COMPARISON OF MAGNETIC AND STRESS RESPONSE
OF MAGNETIC INTRUSION LINE SENSOR (MILES)*

T. F. Ezell
R. W. Madsen
F. G. Yost
Sandia Laboratories,
Albuquerque, N.M. 87115

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INTRODUCTION

The MAID/MILES intrusion sensor detects both stress waves as well as ferrous objects. Stress waves are produced by seismic noise, wind, animals, and other naturally occurring phenomena, as well as by man-made sources, such as vehicles, machinery, people walking, etc. Both modes of detection occur by similar physical mechanisms, but it is not clear that the sensitivities of each mechanism correlate because of soil characteristics and soil coupling and because of magnetic material properties. This paper presents results of both laboratory and field measurements made by Sandia Laboratories on the magnetic and stress properties of MILES cables.

Knowledge that stress and magnetic sensitivities correlate would be helpful in diagnosing problems with installed cables and for quality control in the manufacture of new cables because the magnetic sensitivity can be more easily measured than the stress sensitivity. This paper presents the results of stress-magnetic correlation measurements made at Sandia Laboratories. Rigorous tests indicate little, if any, correlation exists between the stress and magnetic properties even though preliminary walk tests indicated that a correlation might exist.

MAID/MILES System

The MAID/MILES intrusion detection system was designed for the Air Force by Honeywell, Inc., and consists of a buried cable, called MILES (Magnetic Intrusion Line Sensor), and an electronic processor, called MAID (Magnetic Anti-Intrusion Detector). The MILES cable (Figure 1) is a round cable 100 metres long with a sensing coil wound around a stranded

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Figure 1. Construction of MILES cable.

magnetic core. The coil is wound 15.7 turns/cm (40 turns/inch). The sense winding reverses every 1.09 metres (43 inches) (this reversal is called a transposition) in order to provide cancellation for signals originating far from the cable. The MAID processor contains active filter-amplifiers which provides amplification within a 0.2 to 4 Hz passband. Output circuitry produces an alarm if response within this passband exceeds +1 volt in amplitude for a specified time.

Theory of Operation of Sensor

A voltage is generated in the sensing coil of the MILES when the flux density in the core changes. This flux density change can occur in either of two ways: (1) motion of a ferrous object near the cable causes a change in the ambient flux set up in the core by the earth's magnetic field; (2) stresses transmitted by the cable cause a magnetostrictive change in core permeability which in turn causes a change in flux density in the core. The change in flux density induces a voltage according to $E = \int n(d\phi/dt)dl$. Thus, in both cases the induced signal is determined by the magnetic properties of the core, but not necessarily the same properties.

SIGNAL ENHANCEMENT OF OPERATIONAL MILES BY MAGNETIC TREATMENT

This portion of the paper deals with the magnetic state of the MILES core material and how it affects the sensor operation. The MILES stress response has been found to be variable from cable to cable and sometimes even varies along the length of a given MILES sensor. One way to measure the stress response of a buried MILES is to record analog output while a person repeatedly crosses the cable. A surveyor's tape with markers every 1.09 metres is laid on the ground over the cable and a person carrying no magnetic material crosses the markers.

Our first experience with the effect of the magnetic state of the MILES core on the MILES response was at an operational site in late 1975. Here a very noisy MILES cable which produced almost constant alarming through the MAID was compared with a new MILES cable installed parallel to and 1.25 metres from it. The new cable operated very well with a high detection sensitivity and a low background noise level. Leigh Wold of Honeywell was consulting with us at the time and began experimenting with the old MILES by applying a DC current to it. It was found that the background noise of the old MILES could be adjusted up or down depending on the magnitude,

polarity, and sequence of current applications. The DC current flowing through the MILES sense windings was affecting the magnetic state of the core material and the operation of the MILES cable. The old MILES was left in an operational state of having improved detection and a background noise level low enough to operate with a low nuisance alarm rate.

This work was followed by a contract with Honeywell to investigate the effect of the MILES core characteristics on MILES sensor operation. A summary of the results of this contract to date shows that the current injection technique discussed above sometimes works, but in some cases it can also be harmful to sensor operation. Two improved methods of magnetic treatment have been developed. One method involves passing the MILES through a solenoid carrying DC current before the cable is buried (Figure 2). The high magnetic field in the solenoid saturates the core and leaves it in its proper magnetic state. The second method is for buried MILES and involves dragging a large current carrying coil over the surface of the ground above the MILES. The magnetic field produced by the coil is sufficient to saturate the MILES core material even when the MILES is 0.5 metres underground (Honeywell design criteria was a 5×10^{-4} tesla (5 gauss) field at 5 metres). Figure 3 illustrates the use of the coil. The polarity of both the solenoid and the coil are chosen so that the direction of the final magnetic field is in the same direction as the earth's magnetic field. Figure 4 is a picture of the coil mounted on a sled in use.

Magnetic treatment has been observed to have no effect on a uniformly sensitive MILES cable, but for a very poor cable, a drastic improvement is usually noted. Figure 5 shows analog and alarm outputs for a person carrying no magnetic material crossing every 1.09 metres of a MILES before and after magnetic treatment with the sled. The sensitivity of this MILES was improved enough to restore it to operation.

The mechanism of magnetic treatment of the MILES may be explained by referring to Figure 6 which presents the voltage output of a short section of round MILES cable being subjected to a constant amplitude sinusoidal stress and a varying external magnetic field. In effect, the figure illustrates a measure of stress or seismic sensitivity of a MILES sensor as a function of the magnetic field around the sensor. Further information on how these curves are generated is presented in reference 2.

The sensitivity curve of Figure 6 for a buried MILES cable in the earth's magnetic field, H_E (the component parallel to the MILES is represented by the vertical line marked H_E in

Figure 2. DC solenoid.

Figure 3. Concept of coil used in magnetic treatment of MILES.

Figure 4. Coil mounted on sled.

Figure 5. MAID analog signal and alarm output for person crossing cable at every 1.09 metre marking.

Scale: 200 mv/mm vertical, time 1 mm/sec.

Top: Before magnetic treatment

Bottom: After magnetic treatment

Figure 6. Voltage output for a round MILES as it is subjected to sinusoidal stress and external magnetic field (reproduced from reference 1).

Figure 6.), can be used to explain the effect of the magnetizing coil. The operating point of this MILES then must be along the line H_E somewhere between points A and B. Note that random operating points along the line H_E would produce drastically different outputs. For instance, an operating point near A produces approximately a 0.2 volt peak-to-peak output for this stress input while an operating point near B gives an output near zero. The desirable conditions for uniform sensitivity for a MILES cable are: (1) all portions of the core material must have the same characteristic curve such as that given in Figure 6, and (2) all portions must be at the same operating point on the curve.

The magnetic fields at the ends of the sled are in opposite directions (Figure 3). In use, the field at the rear of the sled is chosen to be in the same direction as the earth's magnetic field, and the field produced by the sled is sufficient to saturate the MILES core. Then as the sled moves over the cable, (1) the field from the sled will drive the MILES operating point in Figure 6 to point C (somewhere in negative saturation); (2) as the sled passes, the operating point will begin to move up the lower curve in Figure 6 to point D (somewhere in positive saturation); and finally, (3) as the sled's field passes away the MILES operating point will shift back along the upper curve to point A. All points of the MILES cable will then be at the same operating point if all of the MILES cable has the same characteristic curve. This curve is of course determined by the core material itself and its past history of heat treatment, cold working, and any other factors that influence magnetic properties. It is important that MILES cables come from the production line with uniform core material and then are handled carefully during shipment, storage, and installation so that portions of the cables are not damaged and their characteristic curves degraded.

Magnetic treatment has not been effective in bringing all portions of all MILES cables up to a uniform sensitivity. The explanation for all the magnetic treatment effects is not totally understood but is being pursued in laboratory and field work. One difficulty with field work is that other variables such as soil coupling, burial depth, and variations in cable crossings enter into the measurements.

LABORATORY EXPERIMENTS ON MAGNETIC PROPERTIES

Mechanical Treatment of Core Material

This section presents the results of work performed to determine the effects of mechanical treatment on the magnetic

properties of the core. To illustrate the extraordinary effects of cold work upon magnetic properties of the MILES core material, we determined the DC normal induction curve and hysteresis loop for a single strand of 0.109 cm diameter MILES core wire 30 cm long. These curves are shown in Figure 7. The coercivity is approximately $6.28 \cdot 10^{-4}$ amps/m (0.05 oersteds), and the maximum and initial permeabilities are approximately 98.7. To contrast this material we obtained well annealed wire of the same alloy 0.150 cm in diameter and drew it down to 0.109 cm in diameter for a 50% cold work. The magnetic properties for this material are shown in Figure 8. Notice that its permeability is drastically reduced and its coercivity has drastically increased. This will reduce the magnetic mode sensitivity of MILES cables. Other related experiments, carried out in our laboratory, involving simple bending of core material have shown actual magnetic mode desensitization.

Laboratory Measurements of Magnetic Properties

The magnetic mode sensitivity of MILES cable is largely determined by the reversible permeability of the core material which, due to localized bending and other core inhomogeneities, can vary significantly over the length of a 100 metre cable. Reversible permeability is defined in Figure 9 as the slope of a minor loop located on the normal induction curve at a field value equal to the tangential component of the earth's magnetic field. As ferrous material moves near the cable, it causes a slight change, ΔH , in the field value at that point. This in turn causes a flux density change, ΔB . The limit of the ratio of these quantities, $\Delta B / \Delta H$, as ΔH approaches zero is defined as the reversible permeability. Although we have not studied the effects of bending on reversible permeability, we shall present data taken in our laboratory on an undamaged, well annealed specimen.

To investigate the effects of remnant magnetization and applied magnetic fields on magnetic cable output we injected current into one winding length (1.09 metres, the length between two transpositions) of MILES cable. The cable was excited by a ferrous object swinging above the cable. After a momentary application of current on the order of milliamps to fractions of an amp, no improvement of cable output was observed. With the continual application of larger and larger current, the cable output decreased. This prompted us to wrap 19 strands of 0.109 cm diameter core wire on a 5.38 cm diameter mandrel to form a toroid whose cross section approximated that of a MILES cable. It was then annealed for four hours at 1150°C in dry hydrogen and then cooled according to the

Figure 7. Normal induction curve and hysteresis loop for one strand of MILES core wire.

Figure 8. Normal induction curve and hysteresis loop for a strand of wire of the same alloy as used in MILES cables and 50% cold worked.

Figure 9. The normal induction curve and the definition of reversible permeability.

recommended heat treatment for supermalloy type materials. The toroid was then wrapped with three 0.644 mm (#22 gauge) copper windings. These windings served as a DC bias field winding, a small 60 Hz excitation winding, and a sense winding. All windings had 218 turns. The reversible permeability measurements versus applied bias fields are shown in Figure 10. It is obvious that continually applied fields decrease reversible permeability and, consequently, magnetic mode cable output. From these experiments we conclude that magnetizing a MILES cable enhances the stress mode output and not the magnetic mode output.

Laboratory Stress Mode Experiments

To investigate the stress mode sensitivity of cables we used one winding length (1.09 metres) of both round and flat* versions of the MILES cable and the tapping arrangement illustrated in Figure 11. A wooden drop weight (34.5 gms) was allowed to pivot so that it had a moment arm of 16.5 cm and was dropped from a height of 5 cm.

For a cable that had been demagnetized with an AC current, the cable output was not above noise level for either cable. A momentary one ampere magnetization current was then applied to the sense windings. The output due to the wooden drop weight rose to 2.7 volts peak-to-peak for the round cable as shown in Figure 12a. After several drops (less than 10) the output was reduced to noise level. Repeated application of the momentary current always brought the output up to significant values. This phenomenon was observed with both cable types. To decrease the ambient noise pickup, we repeated the experiment using a short (15 cm) length of flat core material which was wrapped with 100 sensing turns. The output of this short section after similar magnetization is shown in Figure 12b. After ten drops, the output was reduced to .18 volts peak-to-peak as shown in Figure 12c. The section was then bent back and forth many times over its entire length, straightened and retested. The output appears in Figure 12d. The signal produced by the first drop was rather large, but subsequent signals were on the order of those shown in Figure 12c. The section was then remagnetized and the high output was once again restored as can be seen in Figure 12e.

*Commercial version of MILES designed and built by Honeywell, Inc.

Figure 10. Reversible permeability versus applied bias field.

Figure 11. Tapping arrangement used to apply stress wave to cable.

a. 100 mV/mm
MILES cable

b. 100 mV/mm
Short Section

c. 20 mV/mm
Short Section

d. 20 mV/mm
Short Section

e. 100 mV/mm
Short Section

Figure 12. MAID output signals for cable and short section used in laboratory experiments.

STRESS AND MAGNETIC MEASUREMENTS ON BURIED CABLES

In testing buried MILES cables, it was found that the signal from a person walking over the cable varied so much from one crossing to the next as to obscure differences of the order of 50 per cent. The fact that the walker does not step in the same place and in the same way each time creates these differences. In order to obtain a consistent stress signal, a plastic pipe loaded with sand to obtain an acceptable signal was dropped from a tripod. For tests on cables buried in soil, the pipe weighed 4.7 kg. The end of the pipe was covered with a cap and some foam rubber. The purpose of the rubber was to produce a uniform impact and minimum soil disturbance. The effectiveness of the rubber was demonstrated by the fact that the signal from the first drop varied only a few percent from the following ones for a cable which had not been magnetized. This method produced a signal which was repeatable in both amplitude and waveshape (Figure 13). As an indication of the repeatability of the test, for this series of drops, the average value was 3.27 V, the maximum was 3.64 V, the minimum was 2.64 V, and the percentage standard deviation for 17 drops was 7.3%. This cable had not been magnetized, so signal did not decrease as in laboratory results discussed above. This effect is discussed in more detail below for cables in the field.

For the test discussed here, a standard round MILES cable was used, and the output signals were obtained with a MAID processor which had been modified to provide an analog output signal.

The magnetic sensitivity was measured with a battery powered oscillator driving an air core coil. The oscillator frequency (3 Hz) was chosen to be within the MAID bandwidth. No attempt was made to calibrate the coil and oscillator to provide a known magnetic field at the cable, but this could be done. Instead, a constant amplitude was used and measurements relative to other sections of the same cable were compared. The output of the oscillator was adjusted to give a reasonable output from the MAID/MILES and then left at that setting.

The coil and oscillator are useful to determine the location of transpositions in the cable--when the axis of the coil is oriented parallel to the cable, a null in cable output occurs when the coil is adjacent to a transposition. The null is sharp and the transposition can be easily located within a few centimetres (Figure 14). The coil and oscillator can also be used to locate the cable.

Figure 13. Typical pipe drop signal
Scale: 200 mv/mm vertical, time, 5mm/sec.

-20-

Figure 14. MAID/MILES output when excited by coil and oscillator
moving at a uniform rate above buried cable.
Scale: 200 mv/mm vertical, time 5 mm/sec.

Data was taken by performing the drop tests on the center of a given winding and then performing the magnetic sensitivity test on the same winding. The drop test was performed 10-20 times at each test point on the cable and the peak-to-peak readings averaged for the final result for that point. Data was taken at 11 random points along a 100 metre cable. The results are shown in Figure 15. The correlation coefficient correlating stress and magnetic sensitivity for this data was 0.46.

A similar test was performed on a cable set in a concrete pad. This cable was only six windings long. The data for these six windings are shown in Figure 16. It can be seen that the magnetic response was essentially constant, while the stress response varied by a factor of two. The correlation coefficient calculated for this data was -0.13.

In order to determine if results from some of the laboratory experiments could be duplicated in the field, experiments similar to those performed in the laboratory were performed on the cables, one in concrete and one in soil. The pipe drop test, using a 7.6 kg weight, was used to produce stress signals in the buried cable. The cable was either magnetized using a large coil with DC voltage applied to it or demagnetized (according to sequence shown below) using the same coil with an AC voltage applied to it. For the cable in concrete, the following series of results were obtained:

Magnetic Condition	Peak-to-Peak Drop Test Signals
No magnetization or demagnetization previously performed	1.4 volts
Magnetized once	3.1 volts
Magnetized again	3.8 volts
Magnetized again	5.2 volts
Demagnetized	0.6 volts

On all but one of the tests on the cable in concrete, following magnetization of the cable, the signal decreased after the first drop; the signal for the first drop was from 13% to 35% larger than the average for the series; for one series the first drop produced a signal that was equal to the average. This corroborates the laboratory results that showed that after magnetization the sensitivity decreased rapidly after a few pipe drops. However, for a cable either in concrete or in soil the decrease was only 35% or less, compared to the large decrease in the laboratory results. This small effect would not degrade an operational sensor. Also, after

Figure 15. Magnetic and seismic signals for 11 positions along cable buried in soil.

Figure 16. Magnetic and seismic signals for 6 positions along cable buried in concrete.

the decrease had occurred, the sensor was still considerably more sensitive than before magnetization.

SUMMARY

This paper has presented the results of laboratory and field measurements of magnetic and stress properties of MILES cables. It has been shown that the application of a large DC magnetic field has little effect on the magnetic mode sensitivity while it generally increases the stress mode sensitivity. After magnetization this improvement decreases when stressed a few times, but this effect was much greater in the laboratory work than in the field results. The small effect would not degrade an operational sensor, and, even after the decrease, the sensor was more sensitive than before magnetization. The sequence of magnetizing and demagnetizing can be repeated many times with no change in the results observed. Although the laboratory work hints that all cables can be improved by magnetization, some cables in the field are not improved, and it is not known why. Although magnetic properties such as reversible permeability and coercivity are drastically affected by mechanical cold working, the stress mode response does not appear to be as strongly affected. Finally, correlation between stress and magnetic sensitivity is apparently very poor. One as yet unanswered question which could not be addressed in this work is the long-term effects of magnetization. The work reported here was performed in order to better understand the operation of the MILES cable. In those few operational cases where its sensitivity is not adequate, the DC magnetization technique can be used to improve its sensitivity.

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References

1. Starr, J. B., "Status Report for Period 1 July 1976 to 1 August 1976, MILES Signal Enhancement." Honeywell Report W3821-PR3, 9 August 1976.
2. Rome Air Development Center, "Solid Core Round MILES (Feasibility Trade-Off Study)," Honeywell, Inc., RADC-TR-77-46, January 1977.