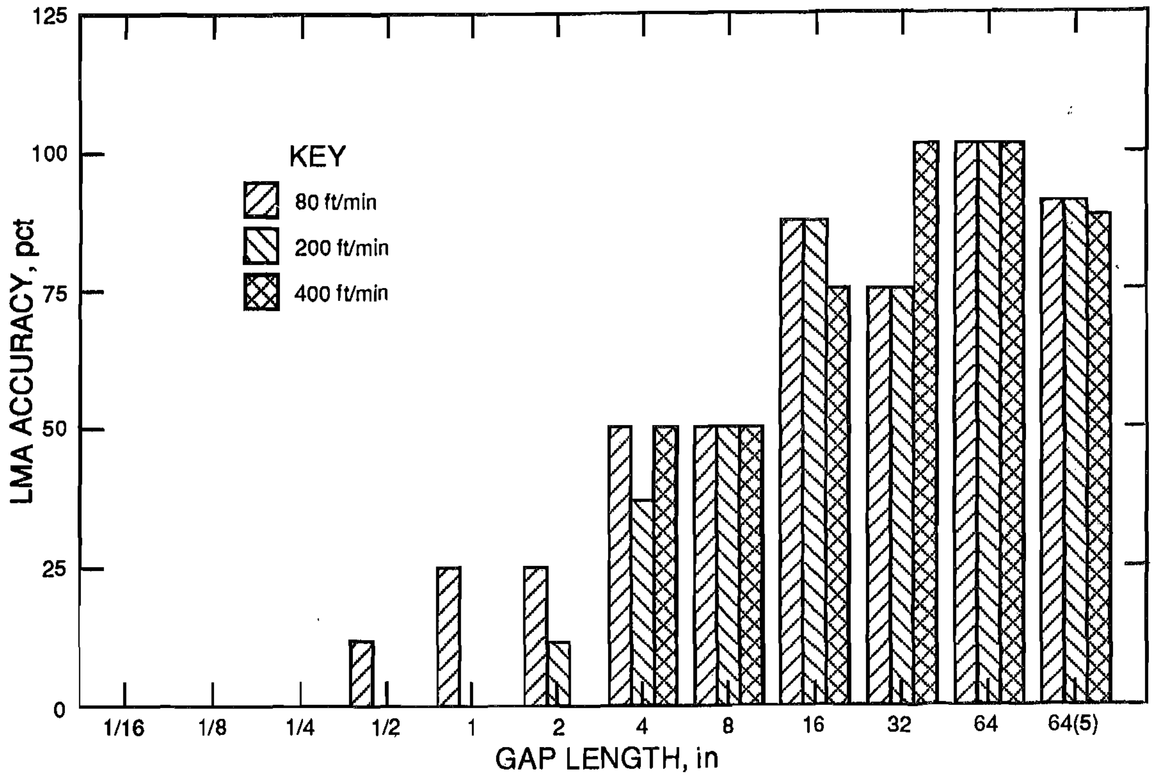


Figure 14.—Effects of gap length and rope speed on accuracy of LMA measurements (instrument A, rope 5).

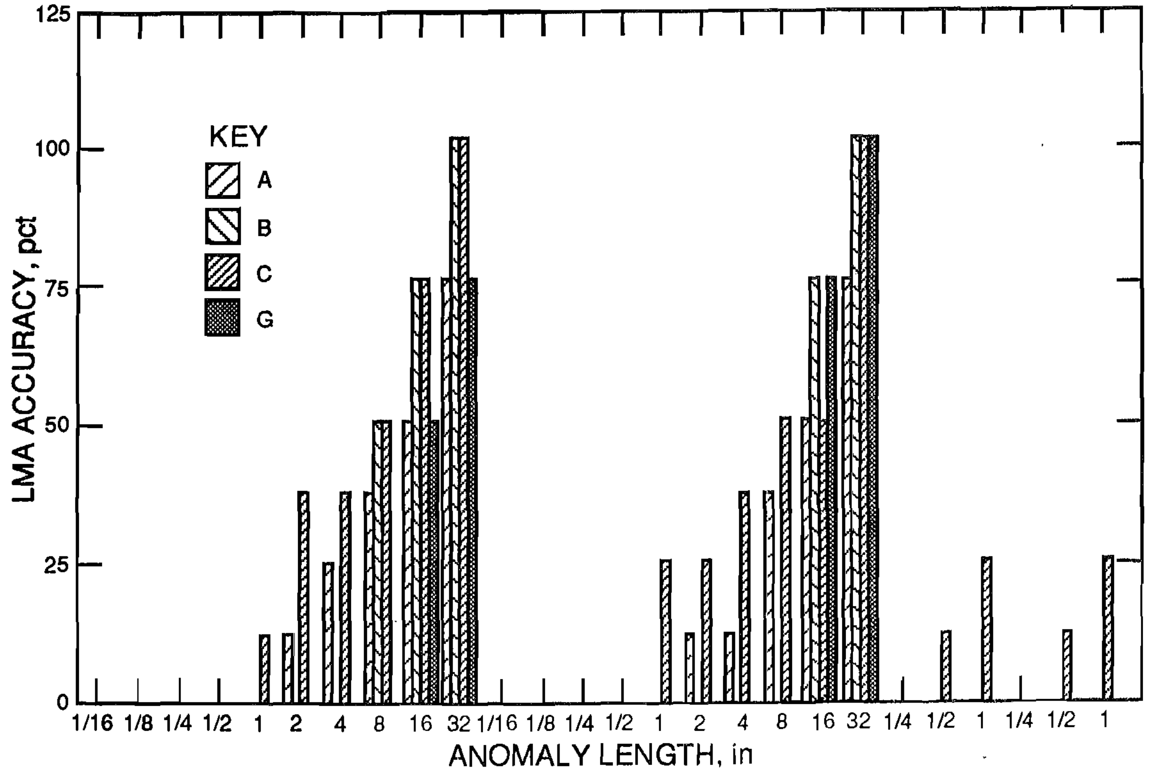


Figure 15.—Effects of gap length and added wires on accuracy of LMA measurements (instruments A, B, C, and G, rope 3).

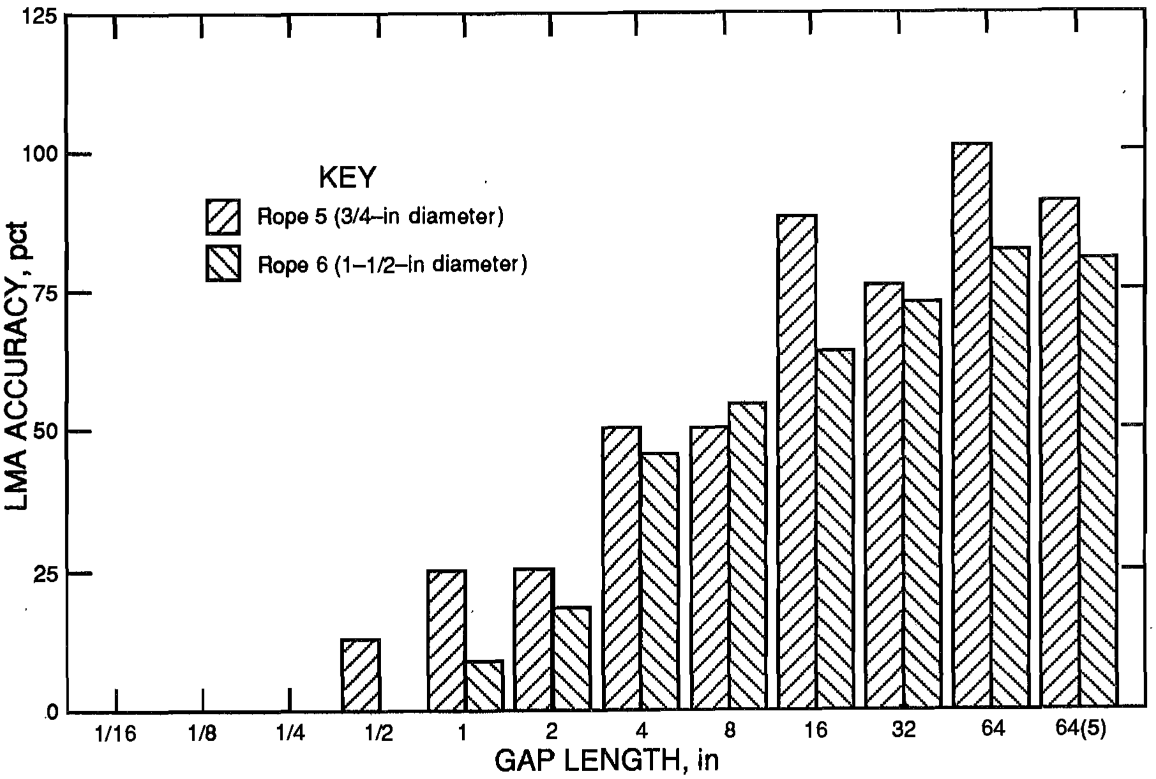


**Figure 16.—Effects of rope diameter on accuracy of LMA measurements [Instrument A, ropes 5 and 6, medium head, rope speed = 24 m/min (80 ft/min)].**

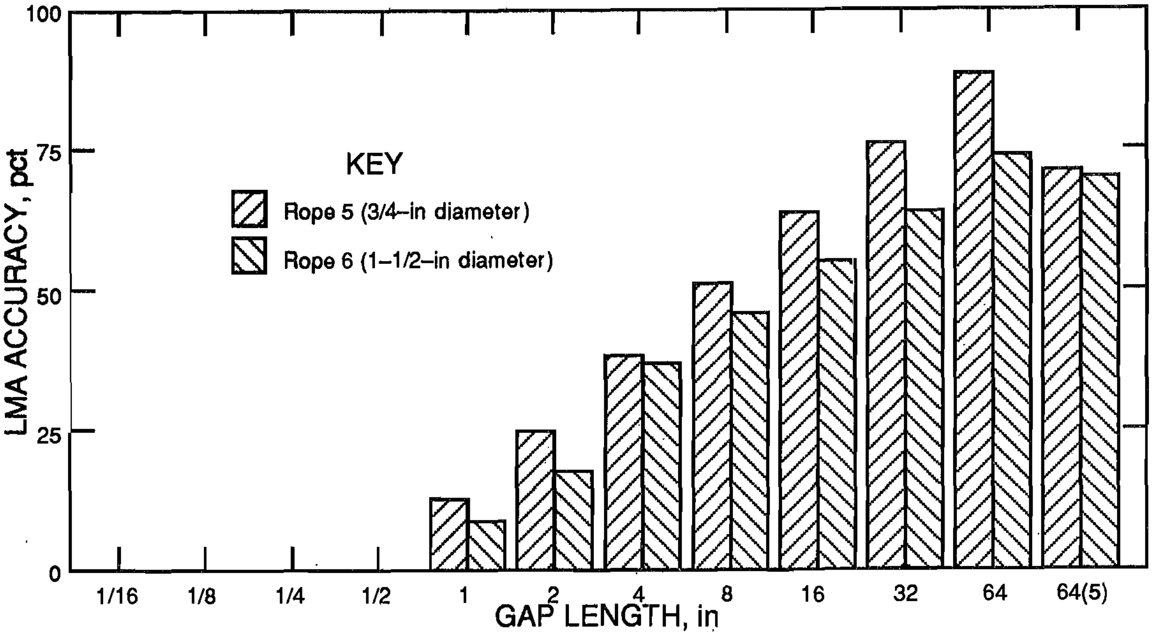


**Figure 17.—Effects of rope diameter on accuracy of LMA measurements [Instrument B, ropes 5 and 6, large head, 24 m/min (80 ft/min)].**

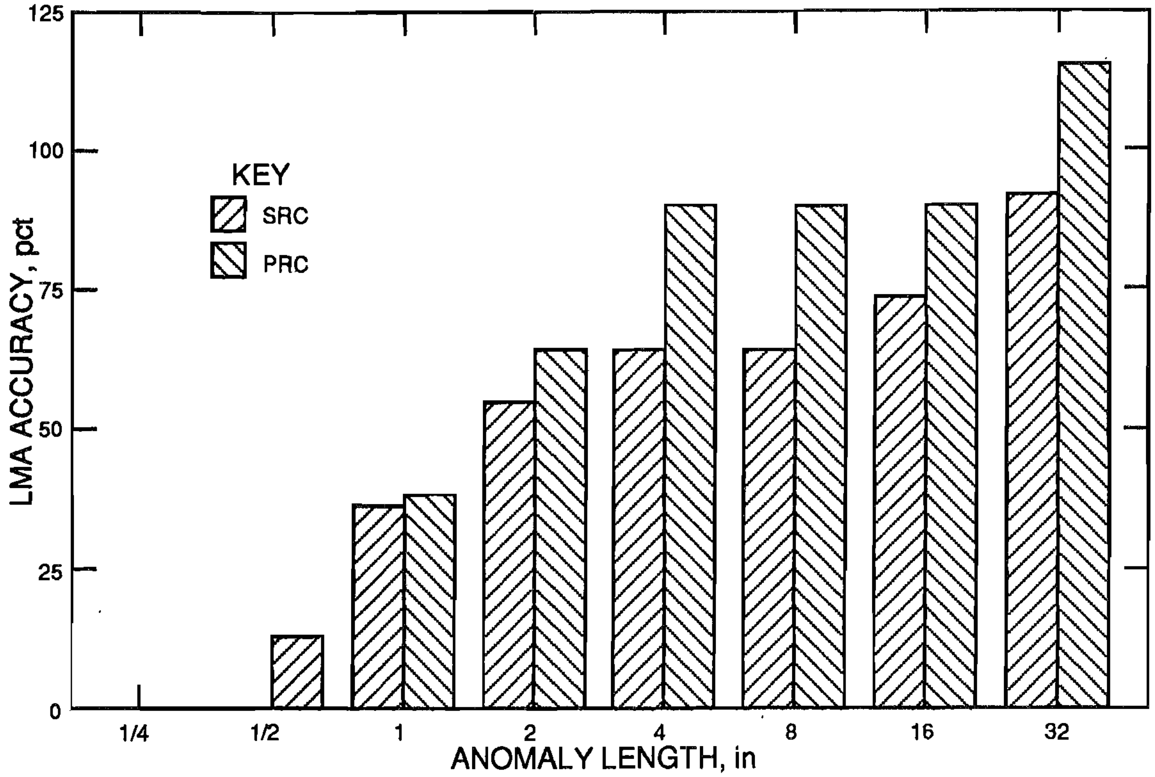


**Figure 18.—Comparisons of accuracy of LMA measurements using different instruments, ropes, operators, and test locations. Rope 1 was tested at PRC and rope 4 was tested at SRC. Both ropes were 3.8 cm (1-1/2 in) in diameter.**

## RESULTS OF TESTING FOR LOCAL FAULTS

### IDENTIFICATION OF ANOMALIES

The LF electromagnetic trace typically has two major components, one from the rope and one from an anomaly. When compared to a solid bar, a wire rope is inherently "flawed" because of the space between the wires. This means that the rope itself creates a background trace.

To be discernible, the actual anomaly must be distinguished from the background trace. Each anomaly has a characteristic shape on the trace that aids in its identification. Because short pieces of wire act as short magnets, the opposing polarity interrupts the field, and this interruption is picked up by the search coil. This causes the two ends of a break to be displayed on the trace as two sharp spikes, one pointing up and the other down. These spikes generally must protrude above and below the background to be detectable. The ratio between the two is known as the signal-to-noise ratio, the magnitude of which depends upon whether or not the rope is magnetically saturated, how close the pickup coils are to the flaw, the length of the flaw, and the construction of the rope. Round strand ropes, for example, produce larger background traces than do flattened strand ropes.

Figure 19, which is a trace from rope 5, shows these characteristic spikes and how they differ for different lengths of gaps on the surface of the rope. The spikes caused by gaps down to 1.6 mm (1/16 in) long clearly show on the trace. The heights of the spikes are dramatically reduced when the lengths of the gaps are reduced. The spikes from gaps over 10 cm (4 in) long are separated enough that the background trace appears between the spikes.

### GAPS VERSUS ADDED WIRES

Figure 20 shows that, when comparing added wires to gaps on rope 3, the gaps are more distinguishable. Gaps 6.4 mm (1/4 in) long both inside and outside the rope are distinguishable, while 6.4-mm- (1/4-in-) long wires added to the surface are not distinguishable.

Figure 20 also shows that wires added to the interior of the rope create smaller spikes than those added to the surface. For example, the 12.7-mm- (1/2-in-) long wire is distinguishable on the surface but is not distinguishable when buried within the rope. However, for gaps, the opposite is true. Gaps inside the rope are more distinguishable than gaps on the surface. Figure 20 shows that

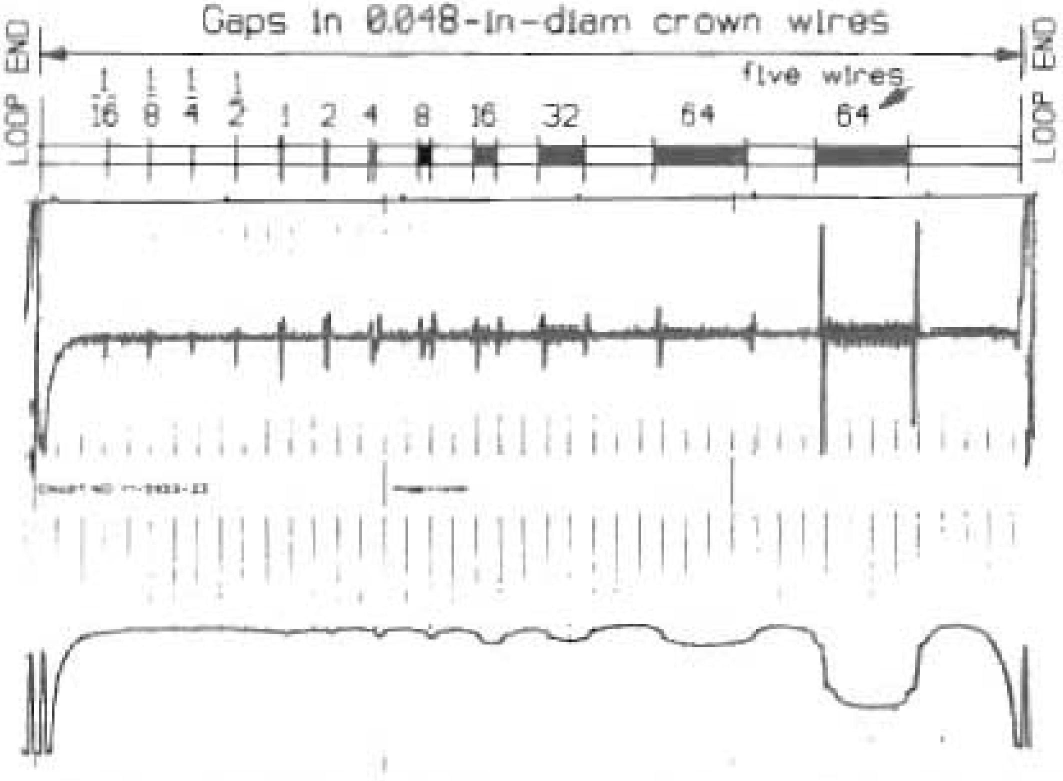


Figure 19.—Traces showing response of Instrument A to LF and LMA [rope 5, Instrument A, medium head, rope speed = 24 m/min (80 ft/min)]. Upper trace = LF, lower trace = LMA.

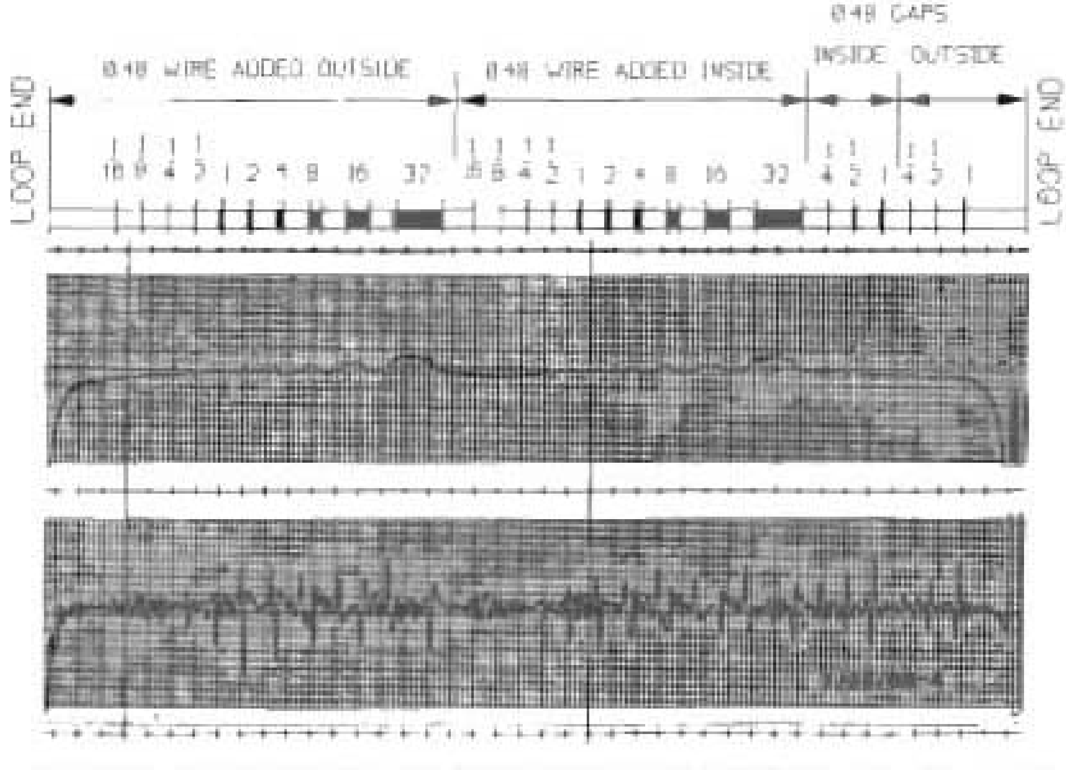


Figure 20.—Traces comparing response to gaps cut from outer wires with short wires added to rope surface [Instrument C, large head, rope 3, rope speed = 24 m/min (80 ft/min), chart speed = 5 mm/s (0.2 in/s)]. Upper trace = LMA, lower trace = LF.

three lengths [6.4, 12.7, and 25.4 mm (1/4, 1/2, and 1 in)] were recorded as distinctly larger spikes when they were beneath the surface as compared with when they were on the surface.

## EFFECTS OF ROPE SPEED

The results in figure 21*A* were obtained when the rope was moving at 24 m/min (80 ft/min) and the chart was moving at 5 mm/s (0.2 in/s). To study the effects of rope speed, the same rope was tested on the same instrument when the rope was moving at 122 m/min (400 ft/min). To aid in the comparison, the trace in figure 21*B* was recorded at a chart speed of 25 mm/s (1 in/s) so as to provide the same length of display per circuit of the rope at a chart speed of 5 mm/s (0.2 in/s) and a rope speed of 24 m/min (80 ft/min). The flaws within the trace obtained at 122 m/min (400 ft/min) are as visible as flaws obtained at 24 m/min (80 ft/min).

## EFFECTS OF ROPE DIAMETER

One would expect that an instrument would be less likely to detect anomalies on large-diameter ropes. However, the results from testing rope 3 [1.9 cm (3/4 in) in diameter] (figure 22*A*) were similar to those from testing rope 4 [3.8 cm (1-1/2 in) in diameter] (figure 22*B*). One explanation was that the diameter of the outside (crown) wires, which were the wires either removed or added, were larger in rope 4 than in rope 3, so that the same percentage of cross-sectional area was present in both ropes. Therefore, the effect on the magnetic field was the same for the two different diameters of rope.

## EFFECTS OF DISTANCE TO SENSORS

Figure 23 shows that, for the best results, the size of the head must be properly matched to the size of the rope. Both traces in figure 23 were obtained from rope 5 [1.9 cm (3/4 in) in diameter] using the same instrument type but different head sizes. The top trace was obtained using a head with a 4.4 cm (1-3/4 in) in diameter hole for the rope to pass through, and the lower with a hole 7.6 cm (3 in) in diameter.

In both cases, the sensors were positioned at the edge of the hole, providing different distances between the sensor and the rope. This distance is called the standoff distance and was 2.9 cm (1-1/8 in) for rope 3 and 1.3 cm (1/2 in) for rope 4. The lesser standoff distance produced greater distinction between the LF and background signals. A 1.7-mm- (1/16-in-) long gap on the upper trace can be seen clearly, but the gap on the lower trace has to be 13 mm (1/2 in) long to be seen. This result shows the importance of using a head with a hole diameter as close to the diameter of the rope as is practical and safe. Unfortunately, manufacturers generally say that a range of rope diameters can be used for a particular head, even though, as shown here, too small of a rope or too large of a head compromises the results. These findings are consistent with the inverse square law: The strength of a magnetic signal varies inversely with the square of the standoff distance.

## EFFECTS OF DIAMETER OF BROKEN WIRE

The diameter of a broken wire influences the signal. Figure 24 shows a trace from rope 2, where two sets of wires were added to the surface of the rope. One set of wires was 1.17 mm (0.046 in) in diameter and the other was 2.03 mm (0.080 in) in diameter. The larger wire provided a much greater response in all cases. Thus, breaks in larger wires, which have the most deleterious effects on rope strength, are easiest to find.

## EFFECTS OF SHAPE OF BROKEN WIRE ENDS

Earlier investigations (Underbakke and Haynes, 1982) indicated that the shape of the broken ends of the wire affected a signal. For this reason, two 13-mm (1/2-in) lengths of wire were added to rope 2, one with both ends squared and the other with both ends beveled (figure 24). The responses at points A and B show little difference, indicating that the shape of the end of a broken wire has no influence.

## INTERFERENCE BETWEEN LOCAL FAULTS

Current regulations (U.S. Code of Federal Regulations, 1982) require that a rope be removed from service when there is more than 5 pct of the total number of wires or 15 pct of the wires in any strand broken within one lay length. The ability of the instrument to detect multiple anomalies within one lay length was tested by taping four 4.8-mm- (3/16-in-) long wires within one lay length on rope 2. In figure 24, the four wires are distinguishable on the trace. When the response to adding a single wire is compared with the response to adding four wires, the height of the trace is similar.

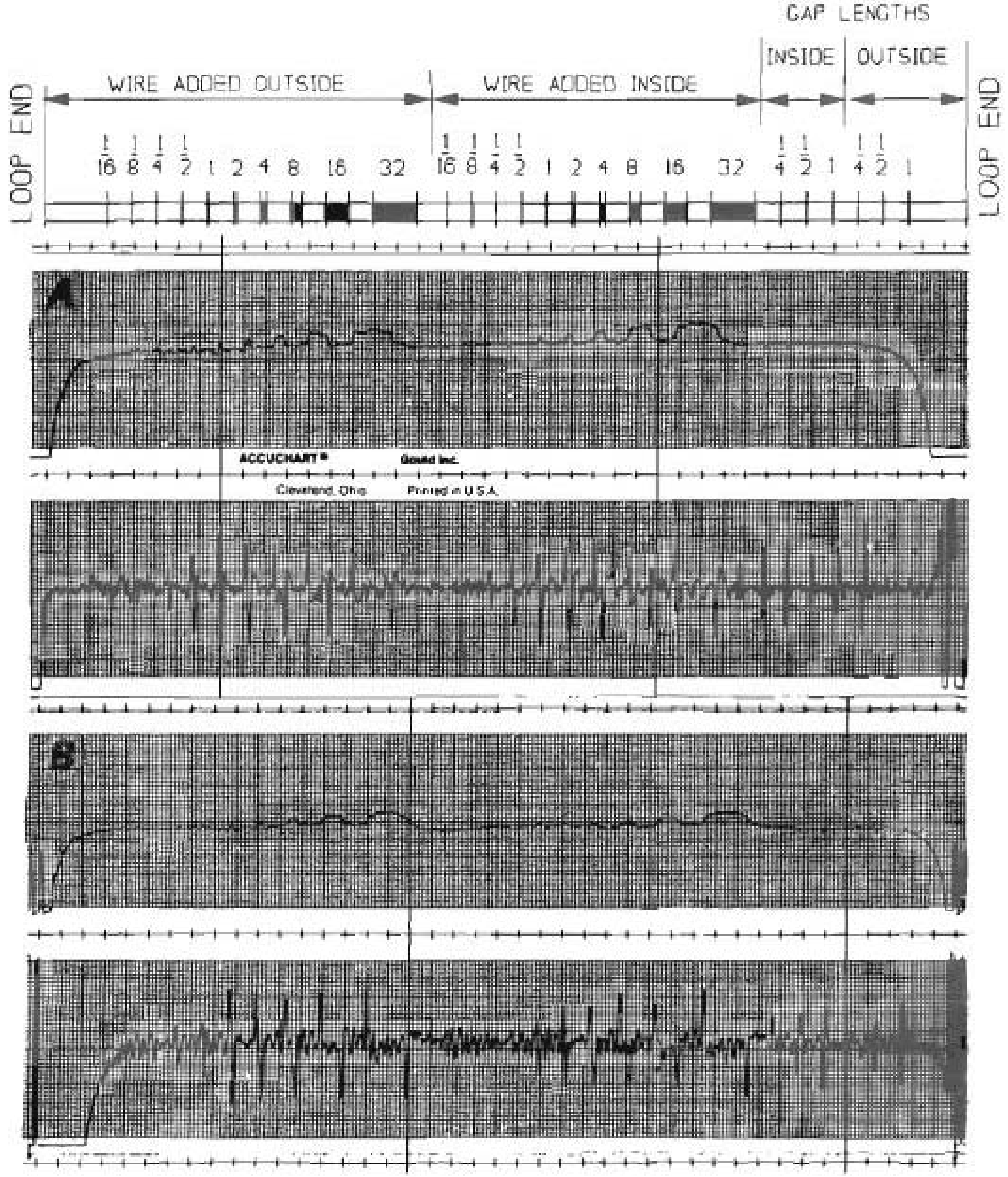


Figure 21.—Traces comparing LF response to rope speed, inches (instrument C, large head, rope 3) Upper trace = LMA, lower trace = LF. A, Rope speed = 24 m/min (80 ft/min), chart speed = 5 mm/s (0.2 in/s); *B*, rope speed = 122 m/min (400 ft/min), chart speed = 25 mm/s (1 in/s).

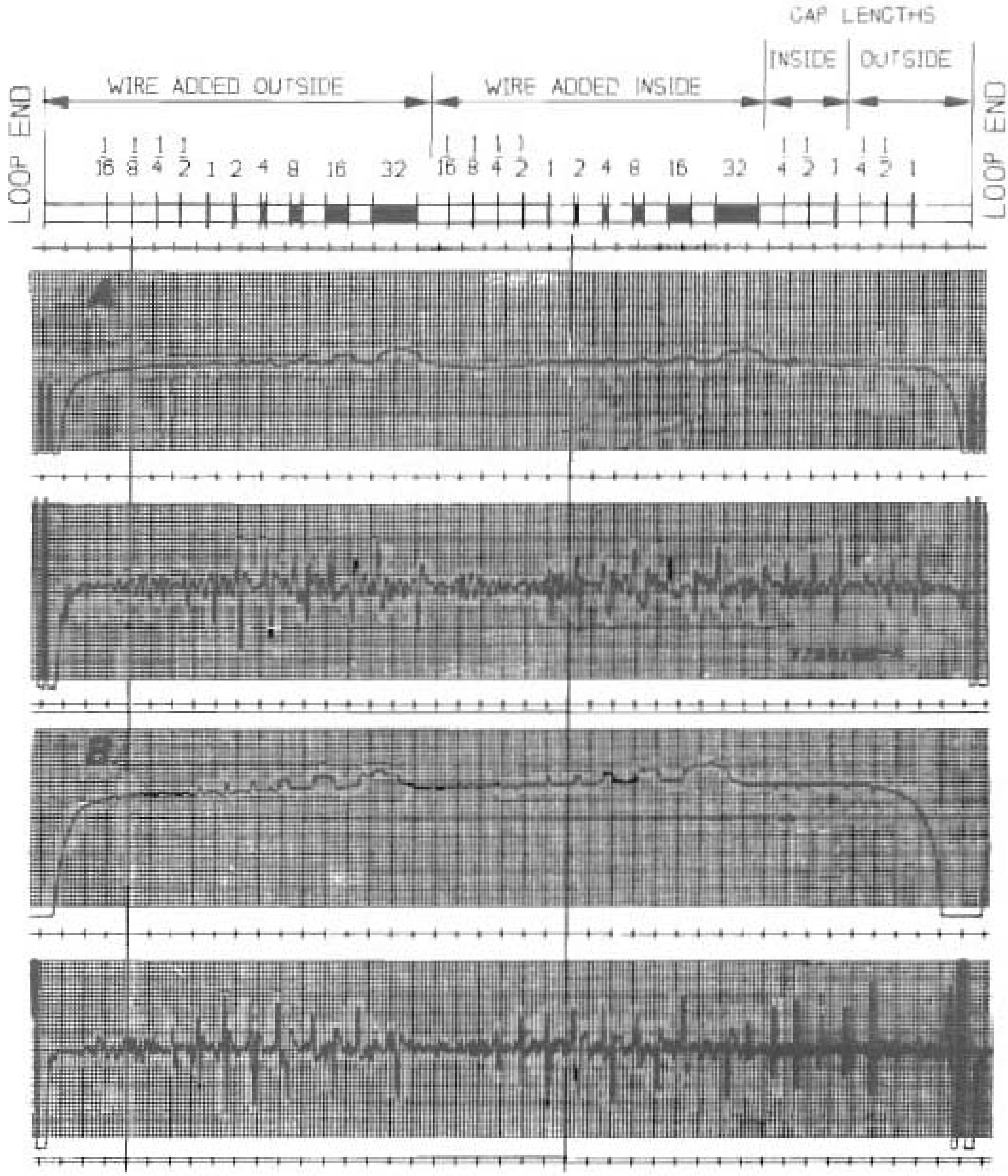


Figure 22.—Traces comparing LF response with rope diameter, inches [Instrument C, speed = 24 m/min (80 ft/min), chart speed = 5 mm/s (0.2 in/s)]. Upper trace = LMA, lower trace = LF. *A*, Rope 3, 1.9 cm (3/4 in) in diameter; *B*, rope 4, 3.8 cm (1-1/2 in) in diameter.

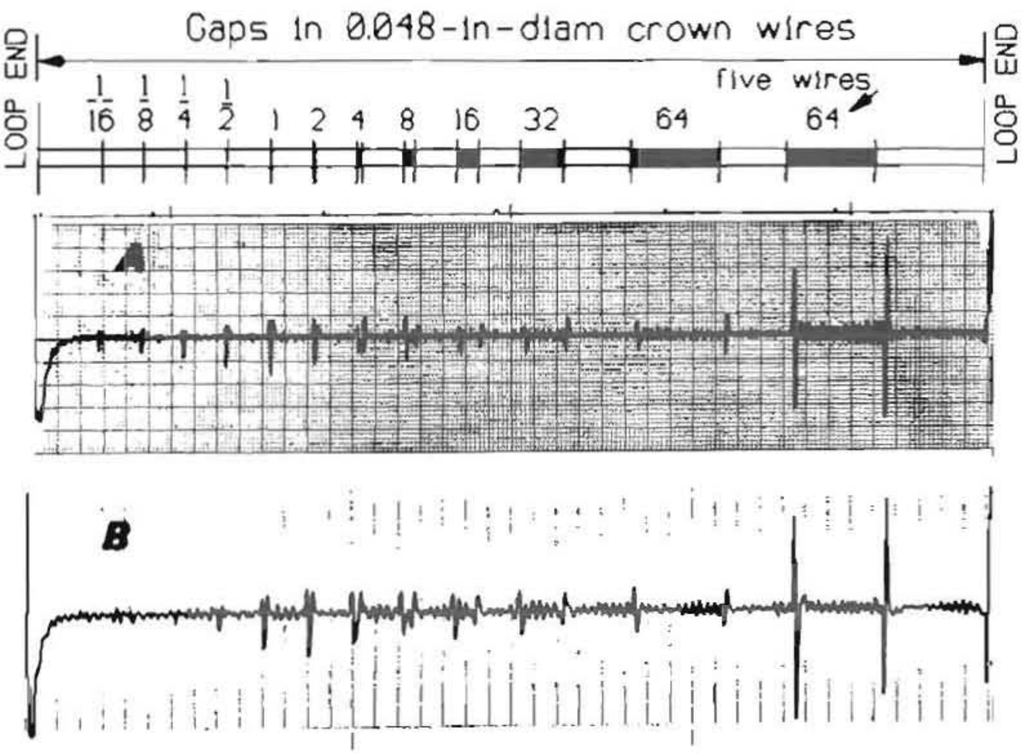


Figure 23.—Effects of distance from instrument sensors and simulated anomalies on accuracy of LF measurements [rope 5, instrument A, rope speed = 24 m/min (80 ft/min), chart speed = 5 mm/s (0.2 in/s)]. *A*, Medium head, diameter of hole in instrument = 4.4 cm (1-3/4 in); *B*, large head, diameter of hole in instrument = 7.6 cm (3 in).

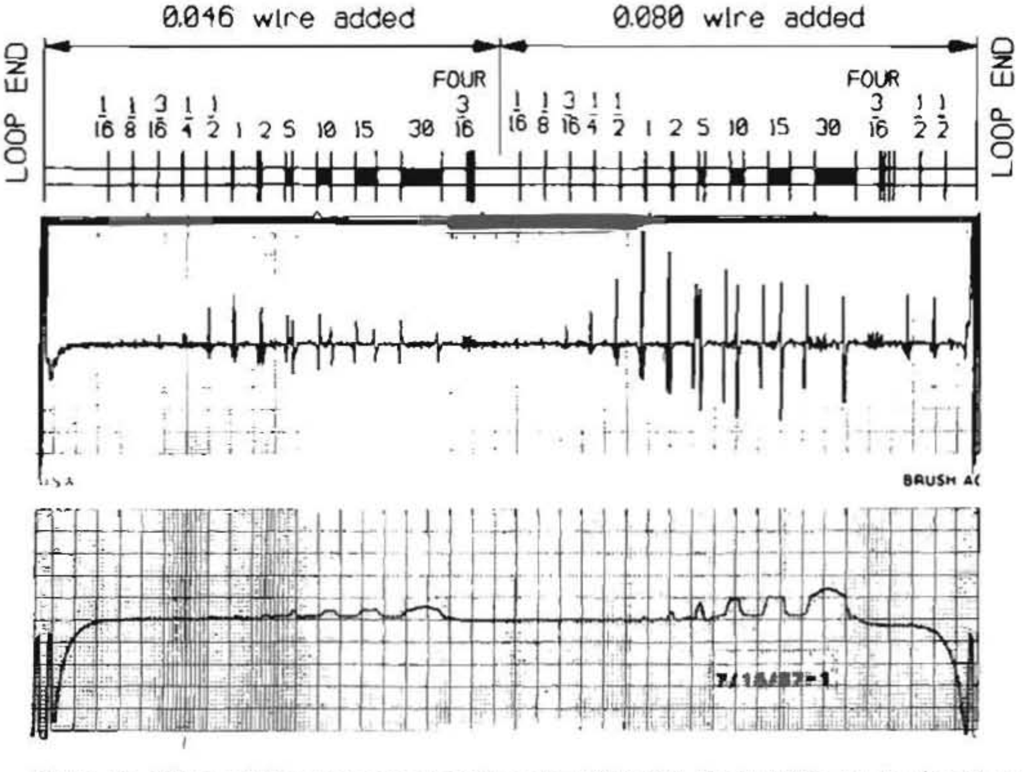


Figure 24.—Effects of diameter of broken wire and multiple wire breaks within one lay length on LF response [rope 2, rope speed = 24 m/min (80 ft/min), chart speed = 5 mm/s (0.2 in/s)].

# RESULTS OF TESTING FOR LOSS OF METALLIC CROSS-SECTIONAL AREA

A characteristic of the electromagnetic NDT method is its inaccuracy in measuring LMA when the loss does not extend approximately three times the length of the magnetic head. Three times the length of the magnetic head is termed the averaging length of the head. The averaging length differs slightly for each instrument. If a length of outer wire is removed that is less than the averaging length of the head, something less than the cross section of the wire will be indicated. The shorter the length of wire, the less LMA that is recorded. One reason for this inaccuracy may be because the instruments do not actually measure change in cross-sectional area, but the change in the rope mass over the measurable length. It is supposed that an instrument cannot measure a difference accurately until its length, and thus its mass, is large enough to influence the total magnetic field.

Figures 14 through 17 show that none of the instruments tested could determine 100 pct of the actual cross-sectional loss when the loss extended less than the averaging length of the head. Fortunately, LMA caused by wear is usually distributed over an extended length of the rope. On the other hand, corrosion can take place over a short distance, because once it begins, galvanic activity is increased by the interactions between the corrosion products and the metal (Fraley, Anderson, and Sands, 1990).

## EFFECTS OF ROPE SPEED

Figure 14 shows the trace from a typical electromagnetic NDT instrument. Given the variable interpretations of the traces, rope speed appeared to have little influence except at 24 m/min (80 ft/min), where a slightly higher percentage of loss was measured.

## EFFECTS OF LOCATION OF ANOMALY WITHIN A ROPE ON LMA MEASUREMENTS

Figure 15 compares LMA measurements when wires of the same diameter are added to the inside and to the surface of a rope. For the four instruments tested, there was little difference in the overall pattern of the response except that two instruments (A and C) were more accurate than the other two (B and G). Instruments A and C were those with the shortest heads and the sensors closest to the rope.

## EFFECTS OF ROPE DIAMETER

Figures 16 and 17 compare LMA results from ropes 5 and 6 using two different sizes of heads at rope speeds of 24 m/min (80 ft/min). The diameters of the wires removed from the two test ropes were such that the actual percentage of loss from rope 6 was higher than that from rope 5 (1.09 pct versus 0.79 pct, respectively). Therefore, the recorded LMA should be higher for rope 6 than for rope 5. Although it was expected that the medium head would be more accurate on rope 6 than on rope 5, because the sensors were closer to the rope 6 surface, the reverse proved to be true for both test heads. This indicated a decrease in accuracy as rope diameter increased.

## EFFECTS OF ROPE TENSION

Figure 25 shows the effect of rope tension on LMA. The weight of the rope and the conveyance causes tension in the rope that can induce LMA even though there is no actual metal loss. If not accounted for, this error could encourage replacing a rope before it was necessary. To better understand the effects of rope tension, a rope 5.1 cm (2 in) in diameter was pulled in a tensile machine to 36 pct of its catalog strength. Diameter and lay length, which influence the metallic cross section, were measured twice: during a first tensioning and then again after the rope had been relaxed and retensioned. Calculations indicated that neither factor accounted for the change in LMA.

It is possible that tensioning changes the magnetic permeability of a rope by changing the ratio of air to metal inside the rope. Small changes in the amount of air space would have large effects on average permeability.

A newly installed rope is often electromagnetically tested to form a baseline for comparison with future tests. Therefore, it is important to stabilize the diameter of a new rope before the NDT and diameter baseline tests. Figure 26 shows that the diameter changed on the first tensioning, apparently through an initial tightening of the rope through stretch. The second tensioning generally had no further effect on diameter. Figure 27 shows that the first tensioning put some set in the elongation of the lay length and that it elongated again during the second tensioning.

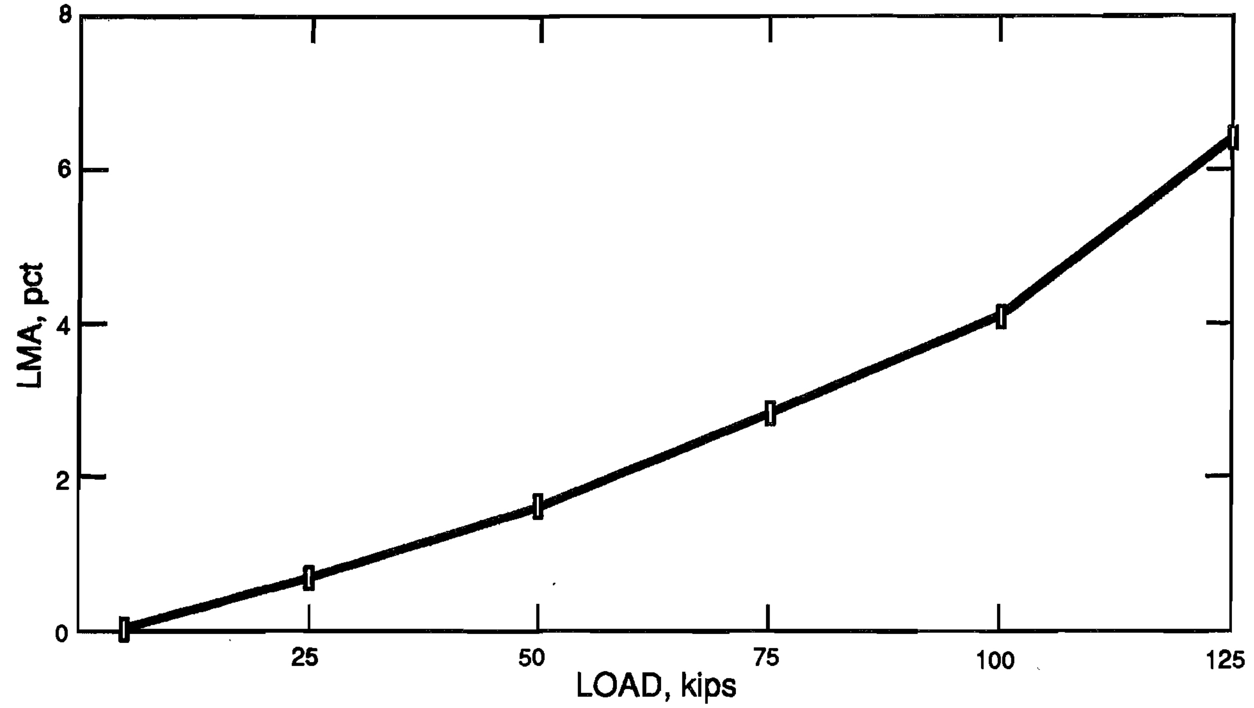


Figure 25.—Effects of load on LMA (rope 1, instrument C).

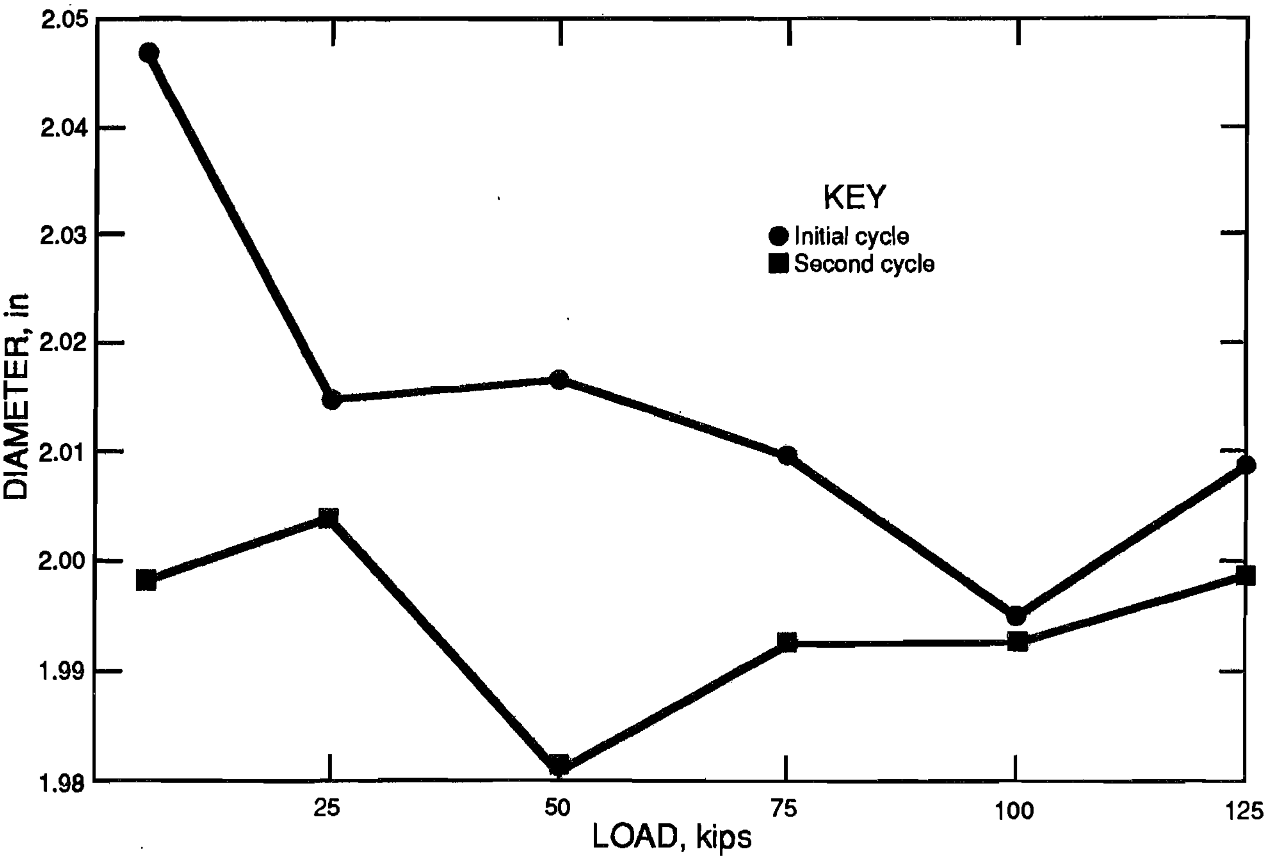


Figure 26.—Effects of load on rope diameter [rope 1, 5.1 cm (2 in) in diameter].

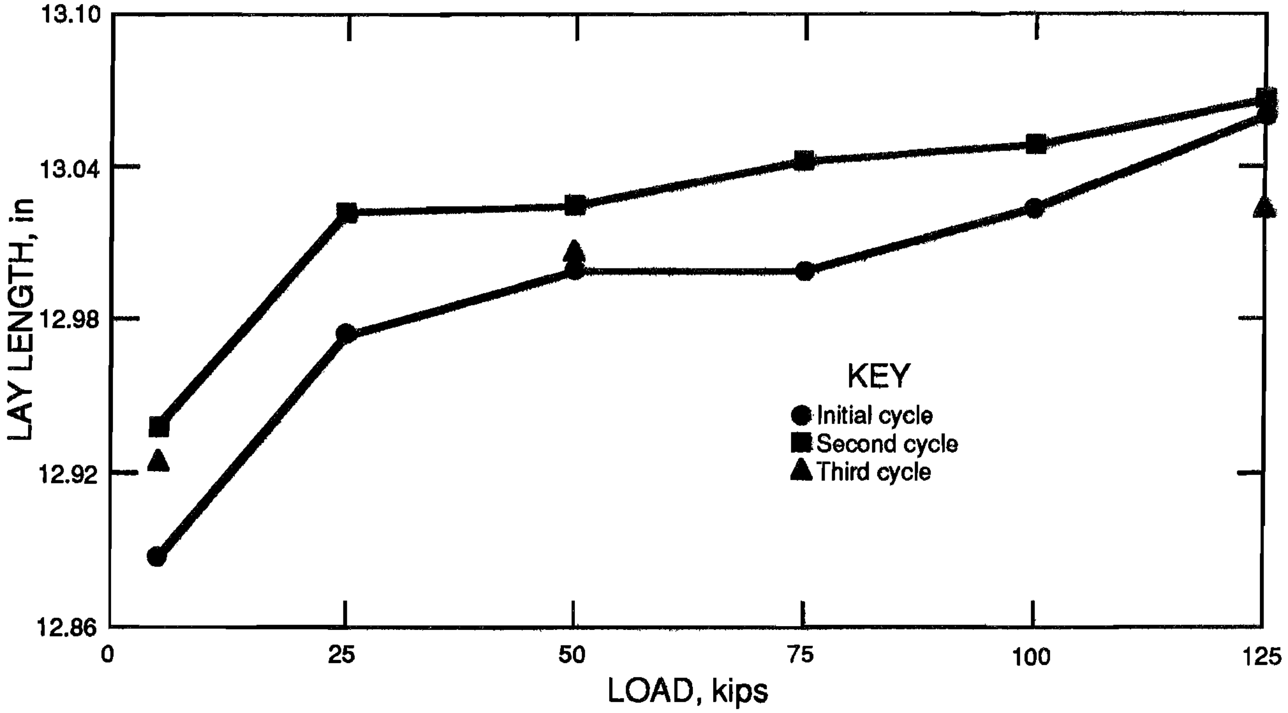


**Figure 27.—Effects of load on rope lay length [rope 1, 5.1 cm (2 in) in diameter].**

## OPERATOR INTERPRETATION

The interpretive abilities of the instrument operator are most important to a successful analysis of the condition of a rope. Adequate training is necessary to accomplish the task.

Figure 28 shows traces taken from rope 3 at 122 m/min (400 ft/min), and chart speeds of 5 mm/s (0.2 in/s) (figure 28*A*) and 25 mm/s (1 in/s) (figure 28*B*) using the same instrument. Note that expanding the trace by a factor of five greatly improved the ability to read the trace. Unfortunately, most mine ropes are of such a length that high chart speeds, while yielding a clearer chart, also result in a chart so long that it is cumbersome to work with during the test and difficult to use when comparing earlier traces taken at different speeds. For these reasons, most traces are taken at lower speeds.

Traces taken in the field require even more interpretation than those developed under laboratory conditions. Rope deterioration in a mine is a relatively complex and subtle process, and the usually slow chart speeds require an experienced eye to decipher the traces. Another factor is that each instrument type, and even each individual instrument, has its own characteristics that require familiarization. Some instrument settings drift, allowing the zero setting of the LMA to shift. Bringing the rope to a stop with the instrument on the rope leaves a magnetized boundary that can create a false indication during later tests. Even a general magnetization from a previous test can alter results. Knowledge of the recorder being used is required to obtain the best gain and speed for interpretation of the results. Furthermore, the mechanisms of rope deterioration should be well understood. For example, one would expect corrosion near the skip where water accumulates; corrosion is usually uniform and causes pitting but no cracks; fatigue breaks in wires would be expected near the sheave with the skip at the bottom loading station.

Commercial operators were more accurate in their readings when they knew what to expect, presumably because they were able to optimize instrument settings. The importance of operator training to achieve accuracy has been acknowledged by others (Geller and Udd, 1991). For this reason, operator training is important, and training offered by instrument manufacturers at the time of purchase of an instrument is essential.

Figure 22 shows the results from two tests to evaluate the effect of operation of the instrument. The figure compares the results of two tests done by two different operators at different laboratories under different conditions.

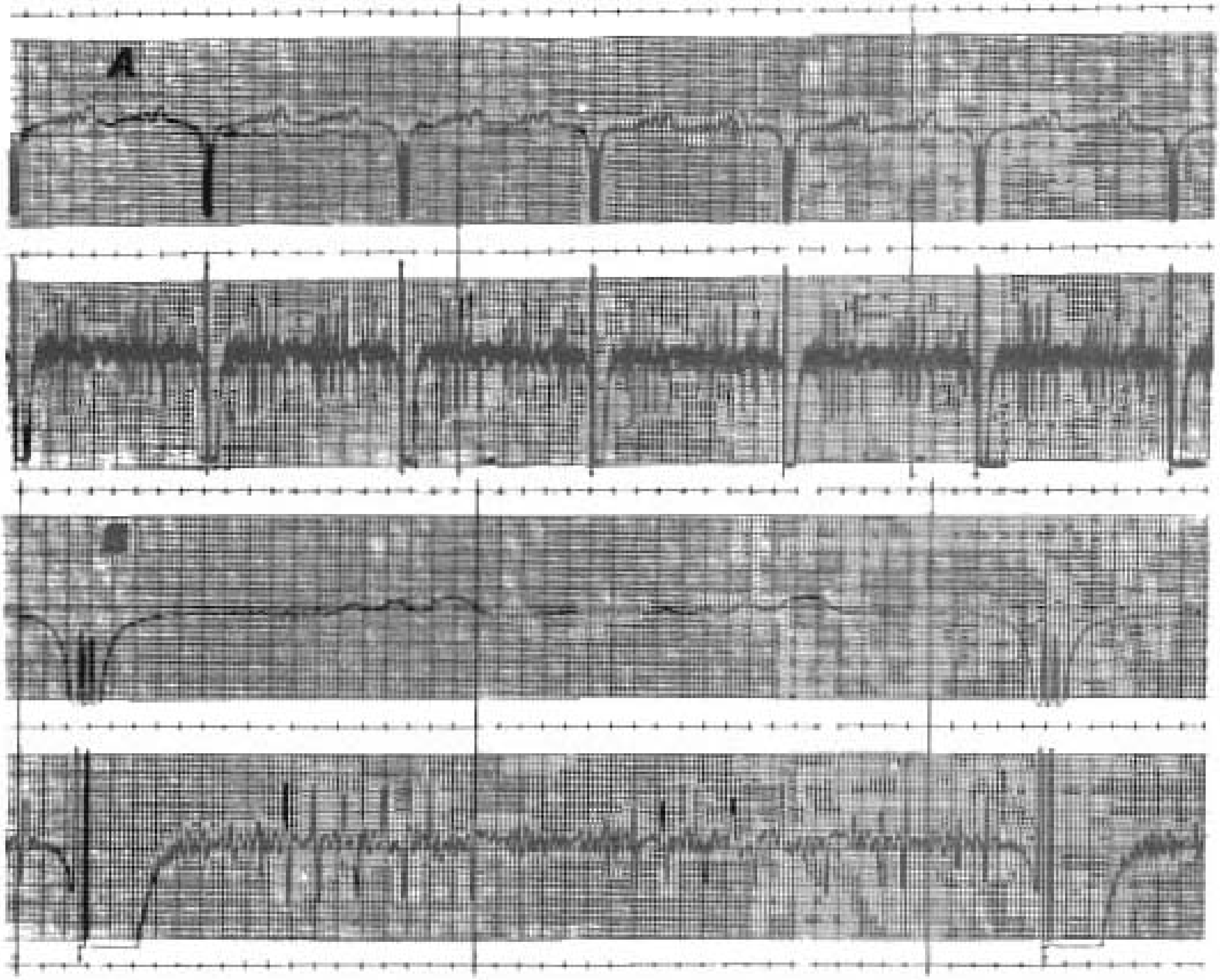


Figure 26.—Effects of chart speed [rope 3, instrument C, rope speed = 122 m/min (400 ft/min)]. Upper trace = LMA, lower trace = LF. A, Chart speed = 5 mm/s (0.2 in/s); B, chart speed = 25 mm/s (1 in/s).

Two separate type C instruments were used, one at the USBM's Pittsburgh Research Center (PRC) and the other at the Spokane Research Center (SRC). At PRC, the instrument was physically moved along a stationary rope at 61 m/min (200 ft/min) and was operated by a commercial operator with extensive knowledge of the instrument. At SRC, the test was done on the test facility at a speed of 122 m/min (400 ft/min) and was operated by inexperienced USBM personnel. Given that speeds below 122 m/min (400 ft/min) have shown no significant difference in instrument response, and even though the two instruments inherently had a slight difference in response, the difference between the results of the two operators was not significantly different. This indicates that the actual operating of the instruments may not be particularly difficult. This, however, does not address the difficulties inexperienced operators have in interpreting the condition of the rope from the trace.

## SUMMARY AND CONCLUSIONS

The results show the capabilities of electromagnetic instruments. In spite of their limitations, such instruments are able to test ropes at much higher rope speeds and provide more detail than can visual inspections. Of particular importance is their ability to provide information on the condition of the interior of the rope, something that is nearly nonexistent in visual inspections. Even though there are claims that one instrument is superior to another, differences in the operator's technique and chart analysis, as well as proper sizing of the instrument to the rope diameter, probably have more influence on the quality of the results than does the instrument used.

Electromagnetic NDT instruments provide a method for finding broken wires when their broken ends have separated between 3.2 and 6.4 mm (1/8 and 1/4 in) both inside and on the surface of a wire rope.

Even though the instruments could detect LMA in lengths as short as 13 mm (1/2 in), the actual percentage of LMA could not be determined unless the length of the loss along the rope was about three times the length of the head.

The diameter of the rope did not affect the response of any instrument to LF providing that the diameter of the broken wire was the same relative to the diameter of the rope. Conversely, for similar anomalies, the LF signal was reduced by an increase in the mass of the rope.

The closer the pickup coil to the surface of the rope, the smaller the LF the instruments could detect. Therefore, the best response is obtained when an NDT instrument is properly matched to the diameter of the rope.

The response of the instrument to simulated anomalies, such as gaps under a strand, was slightly better than the response to gaps on the surface. The instruments responded better to gaps in the wire than to the same length of wire added to the surface. However, it is worth noting that four wires, each 4.8 mm (3/16 in) long, placed within the same lay length were each discernible on the trace.

Rope tension increased LMA. Rope tension decreased the measured diameter of the rope and increased the measured lay length; however, changes in LMA can only partially be explained by changes in the cross section from measured diameter and lay length.

It is important that the operator be experienced with wire rope inspection techniques and with the equipment when interpreting the traces. The interpretations can be aided by increasing chart speed to expand the trace.

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## APPENDIX.—INFLUENCE OF TEST-ROPE CONSTRUCTION

The preparation of the test facility and test ropes required considerable work before an adequate format was found. The results of these efforts are listed here to aid anyone preparing a test facility of their own.

1. Adding wires to the outside and inside of a rope was less time consuming than adding gaps. Knowing the limitations of added wires relative to gaps, an investigator could obtain much useful information from the added wires, particularly when comparing one instrument with another.
2. The length of a change in metallic cross section could be most easily controlled by adding a length of wire to the rope surface than by cutting out a section of wire. The length of a gap could change as the rope flexed over the sheaves.
3. Wires added to the outside of a rope increased the diameter of the rope so that it would not pass through the opening of some of the instruments.
4. Wires longer than 5 cm (2 in) were difficult to bend and lay snugly in place whether they were placed on the outside or the inside of the rope.
5. Adding inside-wire anomalies (under a strand) did not measurably change the rope diameter.
6. Because of the helical nature of rope, the length of gap created by removing a wire was limited to about half a lay length if the gap was still under the strand as an "inside" gap.
7. There were no measurable changes in length of outside gaps [6.4, 12.7, and 25.4 mm (1/4, 1/2, and 1 in)] between the beginning and end of testing on ropes 3 and 4.
8. Forty-six-centimeter (18-in) spacing of defects was suitable for most test runs, but was not enough to allow use of all instrument settings that could be used at all rope speeds. A spacing of 76 cm (30 in) or more is recommended.
9. The round strand construction of the 3.8 cm (1-1/2 in) in diameter test rope had larger waveforms as characteristic background signatures than ropes such as filler wire or flattened strand constructions. This larger waveform can indicate small added defects not normally visible.
10. The instruments reacted to end-termination mass changes (end effects) at the loop splice. Therefore, it is recommended that anomalies should be placed 1.2 m (4 ft) or more from a splice.

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