

Field Test Technology Relationships to Cable Quality

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Abstract—One of the most controversial issues in the field of cable technology involves trying to determine the status of used cable. There is no consensus within the industry or even among the so-called “experts” as to how this decision should be made.

This paper identifies methods and limitations of techniques used by different organizations. These range from recommended practices to company guidelines.

A model for insulation is presented. The results of the model are compared with common criteria used to evaluate cable.

Criteria for any installation are addressed. Simply for convenience, detailed analysis will be applied specifically to electric submersible pump (ESP) cable.

I. BACKGROUND

A VARIETY of test devices and procedures are used in an effort to determine the quality of cable. Even when using the same test device, different interpretations and widely divergent values are used by various companies.

Reuse of cable is a serious consideration in the economic evaluation of a project. A cable may represent up to one-third of the equipment cost of an installation. Even more important is the fact that premature cable failure may well result in pulling the service before payout of the installation.

A specific example is appropriate. Where reinstallation or electric submersible pulling costs are extremely expensive, many operators opt to avoid reuse of cable because of the risk. Junking a \$30,000 cable that may be perfectly good has been determined to be economically prudent in these conditions. A better way of evaluating cable for reuse is critically needed.

II. TYPES OF TESTS—ALTERNATIVES

The power industry is evaluating a number of methods for attempting to determine the acceptability of cable for reuse. There are advantages and disadvantages to each technique.

AC Hi-Pot: Since the 50/60 Hz waveform is identical to the application, this has been the most effective method for finding potential failure sites in cables. The voltage is elevated to induce failure.

The test detects point defects in cable but provides little information about the bulk properties of the insulation.

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The equipment is large, cumbersome, expensive, and potentially more dangerous than other methods. Although it is used by every manufacturer, it has not been extensively used for field cable evaluation.

Power Factor: An alternating current signal is used. It may be 50/60 Hz or high frequency. The current is analyzed to determine the presence of abnormal losses. Power factor is often called $\cos \delta$ and is the ratio of the loss (resistance) to the total energy (impedance) in a cable.

The test detects deterioration of bulk insulation properties. It does not allow characterization and location of point defects.

Multiple frequency units sweep across frequencies from less than 1-60 Hz. This requires an excessive amount of test time and is susceptible to interference from external sources of noise.

Pulsed Resonance: A series resonant circuit is used where the cable provides the capacitance in series with a variable inductor. This allows large signals to be developed from a very small energy supply. Hence, the units are comparatively lightweight and inexpensive. Since a 50/60 Hz waveform is used, the cable is stressed somewhat like application voltages.

The test primarily indicates bulk properties by partial discharge detection and changes in power factor.

The small supply is limited for long cables and cables with different dielectric loss characteristics.

Dissipation Factor Bridge: The dissipation factor is often called $\tan \delta$. This is the ratio of the resistance (loss) to the capacitive reactance (stored energy) in a cable. These devices have similar characteristics to power factor instruments.

The test detects bulk deterioration and is not suitable for locating the site of a particular fault.

Spectroscopy: Spectroscopic devices apply a broad range of frequencies to the cable. The response to the spectrum is displayed on an oscilloscope. The shape of the frequency response is analyzed to predict the present properties of the insulation. This is primarily used for bulk properties.

Very detailed analysis and description of the cable are required. This makes the technique most suitable for research and laboratory investigations. Some of the spectroscopic methods include low frequency dielectric (LFD), time-domain (TDS), propagation characteristic (PCS), and proton annihilation (PAS).

Time Domain Reflectometry: An input pulse is applied to a length of cable. The shape, polarity, and displacement of the reflected pulse can be interpreted to locate substantial impedance changes from the characteristic impedance of the cable.

The test is for locating failures, so it has potential for field testing. Attenuation of the signal becomes a problem when the cable insulation is very lossy. A TDR for communication cables will not have adequate energy for a long rubber power cable. A profile of the cable is required to compare changes in the impedance.

Murry Loop Bridge: The Murry loop is used with a high-voltage dc applied to the cable. A balance bridge is used to determine the relative fault location.

A conducting carbon path is required for the device to work. It will not work with a direct short or multiple faults. Presently it is the preferred method for locating faults.

Capacitive Discharge: A high-voltage, high-current impulse is applied to a faulted cable. The high energy enlarges the fault to the point it can be located by sight or sound.

Point locations will be located, but the insulation will be destroyed in the area of the fault.

The rapid change in voltage can cause damage to the insulation by overvoltage stress—the large energy dissipation in the cable will result in overstressing the insulation. This can lead to deterioration of the insulation when subjected to ac power.

Very Low Frequency: A bipolar pulse wave with sinusoidal transitions at a frequency of 0.1 Hz is applied to the cable. The polarity is periodically changed which quickly initiates a partial discharge at the fault. Since the signal is not a step change or impulse, travelling waves are not generated. Polarity changes prevent the build up of space charges. The test voltage is approximately three times the phase to ground ac voltage. The test is for locating local defects and voids in the insulation.

The process is somewhat similar to a TDR with a high voltage, repetitive wave. This is a new test method without a great deal of correlation to field experience. The patented device is currently available from only one manufacturer.

III. TYPES OF TESTS—DC LIMITATIONS

A number of test methods and devices use dc voltages. There is extensive data to indicate limitations of dc. First there is no correlation between the ac strength of the cable and the dc test voltages.

Next, cable that has been aged and then subjected to dc test voltage has the insulation damaged. When ac is subsequently applied, the insulation will fail at lower levels than if it had not been dc tested. Data for some cables indicate the life may be five times longer if it is not tested with dc [1], [2].

If flashover occurs during breakdown, the voltage stress causes transients which may weaken the remaining cable. The reflected waves will double the peak voltage, which can cause multiple failure or damage points along the cable.

Finally, dc allows the build up of space charge. The electric field necessary to overcome this charge is in addition to the field necessary for the insulation breakdown.

$$E_{\text{total}} = E_{\text{space}} + E_{\text{insulate}}$$

The nominal ac electric field on the insulation for a 5000-V, 90-mil cable is 55 V/mil. The dc field necessary for breakdown may be 10 times greater or more. This unusually high

stress causes deterioration of the insulation which weakens its subsequent ac strength.

Many of these problems have been long recognized on polyethylene power cables. More recent experience indicates they may also apply to rubber insulations. Treeing has been observed on the power cables and is the condition often related to insulation failure. Whether this phenomenon occurs in 5000-V electrical submersible power cables is subject to further investigation.

Despite all the above limitations, if field tests are performed, dc testing is still the method of choice. Although other methods show promise, at this time their limitations exceed their perceived advantages.

IV. TYPES OF TESTS—TRADITIONAL IN FIELD

Various tests are used to determine the performance of cable. The most common are volt-ohmmeter (VOM), insulation resistance (IR), and high potential dc tests (dc hi-pot). As with most things worth doing, more valuable information is obtained from increasingly expensive and difficult tests.

VOM: Since the volt-ohmmeter is common, inexpensive, safe, and easy to use, it is very popular. Although useful for some applications, the volt-ohmmeter is virtually useless for evaluating cable insulation. The instrument usually relies on a 9-V battery to energize the cable.

This test is only used for an initial indication of cable condition while it is still installed. About the best that can be said about a VOM test is that if the reading indicates bad, then the cable or some other component of the electrical system is bad. However, if it indicates good, little or nothing is known about the quality of the cable.

IR: The megohmmeter is a portable, moderately expensive test device that provides limited information about cable quality. The instrument usually contains a 1000-V supply to energize the cable. Some machines are rated up to 5000 V.

The higher voltage can help determine the basic performance level of the cable. However, the meter readings are subject to so many variations that consistent results are seldom achieved.

Hi-pot: The high potential dc tester is an expensive test machine which, given the present state of the art, provides the most information about cable quality [3]. Field machines are usually located at a service center. They typically can apply up to 35 000 V to energize the cable. Some machines at research facilities are rated up to 200 000 V or more.

Elevated voltage can be used to cause virtually any cable to fail at its weakest point. However, it is very difficult to interpret the readings so the quality of cable can be determined without taking the cable to destruction. Experience, skill, and knowledge of local conditions taken in conjunction with test results are major aids in analyzing the suitability of a cable for reuse [4].

V. THEORY: RESISTANCE VERSUS LENGTH

Cable insulation is essentially a large resistor that is spread over a long distance. Using finite element analysis, the insulation can be modelled as numerous resistors. Each resistor

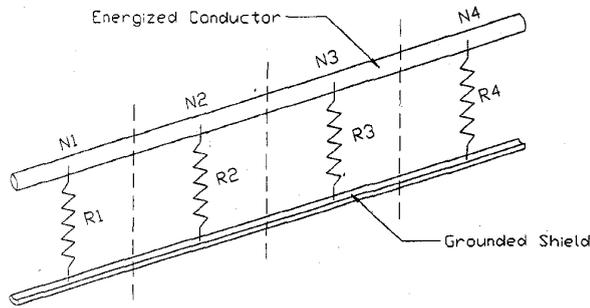


Fig. 1. Insulation resistance for parallel resistors.

represents a unit length. All the resistors between the conductor and ground are then connected in parallel to obtain the total insulation resistance as shown in Fig. 1.

Based on the relationship for parallel resistors, the total resistance will always be lower than the lowest resistor anywhere on the cable. In addition, the value will lower as the length increases.

$$1/R_t = 1/R_1 + 1/R_2 + 1/R_3 + \dots + 1/R_n.$$

The reciprocal of the total resistance, R_t , is equal to the sum of the reciprocals of all the individual resistances along the length of the cable.

End effects, associated with where the conductors are exposed to air, constitute two additional resistors. These are also in parallel with the insulation resistance.

The concept of parallel resistances is important in gaining an appropriate understanding of the total leakage current, the insulation resistance, and the leakage conductance. These have a pronounced effect on the megohmmeter and dc hi-pot leakage current test readings.

VI. THEORY: RESISTANCE VERSUS CURRENT

The insulation resistance (R) in megohms and the leakage current (I) in microamps are related by Ohm's law.

$$V = R * I.$$

It is apparent that the test voltage (V) plays a key role in the relationship. For cable insulation, the resistance varies with the length. As the length increases, the megohm value decreases. For a fixed test voltage, the leakage current must increase as the length increases.

During various tests, we have observed that the leakage current and megohm values vary over a wide range. For a particular group of conditions, one value for leakage current and insulation resistance might be appropriate, but no single number satisfies all conditions. Some of the conditions influencing both leakage current and insulation resistance include length, temperature, material, moisture, and oil gravity.

Cable length has to be incorporated in the Ohm's law relationship. If the resistance is multiplied by length the appropriate units are megohm-thousand feet ($M\Omega$ -kft). The reciprocal is called conductance and has units of micromhos per thousand feet ($\mu\text{mho/kft}$).

TABLE I
EFFECT OF LENGTH AND VOLTAGE ON INSULATION RESISTANCE

Length kft	Voltage kV	Current ua	Conduct uA/kV	Resistance megohm
1	1	0.2	0.2	5000
1	5	1	0.2	5000
1	15	3	0.2	5000
2	15	6	0.4	2500
5	1	1	1.0	1000
5	15	15	1.0	1000
10	15	30	2.0	500

Alternatively, the conductance can be expressed in units of microamps per volt per thousand feet ($\mu\text{A/V/kft}$). This term is often called the "leakage current" even though it is technically leakage conductance. It can only be considered to be leakage current when the value includes the test voltage.

When the insulation resistance is in $1000 M\Omega$, the related leakage conductance has units of microamps per thousand volts per thousand feet ($\mu\text{A/kV/kft}$). Observe that the leakage conductance is directly related to the reciprocal of the insulation resistance.

Traditionally, the industry has strived to determine one megohm number that can be used to judge the quality of any cable. Basic analysis reveals it is futile to try to define performance of all cables by using a single number read from a meter. Length, wire diameter, insulation type, construction geometry, and voltage must be considered. The example below illustrates the effect of length and voltage on the meter reading. These are based on a leakage conductance of $0.2 \mu\text{a/kv/kft}$.

The measured megohm value is not a single number, but varies with length. This corresponds to the parallel resistance model previously discussed.

VII. THEORY: RESISTANCE VERSUS WIRE SIZE

Insulation resistance is related to the dimensions of a material by resistivity (ρ).

$$R = \rho L/A.$$

Characteristic material properties are included in the resistivity. The length (L) and surface cross-sectional area (A) define the volume occupied by the insulation. Previous discussion identified the effect of length on the resistance. The area is calculated from the circumference around the conductor (πd) and the thickness (t) of the insulation.

$$A = \pi d * t.$$

Because cable insulation is essentially a tube around a wire, an alternate form of this relationship is used. It takes into consideration the overall diameter (D), the wire diameter (d), and the bulk resistivity which is a constant (K) for each material [5].

$$R = K \log D/d.$$

Typical resistance constants for high-quality electrical insulations have been determined by the power cable industry.

TABLE II
SIZE EFFECT ON INSULATION RESISTANCE,
EPDM (BASED ON $K = 20\,000\text{ M}\Omega\text{-kft}$)

WIRE Size AWG	Wire Dia (d) mil	75 mil wall		90 mil wall	
		R MO-kft	G ua/kV/kft	R MO-kft	G ua/kV/kft
6	162	5290	0.19	6020	0.17
4	205	4430	0.23	5070	0.20
4s	232	4110	0.24	4710	0.21
2	258	3680	0.27	4240	0.24
2s	292	3390	0.30	3910	0.26
1	289	3350	0.30	3860	0.26
1s	328	3080	0.33	3560	0.28

TABLE III
SIZE EFFECT ON INSULATION RESISTANCE,
POLY (BASED ON $K = 50\,000\text{ M}\Omega\text{-kft}$)

Wire Size AWG	Wire Dia (d) mil	75 mil wall		90 mil wall	
		R MO kft	G ua/kV/kft	R MO-kft	G ua/kV/kft
6	162	13240	0.076	15050	0.066
4	205	11080	0.090	12680	0.079
4s	232	10275	0.096	11775	0.084
2	258	9210	0.109	10600	0.094
2s	292	8470	0.118	9780	0.102
1	289	8370	0.120	9660	0.104
1s	328	7690	0.130	8900	0.112

These are based on years of experience at high-voltage levels. For example, the bulk constant of ethylene propylene diene monomers (EPDM) insulation for use at service levels up to 138 000 Vac is 20 000 $\text{M}\Omega\text{-kft}$ for new insulation. The polyethylene value is 50 000 $\text{M}\Omega\text{-kft}$. Many submersible cables use a polypropylene (poly) insulation. For our purposes, the same value will be used.

Insulation that has been environmentally exposed will have values that are significantly lower than these new resistance constants. Because new insulation is such high quality, lower values on used cable may still represent excellent insulation for this application.

Stranded wire will have more insulation in contact with the wire than a solid conductor. This greater contact surface causes a proportional increase in the area. In addition, a larger size wire will have a greater area.

An increase in area causes a decrease in the resistance of the insulation. Because of the very small dimensions involved in a wire configuration, any increase in area can have a dramatic effect.

The table below shows the impact of the wire configuration. The EPDM constant for new cable is used to determine the minimum insulation resistance and corresponding leakage conductance for cables with nominal 75 and 90 mil insulation thickness. The minimum thickness (t) is 90% of the nominal insulation thickness. The overall diameter (D) is calculated.

$$D = d + 2t.$$

As an example, the overall diameter for #1 AWG, 75-mil insulation is 425 mil (289 + 68 + 68).

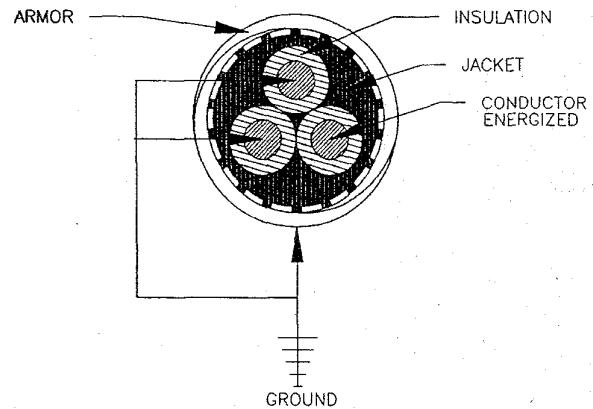


Fig. 2. Voltage gradient between conductor and ground.

It is apparent, that the measured insulation resistance changes significantly with a change in wire dimensions. The resistance will also change depending on the insulation material. The same table is recalculated for polypropylene.

When insulation resistance decreases, the leakage conductance increases. The relationships demonstrate some of the reasons why it is very difficult to have a single value of leakage conductance or insulation resistance for every type cable. These changes are for new cable. The effect is even more pronounced for used cable.

VIII. THEORY: RESISTANCE VERSUS SHIELDING

During a test or use, a voltage gradient is set up between the conductor and the ground plane as illustrated in Fig. 2. This potential difference is distributed across all the insulating materials in the electric field. Therefore, the total measured resistance depends on the insulating properties of all materials between the energized conductors and the ground plane.

If shielding is placed directly over the individual insulated wires, the ground plane is moved closer to the conductor. This reduces the resistance, so it increases the leakage conductance and leakage current. For example, a lead covered cable provides a very effective shield. Hence the leakage current values will be greater for leaded cable than for some other designs.

Most three-phase cables have the three conductors twisted into a triplex configuration. This spacing tends to fog the dimensions between the conductor and the ground plane. Hence, the insulation resistance tends to be greater than most other configurations.

IX. PRESENT STATUS: INDUSTRY METHODS

There are many diverse methods used in an effort to determine if a particular cable is suitable for reuse in an installation. For example, many users merely require that the cable be visually inspected and that it pass a five minute hi-pot dc withstand test at a specified voltage level. Even this rather straightforward evaluation method is complicated by the lack of consensus on the appropriate voltage test level for various types of cable.

For a used 75-mil, EPDM insulated cable, the dc voltages used by service centers vary widely. The minimum voltage used in the industry is usually 11 000 V. At the other extreme, some users reportedly test the same cable at levels up to 25 000 V. This extreme difference indicates a serious lack of understanding about the basic testing criteria for cable.

Furthermore, certain users attempt to establish a specified maximum leakage current. Others specify a leakage conductance which is leakage current per thousand volts per thousand feet. Still others may require that the leakage current or insulation resistance be balanced within a maximum ratio of 3:1.

X. PRESENT STATUS: RECOMMENDED PRACTICE

There are several organizations responsible for recommended practices addressing this high performance cable. An overview of the development of these guidelines has been presented previously at an international conference [6].

The Institute of Electrical and Electronic Engineers (IEEE) has three documents that address the performance of new cables [7]–[9]. These provide conservative criteria for evaluation of newly manufactured cable and acceptance of the shipped cables. The guidelines are supported by broad experience outside the submersible industry. They were developed and accepted by cable manufacturers and operators based on industry knowledge at the time of development.

These provide a starting point for evaluating used cable. Typically, low voltage IR maintenance tests are performed on cables that remain installed. Used cable is usually tested after removal from the installation because considerably higher test voltages can be applied. Therefore, the maintenance values are often regarded by some evaluators as too low for determining the condition of used cable.

Despite the lack of hard data to support their recommendations, an API Task Group is pressing forward in an attempt to provide guidance for reuse testing. At this time, the tentative draft guideline for testing used EPDM and polypropylene (poly) cable is based solely on new cable criteria. More field correlations and research needs to be done.

New cable is tested under controlled conditions at the manufacturing plant. The new cable criteria is derated slightly to allow for less than ideal conditions at the cable test facility. Then, the user and cable test shop are expected to determine their own further derating based on local conditions.

Having a point of reference provided by API will be a major step forward, but it does little to address the need for more test data to support or improve these recommendations. A broader investigation of exactly what electrical characteristics of used cables most accurately predicts field performance is severely needed.

XI. REUSE: MEGOHM CORRELATION

There is considerable controversy about the minimum required megohm reading on a used cable. The test method is widely used, but how it works on this specialty cable is not well understood. Perhaps it will be useful to review what this

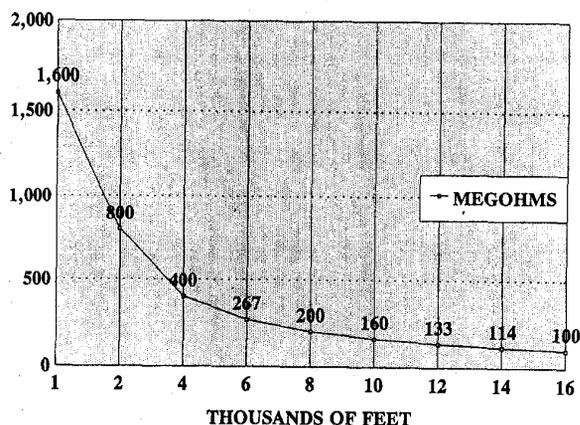


Fig. 3. Insulation resistance versus length.

test actually measures. How test results are related to cable length and other variables are then considered.

An insulation resistance (megohmmeter) test is usually performed by applying 1000 Vdc to one conductor. The other two conductors and the armor are grounded.

Fig. 3 illustrates the relationship between insulation resistance and cable length. Two assumptions are used. First, the resistance is uniformly distributed along the length of the cable. Second, the end effects are ignored.

The curve is based on a 200-M Ω resistance for an 8000-ft cable. This is a value some have used as a threshold for acceptable used cable. However, we will develop a more effective relationship later.

The graph dramatically illustrates that as cable gets shorter, the insulation resistance (IR) reading increases very rapidly. As a result, it is very difficult for those unaware of this relationship to properly interpret megohm readings as a function of length. The relationship is definitely not linear.

In addition, it should be observed that as the cable gets shorter, it becomes more and more difficult to get meaningful results. The meter has limited resolution for values greater than 5000 M Ω .

Furthermore, for short lengths, the end effect resistance begins to dominate more than the actual insulation resistance. The end effect resistance is lowered by increasing humidity, lack of cleanliness, and preparation of the ends.

One other observation from the simple parallel resistance model is worthy of further comment. The megohmmeter will always indicate a value lower than the lowest resistance along the complete length of the cable. The lower value arises because of the parallel nature of the resistors. This effect depicts how the entire length of an otherwise perfectly good cable can be condemned because a small section has been damaged locally.

In other words, one cannot determine the overall quality of a cable from the megohm reading. The value may reflect the insulation resistance and presumably the condition of all the insulation along the cable or it may reflect just the resistance of a local spot along the cable.

Because of these inherent test limitations, it is clear that megohm readings alone do not provide sufficient information

TABLE IV
IEEE TEST VALUES [7]

Thickness mils	Factory kV	Accept kV	Maintain kV
75	27	22	11
90	35	28	14

to be used as the sole criteria for evaluating the condition of a cable.

XII. REUSE: DC HI-POT VOLTAGE

The preferred method of evaluating cable at this time is the high potential dc tester. Even this respected method allows many interpretations. As a result, there is no consensus of the appropriate voltage or current levels for evaluating used cable.

The IEEE Recommended Practice [5] has generally accepted voltage values for factory test of newly manufactured and acceptance test of newly delivered cable. These were given in Table IV.

With the present improved quality of cable and the experience of the industry, the values given for maintenance tests are often considered too low for cable removed from service. Many service centers and users specify much higher dc voltages for evaluating used cable.

One part of the argument is that higher voltage will find more weak spots before installation of the cable in the well. The counterpoint of the argument is that excessive test voltage will unnecessarily damage the insulation of otherwise perfectly good cable. In addition, there is concern in some circles that repeated testing of cable may cause deterioration of the insulation. An underlying problem is the lack of experimental data or information to validate either of these arguments.

XIII. REUSE: DC HI-POT LEAKAGE CURRENT

Another difficulty arises when trying to interpret the microamp current values observed during a hi-pot test. The microamp dc current is made of three components [3], [5], [7]. These are capacitance charging current, absorption current, and conduction current.

The charging current energizes the capacitor formed by the dielectric that exists between the conductor and the ground. This current component starts extremely high and decreases exponentially. If the applied voltage remains stable, the value drops to zero within a few seconds after the test begins.

Absorption current results from the charge absorbed in the dielectric as a result of polarization of the insulation. This current component starts high but decreases somewhat more slowly. The current typically stabilizes after 5 min, although reasonably acceptable data are available after only 2 min.

Conduction current is the steady-state leakage current value. This is the current that flows over, under, around, and through the insulation. Corona discharge current from high voltage sources will also contribute to conduction current.

A low value of steady-state conduction current is commonly accepted as indicating a good cable. However, a much more

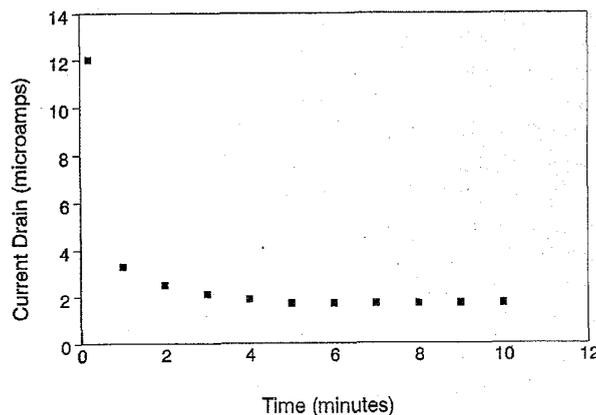


Fig. 4. Leakage current versus time.

thorough evaluation can be made by measuring the leakage current at various voltages and plotting leakage current versus applied voltage [4], [7]. If the resistance is "ideal," it will not be affected by the voltage level and the relationship will be linear. Increasing leakage current with voltage indicates that the insulation has been weakened. As cable ages, deteriorates, or becomes wet, the leakage current increases dramatically for the same applied voltage.

Fig. 4 illustrates how microamp values change during the time of a test. A new cable with a #4 AWG conductor, 75-mil polypropylene insulation, nitrile jacket and galvanized armor was used for the test. A constant 20 000 Vdc was applied to the cable. The current-time curve follows the expected offset exponential decay function, $e^{-t/RC} + F$. Time is represented by t , while $1/RC$ is the time constant, and F is a constant offset because of material characteristics.

Leakage current values are primarily influenced by materials and environmental conditions. The choice of materials for various environments has been identified by industry recognized recommended practices [10].

Some users are not concerned with the current level but simply use a dc withstand test. The approach is to apply a dc voltage level to the cable for five minutes. If the cable does not fail, then it is accepted. This approach provides no true information about comparative quality or suitability for reuse in the particular environment.

Other users try to look at the level of the microamp leakage. However, there are no consistent guidelines for evaluating these current levels.

XIV. CASE HISTORY: MEGOHMMETER LIMITATIONS

Submersible and other cable developed for specialized environments create unique problems. To demonstrate the limitations of low-voltage testers on this high-performance cable, a 3/16-in hole was drilled through the insulation on several cables. A curved, grounded, metal plate was attached above the insulation [3]. The voltage levels necessary to find the break in the insulation are shown in Fig. 5.

As a comparison, the arcing distance in free air was also measured. Two pointed copper electrodes were used. The distance between the electrodes was set with a micrometer.

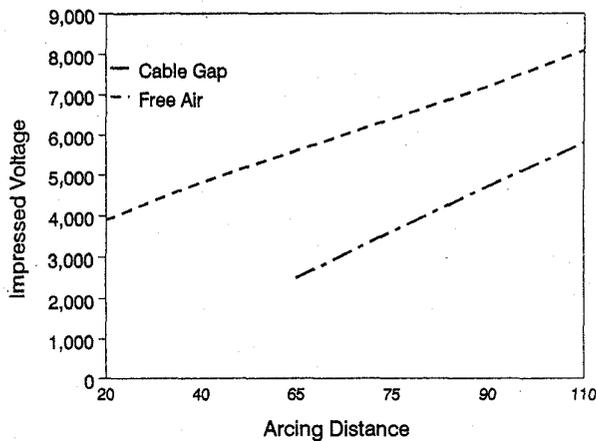


Fig. 5. Breakdown of hole in insulation.

Using a high potential dc tester, the voltage was increased until breakdown occurred.

The cable breakdown levels are lower than the free air values because of contamination around the hole. It is obvious that a megohmmeter or volt-ohmmeter cannot even find a severe breach in the insulation unless the hole is wet or badly contaminated.

XV. CASE HISTORY: UNBALANCED LIMITATIONS

At this point there is little or no data correlating the widely used megohm test with the actual ac dielectric strength of the cable. As a result, cable can be scrapped prematurely before all of its useful life has been exhausted. This situation needs to be corrected to place used cable decisions on a firmer basis.

In many situations, obtaining more complete test information on a used cable can greatly improve the evaluation decision. For example, an EPDM insulated cable was recently sent to a service center after being pulled from service. The cable had a nine-month run in a 6200-ft deep well with a 220°F bottom hole temperature. The reason for the pull was related to other components of the system and was not associated with a cable failure.

Nevertheless, tests at the service center indicated the cable was "bad" because of "low and unbalanced IR readings." The reported values were 1200, 600, and 2100 MΩ. Even though these values are higher than generally considered acceptable values, they did not meet the user's guidelines. The user's criteria were based on previous experience with a variety of different cable installed in his field over many years.

The "low reading" cable was then cut into 500-ft segments to see if any of it was salvageable. Finally, the manufacturer was informed that his product was scrapped due to poor IR readings. To try to gain more information, the user was asked to return the cable segments to the factory for further evaluation. Samples were also submitted to the University of Tulsa Power Application Research Center (TU-PARC) for their evaluation.

When the cable was received at the factory, the segments were found to exhibit much better IR readings than had been reported from the field service center. Because it is well

TABLE V
AC TEST ON "FAILED" CABLE

Phase	KV	ma
A	100	17
B	100	12
C	100	11

known that IR readings are adversely affected by the presence of gasses and light-end hydrocarbons, this finding was not surprising [11].

Several short lengths were then removed and subjected to ac breakdown tests at TU-PARC. A high voltage alternating current was applied to the cable. The voltage level was increased until the cable insulation either failed or the limit of the terminals was reached. The results are shown in Table V.

The average retained dielectric strength exceeded the 100 000 Vac strength of the terminals. That was impressive for a 3000-V rated cable that was scrapped due to "low IR readings."

The data were compared to the average breakdown strength of numerous cables tested during the three years since this service has been available at the Research Center. Typically, cable of this type that has been placed in service will breakdown near 50 000 V. It is apparent that this cable was probably retired prematurely, well before it had rendered its full useful service life.

Unfortunately, this situation is not uncommon in industry. The cause of the problem is largely due to a lack of disciplined investigation of how to evaluate the condition of used cable. The relationship, if any, between megohm, microampere leakage, and ac dielectric strength needs to be more thoroughly investigated.

XVI. CASE HISTORY: TIME BEFORE TEST

The leakage current is influenced by many factors including the physical condition of the cable, the ac strength of the insulation, the physical and chemical condition of the insulation material, and the amount of gas still absorbed in the insulation system. External influences are leakage at the ends because of improper termination, inadequate cleaning, moisture in the air, wind velocity, and insulation temperature. All these factors tend to increase the leakage current.

It is imperative that cable be stabilized to ambient conditions before comparing results. This ensures the temperature will be consistent, while gas and moisture will be allowed to migrate from the insulation system.

We have evaluated cable tested within two hours after removal from service. When the same type of cable was exposed to the same test well conditions during simultaneous tests, but was allowed to "set" for five days after removal, the test results indicated much better "quality."

The cables evaluated in this test had a 75-mil EPDM insulation, a barrier, a 60-mil EPDM jacket, and a galvanized steel armor. Subsequent investigations were made using different materials for the barrier.

TABLE VI
MEGOhmmeter VALUES

Phase	MOhms @1000V	MOhms @5000V
A-B	20,000	15,000
B-C	20,000	16,000
C-A	20,000	14,000
C-G	20,000	9,000
B-G	20,000	10,000
A-G	20,000	11,000

TABLE VII
LEAKAGE CURRENT AND AC BREAKDOWN STRENGTH AFTER DELAYS

Material	two hour		five day	
	KV	ma	KV	ma
Alpha	34	21	39	10
Alpha	34	20	42	16
Alpha	44	28	52	16
Beta	30	24	100	24
Gamma	32	23	48	19
Gamma	28	32	48	16

Representative megohmmeter results taken two hours after removal from the well are shown in Table VI.

The megohmmeter values indicate the wet cable would be expected to be good even though the 5000-V megohmmeter values indicate some deterioration of the cable insulation system.

The cables were then subjected to a high potential ac test at two hours and five days after removal. The test was halted when the insulation failed or the voltage exceeded the termination rating.

Although the magnitude of the results were different for the various materials, the effect was identical. All the cables failed at low levels when energized immediately after pulling. When the cable was allowed to dry, the results were very different. The five-day results show values as good as any used cable we have evaluated.

XVII. WHAT NEXT?: A TECHNIQUE, NOT A NUMBER!

Any values employed to determine the quality of new or used cable must be based on the bulk resistivity of the insulation. The new value is the starting point. Next, voltage and length must be incorporated.

The power cable industry recognized value for EPDM is 20,000 M Ω -kft. This gives a minimum leakage conductance of 0.2 μ A/kV/kft. The actual leakage conductance for a particular wire geometry is given by the following relationship:

$$G = 1/K \log(D/d) \mu\text{A/kv/kft.}$$

A derating factor must be applied to the bulk constant when the material has been environmentally exposed.

XVIII. WHAT NEXT?: RECOMMENDATIONS

Given the complexity of making a thorough cable evaluation, there needs to be greater involvement and cooperation between all parties that have information about the cable and its application history.

Cable manufacturers should be consulted to benefit from their knowledge of the behavior of the specific materials in a variety of well conditions.

Service centers should keep careful records of how various cables have responded to tests and how the cables have performed in conditions.

Users should participate in a program to test and evaluate cable samples on a regular basis.

Finally, manufacturers and users should support basic research into cable test methods to help improve the ability to make a correct evaluation so the maximum return can be gained from each cable investment [12].

XIX. SUMMARY

Determining the status of used cable remains one of the most controversial issues in the cable technology field. Various alternative test methods are used. These include ac hi-pot, power factor, pulsed resonance, dissipation factor bridge, spectroscopy, and time domain reflectometry.

Nevertheless, dc hi-pot remains the most common technique, despite its inherent problems. The procedure relies on leakage current measurement and the associated leakage conductance. A procedure is proposed for evaluating the leakage conductance value. Numerous tables and examples illustrate the development.

The problems of insulation resistance and unbalanced currents are identified. Case histories portray the test procedures. The effects of the cable components are demonstrated. Recommendations for future research and investigation are listed.

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