Comparison of impulse and 3 kilohertz sine wave spark testing

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■ The water immersion dielectric tank test has been required by specification and has been considered the ultimate wire insulation inspection tool for years. Unfortunately this test leaves much to be desired and is not quite as positive as it may appear. Often water does not completely penetrate the layers of the spool, or the copper resistance and wire capacitance reduce the voltage applied to a long length, or failure in the tank test damages adjacent turns and layers on the spool. Material handling, the interruption of continuous production flow, and damage to the product make the water tank test costly. In spite of these difficulties, no other final inspection method has won so wide an acceptance by consumers of insulated wire.

Results of a study were disclosed in 1966 indicating the superiority of a high voltage impulse spark test over the water tank for small diameter vinyl and polyethylene insulated wire[1]. Preliminary results were also given showing the equivalence of the two tests on PTFE insulated wire. As a result of this work the impulse test was incorporated as parts of MIL-C-13777E and MIL-W-16878D as an alternate to the tank test.

The National Electrical Manufacturers Association became interested in more effective testing methods for high temperature wire. The Technical Committee of the High Temperature Insulated Wire section initiated studies by its members of the impulse test and a newly developed high frequency sine wave spark test described by R. S. Thayer[2]. Much of the information in this presentation came as an outgrowth of these studies. It was the conclusion of the Technical Subcommittee that the high frequency sine wave spark test is superior to the water tank test. The Subcommittee also approved the impulse spark test as a substitute for the water tank test.

The shortcomings of the 60 Hz bead box spark test have been discussed by Thayer, Byrnes[3] and others. Among these are factors which prevent intimate contact between the beads and the wire insulation, such as plastic coating of the beads, missing beads, tunneling, and drape. The bead box must be horizontal and of considerable length at high wire speeds. Current sensitivity and response time of the fault detecting circuits in a typical 60 Hz spark tester now in use are apt to be poor. No provisions are ordinarily made for calibration of these important characteristics, and test voltages are sometimes too low to ionize the region between the wire and the beads. There is no certainty that the operator will not defeat the function of the spark tester by improper adjustment or procedure.

It is the purpose of this presentation to examine the effectiveness of the impulse and high frequency sine wave spark tests relative to the 60 Hz water tank test in testing for flaws in PTFE insulated wire.

Henry H. Clinton received a degree of Bachelor of Electrical Engineering in 1949 from Yale University. After spending three years with the Anderson Laboratories, Inc., in the design and development of ultrasonic delay lines, he founded his present company in 1952 and for the last 15 years has engaged in the design and manufacture of equipment for dielectric fault location, spark testing and measuring systems used by wire and cable manufacturers.

Water tank test equivalence using the high frequency sine wave

Tests were conducted on #24 solid wire coated with a 10-mil. wall of PTFE. Lengths totaling 1.49 million feet were divided into two groups in a random manner. Both groups were subjected to a conventional 3.4 kv 60 Hz bead chain spark test. Group 1 was then subjected to a 4.2 kv 3 Khz spark test, followed by a 2.0 kv 60 Hz 1 minute water tank test. Group 2 was tested in reverse sequence with the 2.0 kv water tank followed by the 4.2 kv 3 Khz spark test. Faults were removed as they were found. Results shown in Figure 1 illustrate the nearly identical results obtained. Note that insulation failures are shown cumulatively, so that each bar in the graph represents total detected failures in the group up to the stated test.

In Group 2, the second bar shows

failures occurring in the 4.2 kv sine wave spark test, and is divided. The smaller increment represents the rate at which failures occurred in wire which did not fail in the tank. The larger segment shows the rate at which faults were detected in reels which had failed in the tank, then were screened in a 60 Hz spark test to remove the defects. The greater magnitude of the second segment is attributed to damage to adjacent layers.

Figure 1 thus demonstrates the equivalence of a 4.2 kv high frequency sine wave test and the conventional 2 kv water tank test for the product tested.

Effects of increasing voltage using the high frequency sine wave

A second series of tests was run on 331,650 ft. of the same type of wire. Results are plotted in Figure 2, again in cumulative form. A 60 Hz spark test, a high frequency sine wave test, and a 2 kv 60 Hz water tank test were applied in a repeated sequence to the same wire footage. The high frequency sine wave voltage was increased by 500v for each cycle of the sequence.

As the test voltage was increased, it was apparent that fewer and fewer failures were picked up in the water tank test which followed. The rate of detected failures increased sharply with the applied voltage, as shown in Figure 3, while failures in a succeeding water tank test decreased as shown in Figure 4. No points are plotted for 6.0 and 6.5 kv since no failures were found. Occasional failures would undoubtedly be revealed if enough material were tested.

Water tank equivalence using the impulse spark tester

A new production quantity of #24 AWG solid PTFE 10-mil. wall insulated wire was divided into two test groups. The first group of 149,800 ft. was subjected to a 60 Hz spark test at 3.4 kv. After faults were counted and removed, the group was tested at a voltage of 13 kv obtained from a Clinton Instrument Co. Model IT-25 Impulse Spark Tester used with a ⅝ in. electrode, as specified in MIL-W-16878D.

Again faults were counted and removed. Then followed a 2 kv water tank test, a 14 kv impulse test, a second 2 kv tank test, a 15 kv impulse test, and a third 2 kv tank test. Faults were removed when detected.

The second group of 147,300 ft. was first spark tested at 3.4 kv, 60 Hz, then tested in reverse sequence, with the 2.0 kv water tank test preceding the 13 kv impulse test.

A comparison of the two groups is shown in Figure 6 for the first two tests. Again, note the similarity in the results. The impulse test in Group 1 picked up more faults than the tank test in Group 2, suggesting that the impulse voltage was slightly higher than necessary to match the results in the water tank test.

A typical increment in failures per thousand feet for Type E wire based on figures reported by Alexander for a second water tank test at 2.0 kv is .0574. The value for Group 1 is .0467, again indicating that the impulse voltage may be somewhat higher than necessary to correlate with water tank test results.

It is concluded that a 13 kv impulse test was found to be at least equivalent to the 2 kv 60 Hz water tank test for the detection of insulation flaws in the product tested.

Effects of increasing voltage using the impulse tester

The results of the tests performed on Group 1 are shown in Figure 5,

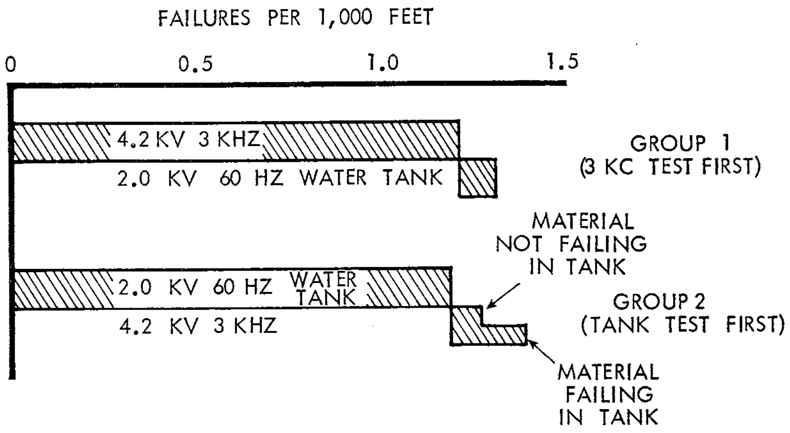
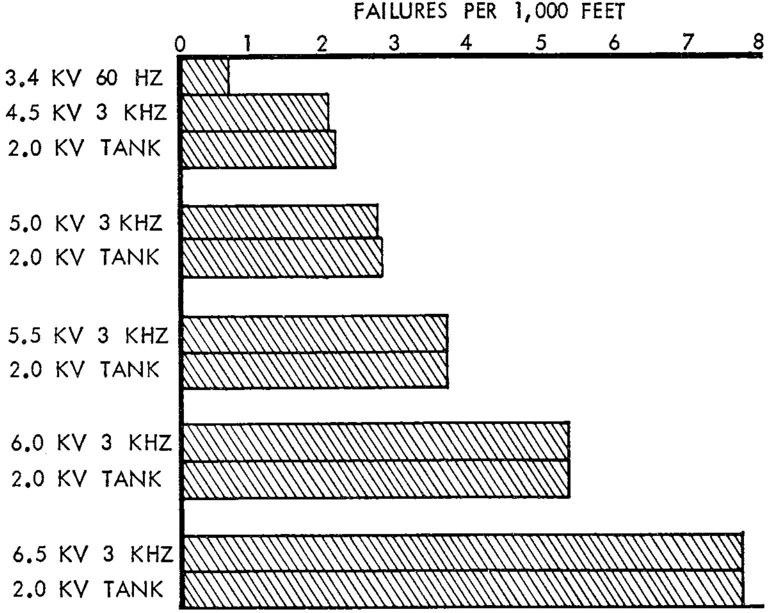


FIGURE 1. CUMULATIVE FAILURES

(EFFECT OF INTERCHANGING SEQUENCE OF 3 KC AND TANK TESTS)

(INCLUDES 60 HZ SPARK TEST FAULTS)



HIGH FREQUENCY SINE WAVE -- CUMULATIVE FAILURES ALL INSULATION TESTS, GROUP 1. FIGURE 2.

which also shows the sequence of tests. The rate at which failures occur during the impulse test rises sharply with increasing voltage (Figure 7). while failures in the succeeding water tank test fall rapidly (Figure 8).

No point was plotted for 15 kv in Figure 8, since no failures were found. A small number of failures would probably appear, however, if test voltage were increased.

High frequency sine wave and impulse comparison

It could be argued that repeated testing in itself during trials at various voltages had improved the results, and that a single impulse or high frequency sine wave spark test at an elevated voltage would not yield equivalent data. To show that repeated testing was not a significant factor, and to obtain a direct comparison between the two spark test methods, a total of 410.390 ft. of the same product which had not been previously spark tested was split into two lots. The first lot was tested with the high frequency sine wave at 5.5 kv, while the second was impulse tested at 15 kv. Each was followed by a 2.0 kv 60 Hz tank test. Results are shown in the table below:

	High Frequency Sine Wave	Impulse
Feet Tested	203,855	206,535
Faults	537	506
Faults per 1,000 Feet	2.63	2.45
Additional Faults Found in Tank	0	1
Additional Faults Per 1,000 Feet	0	.00484

This confirms the results of previous tests.

Effect of repeated testing

Lengths totaling 69,000 ft. were taken from the production line and spark tested by conventional means. This was followed by an impulse spark test at 13 kv, a second impulse test at 14 kv and 10 additional tests at 15 kv. Failures were counted in each test but were not removed.

Results are shown in Figure 9. The number of new faults in repeated testing at the same voltage diminishes with the number of trials. This test indicates that no significant damage to the product results from repeated testing, while insulation flaws which are marginal at the test voltage continue to appear, but at a diminishing rate.

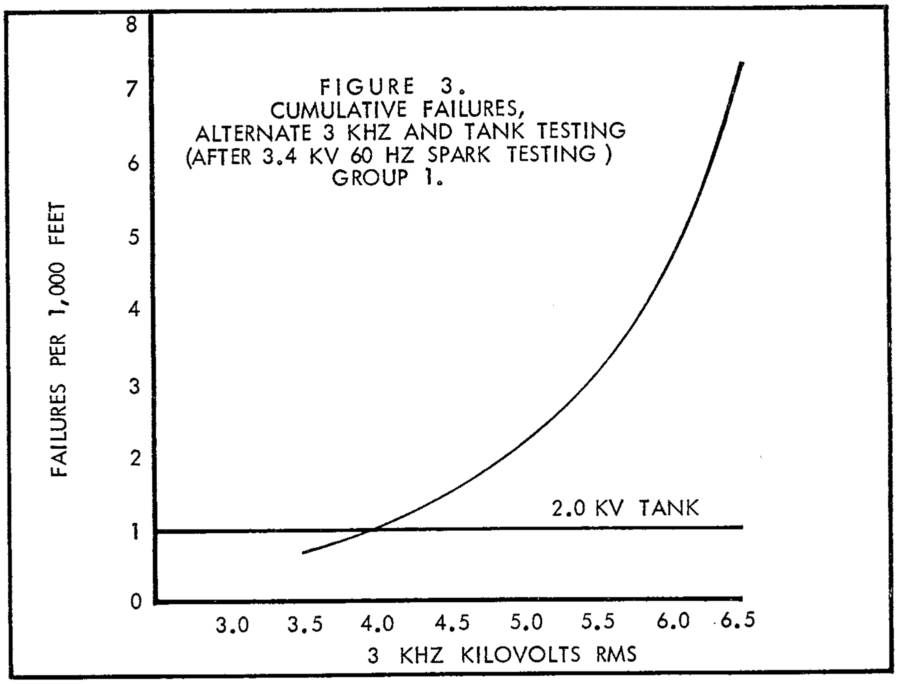


FIGURE 3. CUMULATIVE FAILURES, ALTERNATE 3 KHZ AND TANK TESTING (AFTER 3.4 KV 60 HZ SPARK TESTING) GROUP 1.

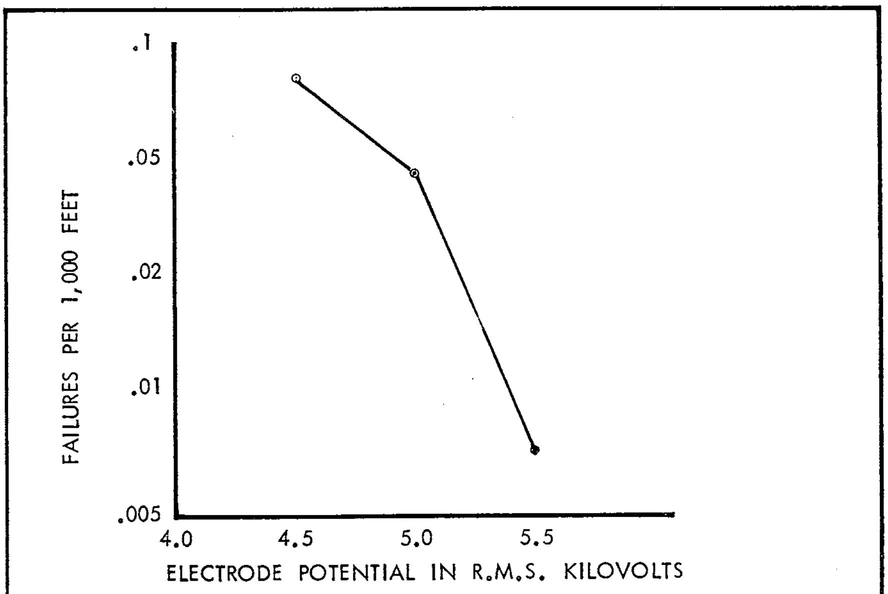


FIGURE 4. FAILURE RATE IN 2.0 KV TANK TEST AFTER HIGH FREQUENCY SINE WAVE TEST

Methods of computing failures

It has been common practice for those comparing spark testing to water tank testing to compute water tank failures in percentage of failing spools to the total number tested. The fallacy in this method is easily shown. Assume that 2000 spools containing 500 ft. of wire each are split into two 1000-spool lots. The first lot is tank tested and 40 spools are found to fail for a 4% rejection rate. The second lot is respooled onto 2000 spools containing 250 ft. each. If faults are distributed uniformly, it would be expected that 40 of these will fail in a tank test for a rejection rate of only 2%. Thus the rejection rate is halved simply by dividing each spool into two parts! Observe, however, that faults per thousand feet remains constant in each case at .04.

Distribution of faults may be such as to cause two or more to fall on a single spool. The likelihood of this occurrence decreases as failures per thousand feet diminishes and as spool length decreases. In any event, failures per thousand feet is regarded as the more accurate measure of results.

Operator errors

If either the impulse or the high frequency sine wave spark tester is part of a final manual respooling step

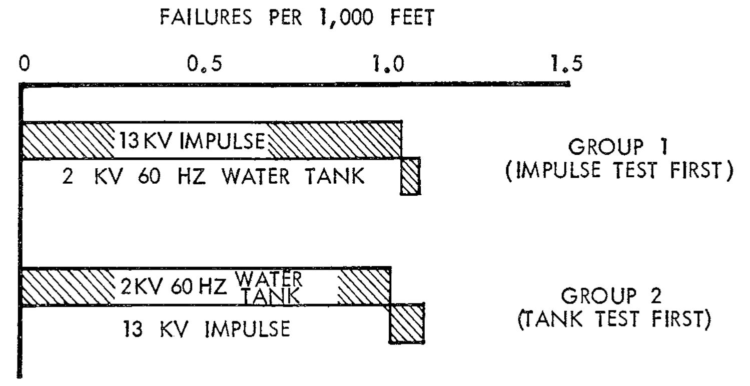


FIGURE 6. CUMULATIVE FAILURES

(EFFECT OF INTERCHANGING SEQUENCE OF IMPULSE AND TANK TESTS)

(INCLUDES 60 HZ SPARK TEST FAULTS)

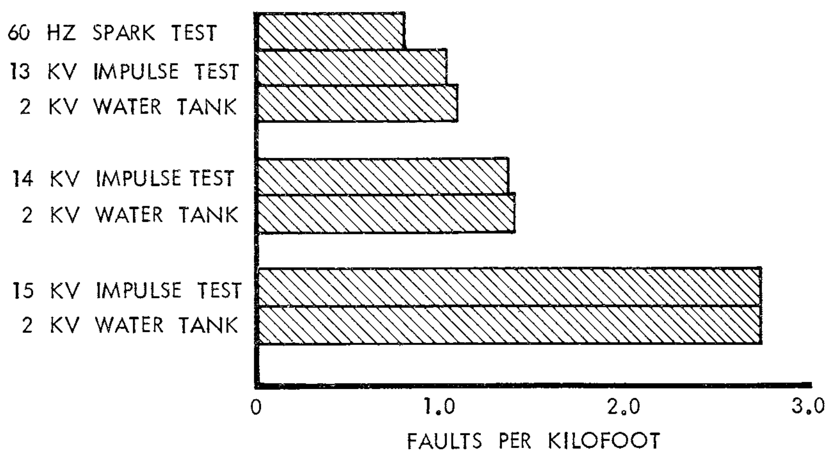


FIGURE 5. IMPULSE TEST: CUMULATIVE FAILURES IN GROUP 1 FOR ALL INSULATION TESTS

in which it is the task of the machine operator to remove faults and set test voltages, the quality of the product rests entirely in the hands of this individual. An incorrect voltage setting can make the test worthless. The inclusion of a single detected fault through carelessness or inattention in either end of one spool in 20 containing an average length of 500 ft. each may double the normal fault rate of the finished product if it is retested. This element was removed as a factor in tests results by the use of a respooler which identifies faults by marking the insulation. Once they are identified, it is an easy task to prevent these spots from appearing in the finished product.

If operator error is not to be a major factor in final inspection when conventional respoolers are used, it is essential to establish foolproof procedures for removing faults. A high voltage probe is helpful in checking the insulation for several feet on each side of a detected fault. Continuous sampling and retesting of each operator's output is also suggested as a quality control measure.

Equipment performance criteria

The spark tester has long been viewed as a go-no-go production tool in the wire and cable industry. As long as the specified voltage was maintained at the electrode, the electrode was clean and in repair, and a fault was registered when the electrode was short-circuited, the device was regarded as functional. No means have been provided to calibrate current sensitivity, response time, or other important characteristics. As a result, many spark testers now in use will not detect the passage of certain types of insulation faults. This unfortunate broadness of specification has been passed down to the new generation of impulse spark testers, so that great differences are found when the product of one test equipment maker is compared to that of another.

British standards for spark testers include a requirement that a device must respond to an arc of known duration between a needle electrode and a metal plate which moves past it in a prescribed manner. Provisions are made for the insertion of a series impedance to limit the arc current. This is the sort of performance criterion which must be invoked if the spark test is to be relied upon as a water tank test replacement.

The critical nature of the test voltage, particularly when the non-contact electrode is used, makes both accurate metering and regulation against line and load changes essential. True peak metering for the impulse tester is particularly important and is not easily accomplished. For example, a capacitive voltage divider from the high voltage terminal together with a rectifier and meter combines stunning simplicity and horrendous error, since the power required to operate the meter movement must be derived from the entire damped waveform. As a result, the meter indicates not only peak voltage but also capacitive and resistive current in the load, repetition rate, and changes in waveform damping.

The calibration method in MIL-C-13777E and MIL-W-16878D calls for a ball gap to be used as a transfer standard between a 60 Hz source of known value and the impulse spark tester. This calibration cannot readily be certified because of the approximate nature of the ball gap measurement, even when used as a transfer device[4]. The crest factor of the 60 Hz source is also a source of error. Another method which has been suggested would use a capacitive voltage divider to select a known proportion

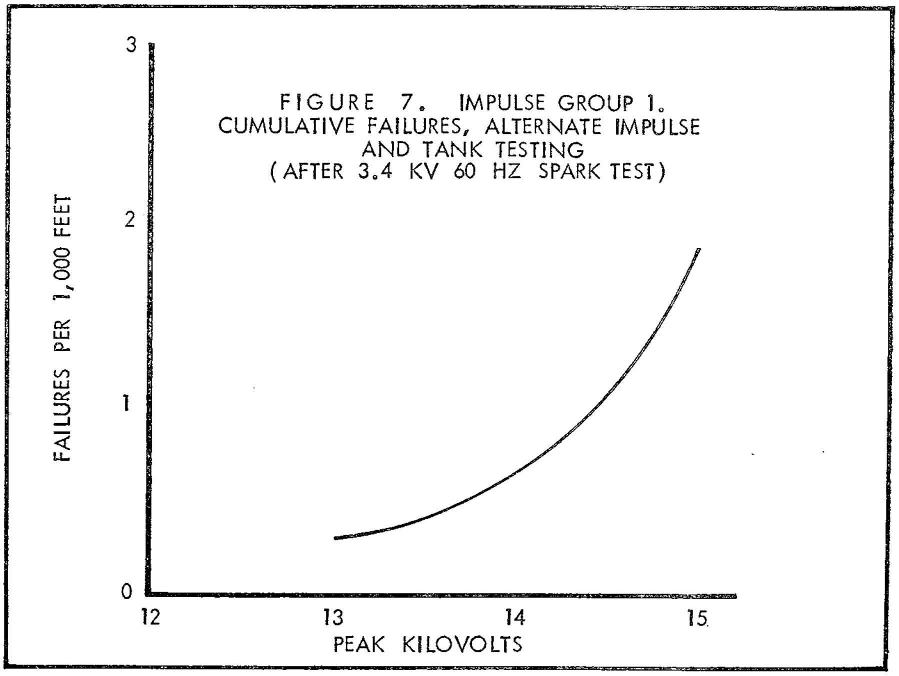


FIGURE 7. IMPULSE GROUP 1. CUMULATIVE FAILURES, ALTERNATE IMPULSE AND TANK TESTING (AFTER 3.4 KV 60 HZ SPARK TEST)

of the output voltage for presentation on an oscilloscope. The voltage reference would be a calibrated DC or 60 Hz source. The accuracy of this method is dependent upon the changes in division ratio with changes in voltage and frequency, and also upon the flatness of the oscilloscope response over the range of frequencies involved. A better calibration means would employ an electrostatic voltmeter with a peak adapter. The combination can be certified within an accuracy of 2%. The impulse spark tester waveform should be monitored with a wideband oscilloscope during calibration to observe possible effects of capacitive loading.

To insure that spark testing results are uniform and reproducible, it is suggested that the following equipment performance characteristics be controlled and periodically calibrated:

1) Peak voltage metering, no load and full load at specified power factor.

2) Fault detector response to an arc of controlled duration and current strength.

3) Response immunity of the fault detector to impedances representing normal products.

Additionally, the following are suggested as capability specifications, without the need for periodic measurement:

4) Output voltage regulation against line voltage and load changes.

5) Waveshape and repetition rate of output waveform under specified load.

Comparison of electrodes

In any discussion of spark testing, the question of voltage drop at the electrode-insulation interface immediately arises. Water or mercury electrodes provide a negligible voltage drop, but are not generally convenient or safe to apply to a production operation. Wet sponges provide a reasonable assurance of low voltage drop, provided they are kept wet and do not wear so as to lose contact with the wire insulation. Also, the water film must be removed from the wire to avoid leakage beyond the electrode.

Bead chain electrode

The spots of insulation which happen to be in direct contact with the beads in the bead chain electrodes receive the full applied test voltage, but most of the insulation surface is separated from the beads by air. If the voltage applied to the electrode is raised gradually, a large proportion of the potential appears at first across the air space. As the electrode voltage increases still further, the breakdown value of the potential gradient in the air is exceeded and the voltage drop across the air gap decreases somewhat with increasing electrode voltage above the ionization point.

The accumulation of a plastic coating on conventional bead chains in 60 Hz spark testers is a notorious source of trouble, particularly when spark test voltages are low. The situation changes at the higher frequencies, however, as follows:

To simplify the rationale, the outside of the wire insulation may be regarded as an equipotential cylinder surrounded by an outer equipotential cylinder made up of metal beads. The two cylinders are separated by the bead coating and the constant potential drop region of ionized air. Since the log ratio D/d is close to unity, the potential difference between the two cylinders is small and nearly the full test potential is applied across the wire insulation. When a fault passes through the electrode, nearly the full voltage is impressed across the bead coating, causing it to puncture as the arc forms. Since ozone is constantly generated at the electrode, any bead coating adjacent to the wire is subject to its attack. In field trials, beads near the passage of the wire have been observed to remain uncoated, while oxidized residue is found in the bottom of the electrode. No effect whatever has been noted in field trials which could be attributed to bead coating.

To confirm these findings, a bead electrode was completely coated with lacquer so that a bare wire could be run into the electrode without making electrical contact under a low voltage DC test. An insulated wire having a pinhole fault was tested at high voltage at 3000 Hz in an untreated electrode and in the coated one. No difference could be found in the behavior of the two electrodes upon passage of a fault.

Cylindrical electrode

A large diameter cylindrical electrode with flared ends will next be considered. If an insulated wire is centered in the electrode, the length of the air path to the insulation is much greater than in the bead chain electrode. The electrode voltage necessary to bring the air gap potential gradient to the breakdown point is also much greater. Experiments have suggested, moreover, that the voltage appearing on the wire insulation is related to the electrode voltage in a complicated way for several thousand volts above the corona inception value.

Annulated electrode

The annulated electrode used with the impulse spark tester is similar in behavior to that of the cylindrical electrode, except that the electrostatic

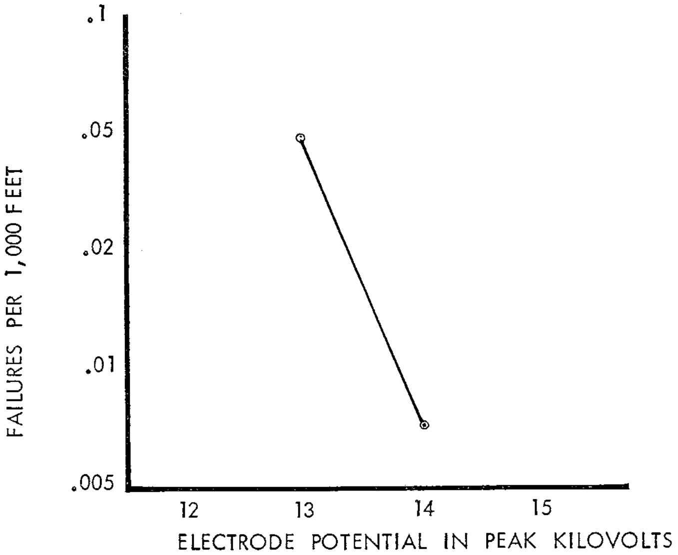


FIGURE 8. FAILURE RATE IN 2.0 KV TANK TEST AFTER IMPULSE TEST

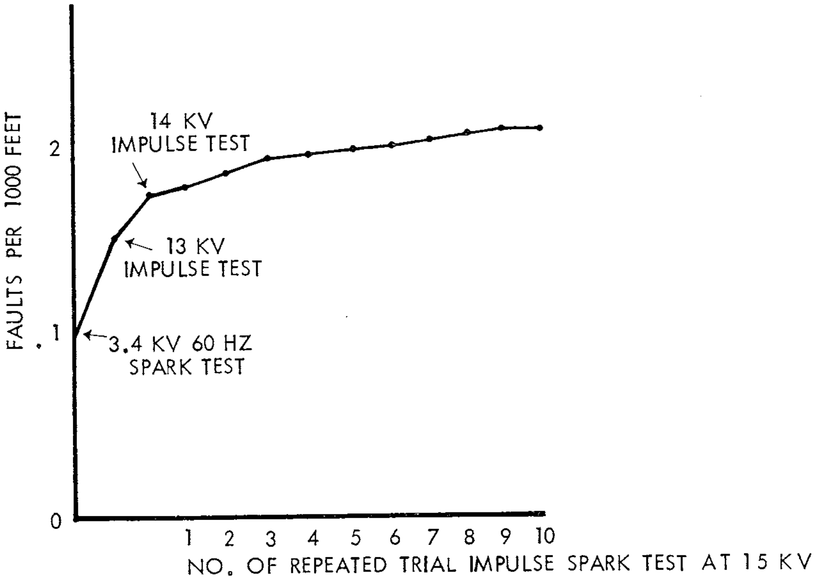


FIGURE 9. EFFECTS OF REPEATED IMPULSE TESTING ON #24 AWG SOLID .01 PTFE INSULATED WIRE

field near the insulation is not uniform along the axis. The relationship between electrode voltage and the peak voltage on the wire insulation, averaged along the electrode length, seems more linear above corona inception.

Comparison of electrodes

Figure 10 shows the approximate effects of the voltage drops across the interfaces of two electrodes, for #24 AWG solid wire with a 10-mil. PTFE wall. If a peak voltage of 6 kv is required from the insulation surface to the conductor, for example, a peak voltage of 6.4 kv is required on the bead chain electrode or 14 kv on the annulated electrode. If the electrode voltage increases from its proper value by 5% or .7 kv, the voltage applied to the insulation increases by 5% in the bead chain electrode and by 2.8 kv or 46.7% to 8.8 kv in the annulated electrode. The need for precise voltage control when the annulated electrode is used is obvious.

The effects of barometric pressure and humidity on sharp electrodes are described by Laws[4]. The breakdown potential between sharp points varies widely with their exact shape and sharpness and with humidity, particularly when applied potentials are above 10 kv. The effects of these factors on the operation of the annulated electrode have not been determined, but day-to-day variations in the applied voltage have been noted in the steep part of the curve of Figure 10. The annulated electrode was designed by the Addison Co. of England primarily for spark testing applications which prohibit contact. While it is comforting to regard the violet glow accompanying corona discharge as a conductive fluid which penetrates every insulation flaw, it should be observed that the corona discharge is simply a visual symptom of a large voltage gradient which appears instantaneously during each voltage cycle. The ⅝ in. electrode was intended for wire outside diameters larger than ¼ in. The voltage applied to the insulation of various products differs with inner and outer diameters, as well as with the insulating material used. Centering in the electrode is vital if the puncturing of insulation due to overstress is to be avoided.

Contact electrodes such as properly designed small diameter bead chains or wire brushes bring the test potential directly to the surface of the insulation with only a minor voltage drop in non-contacting regions, provided the test voltage used is above a few thousand volts.

Conclusions

1) Either the impulse or the high frequency sine wave spark test

may be used under properly controlled conditions to match or improve on the results of water tank testing for the product tested.

2) No simple way to determine the actual test voltage acting on the wire insulation over a range of product sizes was found when the annulated electrode was used. Electrode voltage drop was found to be a marked function of the D/d ratio, insulation material, insulation thickness, and wire centering in the electrode.

3) Voltage drop across the air space in the contact (bead chain) electrode was found to be low compared with the voltage applied to the insulation when test voltages of at least 4000v RMS were used in the high frequency sine wave test.

4) Strict control of both operator performance and spark test equipment performance is necessary to insure that the retest fault level in the finished product is below that which would be achieved in the water tank test.

5) The quality of the product is much higher when a properly controlled spark test is substituted for the water tank test because of the elimination of undetected adjacent layer burns caused by failures in the water tank test.

6) No indication of product damage due to repeated spark testing was found.

Appendix

Methods for determining electrode drop

A sample of wire under test was placed in a ⅝ in. annulated electrode connected to an impulse tester. The conductor of the sample was returned to equipment ground through a capacitor in the range .005—.02 mfd. shunted by a protective spark gap. Voltage across the capacitor was monitored by a 10 Mhz bandwidth oscilloscope having a high impedance probe. After a reference reading was obtained, the sample was coated with conductive paint for the length of the electrode and enclosed by a contacting metallic shield terminated at each end with a small stress flare. With the shield connected directly to the high voltage electrode, the impulse tester was then adjusted to obtain the same peak voltage as before across the capacitor. The new impulse voltage setting then corresponded to the voltage across the insulation.

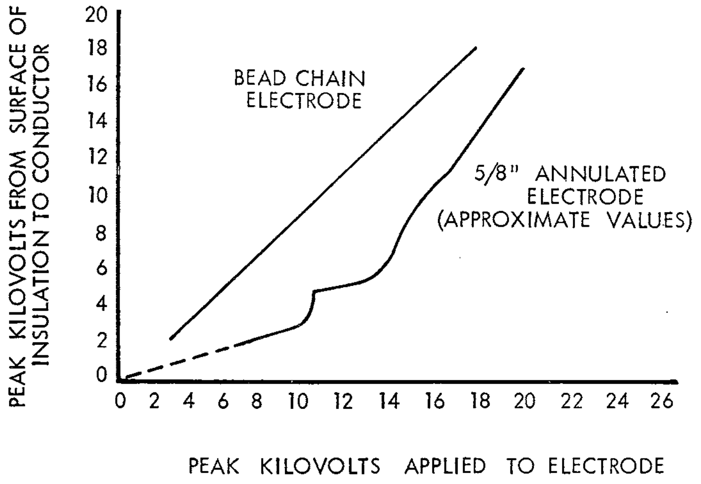


FIGURE 10. POTENTIAL APPLIED ACROSS WIRE INSULATION # 24 AWG SOLID, .01 PTFE

COMPARISON CHART

SPECIFICATIONS OF HIGH FREQUENCY SPARK TESTERS USED IN TRIALS

	(CIC Model IT-25) Impulse	(CIC Model HF-20) Sine Wave
Nominal Repetition Rate	240 pps	3000 Hz
Maximum Speed, 3 in. Electrode, 3 Voltage Cycles	1,200 ft/min.	15,000 ft/min.
Fault Detector	Single Shot Multivibrator	Single Shot Multivibrator
Output Voltage Regulation, Line Voltage Variation 105-135v	±1%	±3%
Output Voltage Regulation, No Load to Full Load	±2%, 0-50 pf at 20 kv	±5%, 0-500 Microamperes resistive
Metering	True Peak, ±3% F.S.	Average, ±3%, F.S.
Voltage Range	0-25 kv Peak	0-15 kv RMS
Electrode	⅝ in. D, 3 in. Long Annulated	240 1/16 in. Stainless steel bead chains 2 in. long in 1 in. x 2 in. pattern
Fault Criterion	700 Kilohm resistor	10 Megohm resistor at 10 kv

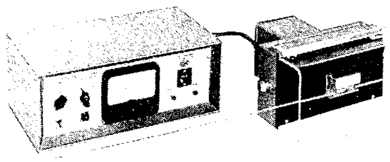


Figure 11: Clinton Instrument Co. high frequency sine wire tester, Model HF-20.

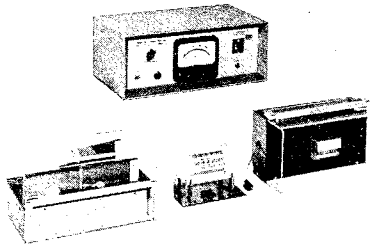


Figure 12: Clinton Instrument Co. impulse spark tester, Model IT-25.

The annulated electrode was compared to a ⅝ in. I.D. cylinder of the same length. Each electrode caused very nearly identical currents in a centered specimen when impulse voltages below corona inception were applied. Furthermore, a conductive coating on the specimen in the annulated electrode below corona inception made no difference in the specimen current. It was therefore concluded that the electrode may be treated like a cylinder of the same length and inside diameter for very approximate determinations of the voltage actually impressed on the wire insulation. A close-fitting shield the same length as the electrode was used as before for calibration purposes.

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