Bureau of Mines Research
on Trailing-Cable-Fault Locators
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By George J. Conroy

ERRATA

On page 3, lines 4–6 should read as follows:

where \( R_1 \) is measured between A and C when A and B are shorted together and C and D are also shorted together,

\[ R_2 \]

is the measurement between A and B with the opposite end open-circuited,

and \( R_3 \) is the measurement between C and D with the opposite end open-circuited.
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ABSTRACT

This Bureau of Mines publication describes several fault locators and methods, including time domain reflectometers, a frequency domain reflectometer, tone generators, an infrared method, the Murray loop method, and high-voltage "click" methods. The Bureau of Mines has been conducting research into these methods for several years, to improve mine safety and facilitate production through rapid, safe location of trailing-cable faults. The problems encountered in practical applications are discussed, and schematic diagrams of several instruments fabricated by the Bureau are presented. Since no present single method of locating trailing-cable faults is universally applicable, a kit composed of several of the more promising fault locators is advisable.

INTRODUCTION

At the Bureau of Mines, research into various methods of locating faults in trailing cables has been pursued for several years. The types of fault concerned are trailing-cable short circuits and open circuits which, either because of the nature of the fault or because of the rapid action of protective devices, do not at the time of occurrence discharge sufficient energy into the insulation to cause visual evidence such as a scorch mark, swelling, or blowout. The term "short circuit" as employed herein is not restricted to zero-resistance faults, but includes partial shorts with high values of shunt resistance. Similarly, the "open circuits" discussed here need not have infinite resistance. It is usually best to try to locate faults of this type quickly, with the cable right in place, because cooling, drying out, and mechanical movement can each have effects that tend to temporarily clear or cancel the fault. (Mechanical movement can also have the opposite effect, which is why it often pays to flex the cable at suspicious points when making tests.)

Table 1 at the end of the report summarizes fault-location methods examined by the Bureau of Mines.

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ESTABLISHING THE CHARACTER OF THE FAULT

The first step in electrically locating a fault should be to obtain its resistance. If the cable can be physically disconnected at both ends, this isolation should be done; otherwise, the cable should be uncoupled at the power center and switched off, if possible, at the machine. An exception might occur when using an infrared probe detection method (to be discussed). Generally, however, the cable should be electrically isolated.

Usually the first measurement is made with a Megger\textsuperscript{2} tester (fig. 1). The "ohms" scale of the Megger can be used to check on conductor continuity to find an open circuit; the various ranges can be used to detect short circuits. A low insulation resistance between two conductors indicates a short. If the value using the "ohms" scale of the Megger is zero or very low, it pays to measure resistance with a battery-powered instrument such as a multimeter. The Megger tends to read low compared to such instruments, and since just a few ohms' resistance can render many fault location methods unusable, it is well to know from the beginning what to expect.

FAULT LOCATION BY RESISTANCE MEASUREMENT

Searching for the fault is easier if an approximate location can first be determined through measurements at the terminals of the cable. In theory, a series of simple resistance measurements could accomplish this. The problem here is the requirement for precision and sensitivity. Figure 2 is a representation of a short-circuited cable. With three measurements, the

\textsuperscript{2}Trade names and company names are used to facilitate understanding, and their use does not imply endorsement by the Bureau of Mines.
The value of the fault resistance cancels out, and the ratio of fault distance, X, to the total length, L, is found to be

\[
\frac{X}{L} = \frac{1}{2} - \frac{(R_2 - R_3)}{8R_1}
\]

where \( R_1 \) is measured between A and B when C and D are shorted together,

\( R_2 \) is the measurement between A and B,

and \( R_3 \) is the measurement between C and D.

As an example, in figure 3 if we measured \( R_1 = 0.06 \), \( R_2 = 10.04 \), and \( R_3 = 10.20 \) ohms:

\[
\frac{X}{L} = \frac{1}{2} - \frac{(10.20 - 10.04)}{8 \times (0.06)} = 0.5 - 0.33 = 0.167
\]

\[
\frac{X}{L} = \frac{1}{6}
\]

The difficulty is that the resistance measurement must have much better than 1/2 percent precision, in order that the conductor resistances, on the order of hundredths of an ohm, can be distinguished in the presence of the 10-ohm fault resistance. If the fault had higher resistance, even more precise and sensitive resistance measurements would be required.

**BRIDGE METHODS**

A resistance method that avoids the problem of extremely precise measurement is the Murray loop method (fig. 4). It is drawn as shown to emphasize the bridge aspect. As the fault is not part of the bridge arms, it does not dictate the precision requirements. There is a limit as to how high the resistance can be without reducing sensitivity to below a practical level, and this limit depends on the kinds of current source and null detector used; however, with available apparatus, shorts with several thousand ohms can be located. The expression for locating the fault is

\[
\frac{X}{L} = \frac{R_1}{R_{\text{total}}}
\]
If there are intact conductors in the cable in addition to the faulted ones, it may be possible to use them as connecting leads, with jumpers at the far end of the cable, to avoid problems of stretching wires to both ends. This only applies, of course, if the far-end terminations are accessible for connection.

The short-circuit locating apparatus can be ac or dc. There are some advantages to low audiofrequency measurements, because interference can be better controlled. Also, since there are fewer problems in amplifying an ac signal than a dc one, highly sensitive null detection is easier to obtain. The apparatus utilized in recent Bureau of Mines tests at low frequency was laid out on a breadboard for the purpose; no commercial units have been evaluated for use in mine environments. The components consisted of a slidewire potentiometer prepared from a single strand of high-resistance wire about one-half meter long (5 ohms' total resistance), a machined-brass slider contact, terminals, a capacitor-isolated tone generator with added series resistance to limit overloading, and an oscilloscope to serve as a null detector. Trials with a 10-turn wire-wound potentiometer indicated that this might be a suitable replacement for the slidewire, provided a commercially available unit can be obtained that has a total resistance well below 50 ohms.

In analogy to the resistance method of locating short circuits, there is a capacitive method for open circuits. Figure 5 shows a representation of a cable with one conductor open-circuited. The capacitors in the sketch represent the distributed capacitance between conductors. An ac capacitive impedance method can be used to locate this fault, as shown in a simplified manner in figure 6. The circuit shown is academic and is not available in a commercial instrument. Available commercial devices utilize a Wier, Schering, or other bridge circuit incorporating resistances in the branches. Using the commercial devices, it would actually be necessary to independently measure the capacitances from each end of the cable. Finally, however, the expression for fault
FIGURE 5. - Cable with open-circuit fault. Distributed capacitance per unit length is represented symbolically by lumped capacitances.

FIGURE 6. - Theoretical representation of a capacitive bridge method of locating open-circuit fault. Location would be the same as for the bridge circuit shown:

\[ \frac{X}{L} = \frac{C}{C_1 + C_2}. \]

A problem that in many circumstances rules out the capacitive method, at least for unshielded trailing cables, is that the long cable length picks up radiated interference and makes it difficult or impossible to find a null. This problem does not occur so prominently with the resistance bridge method of locating short circuits because relatively high measurement currents are involved there, making interference less noticeable.

There are other bridge methods used for fault location. In some, applicable to cable manufacturing facilities, etc., a standard cable is compared with the faulted cable. This probably gives the highest accuracy since normal cable inductance, capacitance, series resistance, and insulation resistance will be balanced out simultaneously.

CONTINUOUS-HIGH-VOLTAGE AC OR DC

If a continuous high voltage in the range 10 to 40 kv is impressed across a faulted pair, there can occur a release of energy at the fault sufficient to permit detection either by visual or acoustic means or by detection of the magnetic field. Visual methods include observation of smoke, but a more reliable scheme requires that the cable be immersed in a water trough and observed for the occurrence of streams of bubbles. The acoustic method involves observing the cable to hear the crackling of an arc, usually using a probe containing a microphone and amplifier. A probe is also required for detecting the presence of a magnetic field caused by a current loop through the cable. The contribution made by the high voltage is to
break down a high-resistance fault to a value low enough for the current to flow at least momentarily. High-voltage methods are much used in cable repair shops, because they can reveal insulation weaknesses as well as established faults. The high voltage itself, however, can have a weakening effect on good insulation. Also, a considerable personnel hazard is involved unless test conditions and test area are carefully controlled. An improvement over the continuously applied-voltage method employs "chumper" apparatus, as shown in figure 7; however, this method retains some of the personnel hazard aspects and is not presently recommended for inplace fault locating in underground mines. "Blowing" the fault by connecting the cable to a trolley line or other

FIGURE 7. - Biddle Co. impulse generator.
high-power source is likewise not recommended, because of fire hazard and the possibility of injuring personnel.

PULSE-ECHO METHODS

Another category of pulse testing, the pulse-echo methods, has none of the danger of the high-voltage test and yet is an extremely versatile means of fault location for open circuits and low-resistance shorts. Any discontinuity in a conductor or the insulation in a cable will tend to reflect a pulse back to the origin. If the discontinuity is an open circuit, the echo will add to the amplitude of the pulse; if it is a short circuit, the echo will subtract. If an electronic circuit is built capable of distinguishing this amplitude effect and of measuring the time interval between the start of the pulse and the arrival of the echo, both the nature and the location of the fault can be established. Figure 8 is a simplified illustration of a pulse-echo system.

More than one basic system fits into this category. The amplitude or the frequency of the originating pulse may be varied, with corresponding selection of the detection circuitry. The system may rely on analog or digital processing. A cathode-ray oscilloscope is essential to some approaches but can be eliminated in others. The systems that have been the subject of Bureau of Mines development programs involve time domain reflectometers (TDR) and frequency domain reflectometers (FDR). A combination TDR and tone generator was built by FMC Corp. in 1973 under Bureau contract.\(^3\) This unit locates short circuits that have resistance values no higher than several ohms and open

\(^3\)FMC Corp. Protection and Troubleshooting of Coal Mine Electrical Cables.


circuits that have at least 100 ohm's resistance. An improved version was developed by Carnegie-Mellon Institute, Pittsburgh, Pa., again under Bureau contract, and was then the subject of a purchase contract with Preiser Co., Charleston, W. Va., under which four mine-duty models were built (fig. 9). These units can define and locate short circuits with resistance of 100 ohms or less and open circuits of 100 ohms or more. The logic diagram for the latest version is shown in figure 10, and its schematic diagram is presented in figure 11. Some minor research is continuing on this model, seeking to replace some of the TTL (transistor-transistor logic) integrated circuit modules with CMOS (complementary symmetry metal oxide semiconductor) modules, in order to reduce current drain and thereby extend the interval between battery charges.

A third-generation system was also developed by Carnegie-Mellon, with field-test models being fabricated by Bendix Corp., Baltimore, Md., under Bureau contract. It includes a microprocessor programed to provide immunity from noise and other causes of inaccuracy, and a time-varying pulse detection concept by which a number of discontinuities can be located in one operation, if several are present along the cable. The Bendix model utilizes a single-card Intel 8080 microcomputer and incorporates an independent "gross fault" indicator intended to provide preliminary fault detection. Twelve units are currently being tested by the Bureau of Mines.

One of the most effective methods of utilizing a TDR has not yet been applied to inplace testing of underground mine cable. It involves direct comparison, on an oscilloscope screen, of the traces from a good and a faulted conductor pair. The anomalies provide fault location information. There is a high probability that the latest microprocessor TDR can be further improved to approximate this method of operation while retaining the advantages of a digital display, by including nonvolatile memory capability. This is one of the aspects being investigated by Carnegie-Mellon University under Bureau contract.
FIGURE 10. - TDR logic diagram.
FIGURE 11. - TDR schematic diagram.
There are TDR's on the market other than the Bureau of Mines items. Hewlett-Packard has had one for years. Tektronix currently supplies two models of an instrument (fig. 12) that includes a tiny chart recorder as well as a cathode ray tube. Biddle's "radar" unit employs pulse-echo principles. Furthermore, TDR's can be built up from a few integrated circuits and an oscilloscope. For underground mine use, the digital display is preferred to an oscilloscope pattern, because lower voltages are present in the apparatus and because less specialized skill is required for interpretation of results. Also, the simpler TDR circuits do not detect high-resistance short circuits.

The use of the microprocessor promises to increase the upper limit to 10,000 ohms or higher.

FIGURE 12. - Tektronix, Inc., TDR.

A limitation of the use of pulse methods such as the TDR is that, even assuming the electronic location is precise, the distance read must be associated in some way with distance along a real cable lying on the ground. It would take unusual confidence to pace off a stated distance and cut the cable at a particular spot, with no better evidence than the TDR reading. What is needed is a probe that provides an unequivocal indication when it is brought into the immediate vicinity of the fault.

If an audiofrequency signal is applied to the end of a shorted pair, the current will flow as shown in figure 13. A magnetic field is produced by the current flow. If we consider current "i" at a particular instant, we see that while the electromagnetic fields from the two wires would cancel each other at any large distance from the cable, they do not balance out in its immediate vicinity. Therefore, if a probe with a loop of wire is brought close to the cable as shown, the net field will induce a current in the coil. This is amplified and yields meter deflection results.

This location method is very effective for low-resistance shorts, where the loop current is appreciable with low applied voltage, so that a fairly strong magnetic field is there to be sensed. A low applied voltage is advantageous for trailing-cable-short-circuit detection using a probe, because otherwise the potential on the conductor can provoke a response due to electrostatic coupling; sufficient potential may continue to be present at points beyond the short circuit so that this response is still provoked and the fault location is not therefore evident.

A higher resistance short may be detected by increasing the sensitivity of a probe; however, one other effect must be considered in some cases. If multiple short circuits exist, and one closer to the tone generator has higher resistance than the others, two or more branching-loop currents may be established, masking the location of the first short. It is then necessary to begin the location process at the far end of the cable, clearing each short circuit before proceeding to locate the next.
While the TDR finds the approximate location of short circuits with equal ease in shielded and unshielded cables, the precise location by the tone generator method is significantly more difficult in shielded cable. The shield severely attenuates the signal, and the generator must be capable of supplying a range of frequencies in order to provide a penetrating signal. The probe must have high sensitivity.

The tone generator utilized may be included in the same enclosure with the TDR, to provide immediate use without changing connections after the TDR's approximation has been obtained, or it may be a separate item to be used alone. Figure 14 shows a miniature, low-cost tone generator and probe combination.

**FIGURE 14.** - Low-cost tone generator-probe set for short-circuit location.

**FIGURE 15.** - Tone generator schematic diagram.
designed by the Bureau for locating low-resistance short circuits. The schematic diagrams of the tone generator and the probe are presented in figures 15 and 16, respectively.

With a few modifications, the basic system can be adapted to locate open circuits through sensing the electrostatic field. The modified set is shown in figure 17, with schematics presented in figures 18 and 19.

FIGURE 16. - Audioprobe schematic diagram.

FIGURE 17. - Low-cost set for open-circuit location.
FIGURE 18. - Tone generator modification for open-circuit location.

FIGURE 19. - Modified audioprobe schematic diagram.

While a switching scheme has not yet been adopted for these particular units, there is little doubt that the changeover from short-circuit to open-circuit location mode could be accomplished by switching a single system, just as is done for the combination incorporated with the TDR, rather than having one complete circuit for open circuits and another for short circuits.

One apparent disadvantage of the method involving only a tone generator and probe—-that of having to walk the entire length of a cable while holding the probe in contact—can be avoided to a large extent by using a bracketing technique. After listening for the tone at one end, spot-check every
hundred feet or so along the length, and when a change in tone is experienced, go back half the distance from the last spot and listen again. Successively reduce the separation between readings until the cable length that must be continuously probed is a manageable distance.

Other methods of utilizing the tone-generator-plus-probe approach are currently under study at the Bureau of Mines.

INFRARED DETECTION

There might be one exception to the desirability of isolating the cable prior to fault location attempts. This would occur when an infrared detector probe is immediately available in the mine section just after a fault has occurred. Cable condition could then be explored before the heat dissipated in the fault has distributed itself over the cable and its surroundings.

The more common case of infrared fault detection, however, requires that the cable be isolated from source and machine, and connected to a high current-low voltage power supply. Only faults of resistance less than 70 ohms can be located in practice, and the ideal fault for the device is a "bolted" short created by a strand of wire that pierces the interconductor insulation. The infrared probe developed by the Bureau of Mines (fig. 20) is sensitive to a variation of 1° or 2° F, which can be obtained by dissipating about 30 watts at the fault for a few minutes of warmup time.

FIGURE 20. - Bureau of Mines infrared probe.
Despite its limitations, there is an important reason for using infrared detection. It is easily applied to shielded cable. Cable shielding strongly attenuates electric and magnetic fields but does not block the transmittal of heat. A useful combination of instruments for shielded-cable installations is a TDR, a high-current source, and an infrared probe.

**Swept Frequency Method**

An approach strongly analogous to the TDR method is the frequency domain reflectometer (FDR) system, currently the subject of Bureau-sponsored research at Stanford Research Institute. In this system, connection is made to the faulted cable pair at the power center end, and the characteristic impedance is sounded by a signal whose frequency is swept from 10 MHz to 45 MHz at a sweep rate of 100 MHz per second. A directional coupler picks off the reflected signal, which is then mixed to produce low-frequency tones in which the tone frequency is given by the equation

\[ f_t = \frac{\tau}{S}, \]

where \( \tau \) is the round-trip time to a reflecting discontinuity and \( S \) is sweep rate. The round-trip time is then related to the distance along the cable by digital circuitry.

An advantage this system has over the TDR is that relatively large energy can be directed into the cable without necessitating a high pulse voltage. Because of this and the frequency range utilized, the signal can penetrate shielding, and the precise location of a fault can be bracketed by placing a hand at various positions along the cable while the display is being observed to note location indications and relate them to that for the fault. Twelve field-test models of the FDR system will be fabricated by the contractor for evaluation in various mine and cable shop situations.

**Summary and Conclusions**

Table 1 lists the various fault-location methods examined during this research with a brief comment on each. The steps to locate a fault are, in general, as follows:

1. Isolate the cable, disconnecting from the power center, and if possible disconnecting or switching off at the machine.

2. Identify the character of the fault, using a Megger and, if necessary, an ohmmeter or multimeter to obtain a more precise reading for low resistance.

3. Approximately locate the fault using a terminal method such as the TDR.

4. More precisely locate the fault by exploring the suspected region of the cable with a probe responsive to an audio signal supplied by a source at the terminals. Short circuits in shielded cables are not in practice locatable by this audio signal but may be located by an infrared detector probe which responds to the temperature rise at the fault.
Several methods of trailing-cable-fault location have been described; none are universally applicable, but all have some possibility of application, depending on the individual circumstances. The easiest present method to use for open circuits and low-resistance short circuits in either unshielded or shielded cable is the time domain reflectometer with digital readout. At present the accuracy of this system is somewhat limited, and in any case the electrical reading must somehow be correlated with distance along the exterior of the cable. Therefore, a probe method of one type or another is usually employed after the approximate location is found by the TDR. For unshielded cable, an audiofrequency probe system is very effective for finding open circuits and low-resistance short circuits. An infrared probe system works well for low-resistance short circuits in shielded as well as unshielded cables.

Current research promises to extend the range of application of the TDR with regard to the fault resistance values that can be detected and to the precision of the location measurement. Research into FDR methods may eliminate the necessity for a separate electronic probe for relating the length information to an actual physical location, in shielded and unshielded cable, by reacting to the presence of a passive element such as a man's hand.

Meanwhile, as none of the above methods has been demonstrated to be completely effective in all situations, it is at present desirable to have a variety of instruments available for cable-fault locating, preferably assembled in kit form.

**Table 1. - Fault-location methods examined by the Bureau of Mines**

<table>
<thead>
<tr>
<th>Method</th>
<th>Equipment used</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megger</td>
<td>Biddle Co. Major Megger (many others available).</td>
<td>Preliminary to fault locating.</td>
</tr>
<tr>
<td>Murray loop</td>
<td>Breadboard (General Radio, Leeds &amp; Northrop, etc., bridges may be used).</td>
<td>Short circuits only; low or high resistance.</td>
</tr>
<tr>
<td>Capacitance bridge</td>
<td>General Radio Co. 1608A impedance bridge (smaller devices available).</td>
<td>Open circuits only.</td>
</tr>
<tr>
<td>Thumper</td>
<td>Biddle Co. 650125 impulser with 40-kv dc test set.</td>
<td>Aboveground only.</td>
</tr>
<tr>
<td>Breakdown</td>
<td>Biddle Co. 40-kv test set, water bath.</td>
<td>Do.</td>
</tr>
<tr>
<td>TDR (time domain reflectometer).</td>
<td>FMC/Bureau, CMU/Bureau, Tektronix 1501.</td>
<td>Open circuits and up to 1,000-ohm short circuits, at present.</td>
</tr>
<tr>
<td>Tone generator plus probe.</td>
<td>FMC/Bureau, CMC/Bureau, Biddle HV tone generator, with cable route tracer.</td>
<td>Open circuits and low-resistance (4 ohms or less) short circuits; unshielded cable only. Short circuits only; unshielded cable only. Short circuits only.</td>
</tr>
<tr>
<td>155-v 60-kHz source plus probe.</td>
<td>Pyott-Boone Megatron, Biddle cable route tracer.</td>
<td></td>
</tr>
<tr>
<td>Infrared probe..</td>
<td>FMC/Bureau, Barnes Engineering Co. PRT-10.</td>
<td></td>
</tr>
</tbody>
</table>