Cable Neutral Corrosion, Phase II Outdoor High Voltage and High Current Short Circuit Tests on Single Phase Extruded Dielectric Primary Distribution Cables

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ABSTRACT

Severe deterioration of the concentric neutral conductor as a result of corrosion presents a problem of serious concern to power and communication companies as well as to other utilities using direct buried metallic facilities. Loss of or discontinuity in the power cable neutral can cause improper operation of protective devices, unbalanced line voltages, and improper operation and possible damage to buried communication facilities. It can also create safety problems.

Corrosion of the bare copper concentric neutral wires of cables installed underground has been reported since the early 1960s. Such instances were considered isolated and due to unique circumstances such as soil conditions and galvanic action. In recent years, incidences of corrosion have been increasing and are widespread geographically. Corrosion of the bare copper wires is now attributed to soil conditions, galvanic action, concentration cells, and stray currents. In a number of cases, the cause of corrosion has not been identified with any degree of certainty.

A number of electric power utilities have employed an insulating-type or semiconducting jacket over the concentric copper neutral conductor as corrosion protection in known corrosive locations. The National Electrical Safety Code does not presently recognize the use of a jacketed concentric neutral cable in joint-random installation with communication cable unless agreed to by the parties involved and unless a separate bare neutral conductor, of adequate size, is provided close to the power cable. Hence the use of jacketed cable has been restricted to cable buried in a separate trench or in a common trench with minimum specified spacing maintained from the communication cable.

The objective of this project was therefore to establish the performance of insulating-type and semiconducting jacketed concentric neutral cables in comparison with bare copper concentric neutral cable under fault conditions from the standpoint of transient voltage gradients developed in the earth. It was considered that data generated in this project could be employed as substantiation for a change in the National Electrical Safety Code to permit the use of jacketed

concentric neutral cable in joint-random installation with communication cable in locations corrosive to bare copper.

The tests encompassed staged and prestaged fault tests on direct buried, 15-kV and prestaged fault tests on direct buried, 35-kV crosslinked polyethylene insulated cables of various concentric neutral conductor designs without jackets; insulating and semiconducting jackets were included as dictated by good design practices. The fault tests on the 15-kV cables were performed at rated voltage to ground with symmetrical currents of 5 and 10 kA with a prescribed sequence of circuit breaker reclosures. The 35 kV cables were similarly tested at 10 kA only. The tests were performed in a generally similar manner to those conducted in 1959 by the Joint EEI-Bell Systems Subcommittee to Study Buried Distribution Systems.

The main conclusions drawn from this project are:

- Bare and semiconducting jacketed cables exhibit essentially the same transient voltage gradients (touch-and-step voltages) when tested under similar conditions.
- Cables with an insulating type jacket will yield higher touch voltages and lower step voltages than cable with bare or semiconducting jacket under equivalent circuit impedance and earth resistivities.
- The voltage at the fault is determined by the supply voltage and circuit impedances and is a dominant factor in determination of touch-and-step voltages.

This report will be forwarded through proper channels for study by the members of the committee of the Underground National Electrical Safety Code. This committee will be requested to consider acceptance of jacketed concentric neutral cables in joint-random installation with communication cables.

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Section 1

INTRODUCTION & SUMMARY

INTRODUCTION

The earliest installations of bare concentric neutral rubber insulated single phase underground residential distribution (URD) cables rated at 5kV dates back to the late 1930's. Similar cable rated 15kV and new designs of bare concentric neutral single phase cables employing extruded high molecular weight polyethylene insulation, a semiconducting polyethylene insulation shield and a concentric tinned copper conductor were first used for 15kV URD late in the 1950's. Crosslinked polyethylene insulation was first used for similar applications early in the 1960's. The satisfactory performance of bare copper conductors buried directly in earth for decades gave the industry a sense of security that the bare concentric neutrals would not be adversely affected by a hostile environment.

By the early part of 1959 consideration was being given to joint-trench installations of power and telephone cables in the interests of reducing the cost of URD. In order to obtain information about the probability of damage to telephone cable from faults on adjacent power cables in joint-trench installations and on the possible hazard to personnel from power cable faults initiated by digging operations, a test program was conducted by the Joint EEI-Bell Systems Subcommittee to Study Buried Distribution Systems. These tests were conducted at the old Line Materials Industries Short-Circuit Laboratory near Franksville, Wisconsin. Test results obtained in this investigation, and the subsequent recommendation made in the report[+], [++]led to requirements imposed on the electric utilities by the National Electrical Safety Code and communication companies. These requirements stated that a buried bare

[+]A Report of the Joint Subcommittee to Study Buried Distribution Systems Edison Electric Institute and Bell Telephone System Entitled "Buried Power and Telephone Distribution Cable Effects of Primary Faults", dated November 1960.

[++]EEI Publication 68-62, June 1968 "Buried Power and Telephone Distribution Systems Analyses of Primary Cable Fault Tests and Evaluation of Experience with Random Separation."

conductor in close proximity to the primary cable or as a concentric conductor over the outside of the cable must be provided in joint random installations of power and communication cables. This practice was deemed advisable in order to minimize step and touch voltages under fault conditions.

This recommendation, in conjunction with the successful experience with bare concentric neutral type single phase URD cables, perpetuated the practice of using bare concentric neutral type cables for URD applications in underground duct and direct earth burial. Corrosion of the copper concentric neutral wires was first reported in the early 1960's. There has been a steady rise in reported incidences of corrosion since that time. In the mid 1960's, a cable employing a semiconducting polyethylene jacket over the concentric conductor was utilized in isolated cases where corrosion of the tinned copper neutral wires was experienced. However, this type of cable was restricted to installations other than joint random-lay.

The manifestation of copper concentric neutral wire corrosion was cause for serious concern by the electric utility industry. Deterioration of the neutral wires impacts economics, reliability, service quality and safety. In recognition of the seriousness of the situation, Task Force 6-21 of the Insulated Conductors Committee of the IEEE reacted by defining a research program to develop corrosion mitigating methods. The program was forwarded to EPRI for funding consideration and consisted of the following projects:

- Study the Mechanism(s) of Corrosion of Copper Concentric Neutral Cable and Determine the Test Procedures for Early Detection and Mitigation of Corrosion on Installed Cable
- Evaluation of Commerically Available Semiconducting Thermoplastic Jacket Compounds
- Outdoor High Voltage and High Current Short-Circuit Tests on Single Phase Extruded Dielectric Primary Distribution Cables

The EPRI Distribution Advisory Task Force reviewed this research program and recommended funding. EPRI agreed to fund the evaluation of commerically available semiconducting thermoplastic compounds (RP 671 Phase I) and the outdoor high voltage short-circuit tests on single phase extruded dielectric primary distribution cables (RP 671 Phase II). General Cable was awarded a Research Contract for both phases of the project. Under the terms of the

Contract for Phase II, Georgia Power, Long Island Lighting and McGraw Edison acted as subcontractors to General Cable. The McGraw Edision Laboratory at Franksville, Wisconsin was used to perform the simulated fault tests.

SUMMARY

This report pertains to the outdoor high voltage and high current tests (Phase II) of EPRI Project RP 671-1. Phase II encompassed staged and pre-staged fault tests on direct buried 15kV and 35kV crosslinked polyethylene insulated cables. Various concentric neutral conductor designs were tested including cables without jackets and with insulating and semiconducting jackets over the neutral wires. Appendix A contains a list of the cable designs tested. The fault tests on the 15kV cables were performed at rated voltage to ground and with symmetrical fault currents of 5 and 10kA. There was a prescribed sequence of circuit breaker reclosures. The 35kV cables were similarly tested but only the 10kA symmetrical fault current was employed. A detailed description of the test program performed at the McGraw Edison Short-Circuit Laboratory near Franksville, Wisconsin including the instrumentation employed in these tests is included in this report. The test results are in the form of graphs that show equipotential lines at the surface of the earth as a percentage of supply voltage. Similar graphs show individual voltages to remote ground caused by the faults on the various designs of URD cables tested. The respective touch and step voltages can be readily derived from these plotted data. A method was developed to calculate approximate equipotential lines in the earth. It is applicable to bare and semiconducting jacketed concentric neutral cables under short-circuit conditions as a function of the measured resistance of the concentric neutral conductor to remote ground at low voltage. The method is described in Appendix B of this report.

The transient voltage gradients (touch and step voltages) present in the earth during short-circuit tests were found to be determined by a) the voltage at the fault and b) the conductance from the concentric neutral conductor to remote ground. These parameters are influenced by the following factors:

A) <u>Voltage at the Fault</u>

- Magnitude of the supply voltage

  The touch and step voltages increase proportionately with the supply voltage for a given set of fixed conditions.

- Ratio of fixed current limiting impedance inserted in the high side leg of the power supply circuit to the ground leg impedance.

  This ratio relates to the ratio of the positive and zero sequence impedances of the distribution circuit.

- Time of cable dielectric breakdown at the fault with respect to instantaneous circuit voltage.

  During a cable dig-in or a similar fault, the insulation may breakdown at any instant. The resulting voltage magnitude at the fault location will be influenced by the asymmetry of the voltage wave form as controlled by the $\frac{X}{r}$ ratio of the governing circuit.

- The size of the neutral conductor on the concentric neutral cable.

  This may influence the touch and step voltages depending on its influence on the overall low side impedance. Under the conditions of this test, the size of the neutral conductor did not significantly influence the touch and step voltages. This was due to the lengths of cables tested with respect to the overall impedance of the circuit.

B) <u>Conductance from the Concentric Neutral Conductor to Remote Ground</u>

- Resistivity of the earth in proximity of the cables.

  Touch voltages increase and step voltages decrease with the increase in resistivity of the earth in proximity of the cables.

- Location and thickness of soil layers with respect to the cable and magnitude of the resistivity in each layer.

  The resistivity of the soil surrounding the cable significantly influences step and touch voltages. A strata of low resistivity soil immediately below and in proximity to the cable will serve to decrease touch and increase step voltages as compared to a soil of the higher resistivity.

- Instantaneous impedance of the arc to earth after initiation of a staged fault (open trench).

  For concentric neutral cable with an insulating type jacket over the neutral and, to a lesser extent, for bare and semiconducting jacketed cables depending on earth resistivity, the magnitude of the current in the earth surrounding the fault may be negligible prior to the arc plasma contacting the earth. When the magnitude of the current in the earth surrounding the fault is negligible prior to the arc plasma contacting the earth, the touch voltages will be high and the step voltages negligible up to the time that the plasma contacts the earth. After the plasma contacts the earth, the contact resistance of the arc plasma is affected by the size and impedance of the arc, by the length of the arc due to conductor burn-back and/or the dimension of the earth containment or crater adjacent to the cable fault.

Results and conclusions incorporated in this report are applicable for the circuits and environmental conditions that existed at the test site and in the performance of these tests. Employing Figures B-1 through B-6, and Appendix B, approximate determination of touch and step voltages can be made for bare and semiconducting jacketed concentric neutral cables buried at a depth of 2.5 feet. Analytical calculations can be made for extension of these results to other depths of burial. A computer program developed by Georgia Institute of Technology under RP 797-1 can be employed for this purpose.

Section 2

TEST SITE

The cable testing program was conducted at the McGraw Edison Research Center in Franksville, Wisconsin. The test area, located south of the Short-Circuit Laboratory, covered approximately twelve acres of rolling pasture terrain. An aerial photograph of the test site is shown in Figure 2-1.

The test area was divided into five equal rectangular plots, each plot measuring approximately 600 feet by 100 feet. See Figure 2-2. The test plots were numbered 1 through 5 from west to east. Trenches for burying the cable samples measured 100 feet in length, 30 inches in depth, and 8 inches in width. There were 13 trenches in Plot No. 1, 16 trenches in Plot No. 2, 14 trenches in Plot No. 3, 16 trenches in Plot No. 4 and 13 trenches in Plot No. 5. The spacing between cables were determined by preliminary short-circuit tests and were selected to be effective in reducing the influence of adjacent cables on measured data.

Cable Faulting Devices

Two types of faulting devices were used in the test program. The faulting device shown in Figure 2-3 was applied at the center of the cable prior to burial. This type of fault was designed to simulate cable damage during installation that would initiate a fault when the cable is energized. It was designated as a pre-staged fault. The faulting device shown in Figure 2-4 was assembled at the center of the cable after the cable had been buried in the trench. This faulting device was designed to simulate a "dig-in" while the cable is energized. It was designated as a staged fault. This faulting device is equipped with two dc solenoids mounted on the upper section. The smaller solenoid controls the initiation of the fault from a remote location by releasing a trigger which normally holds the weighted steel rod in the normal ready position. A large powerful solenoid is used to supply added driving force for the weighted steel rod. The large solenoid thus accelerates the movement of the weighted steel rod. The dynamic force in the weighted steel rod is sufficient to initiate the fault by driving the faulting pin through the test cable insulation. The staged fault tests were conducted on 15kV cables only. The 35kV cables were subjected only to the pre-staged faults.

Figure 2-1. Aerial Photograph of Test Site McGraw Edison Research Center, Franksville, Wisconsin.

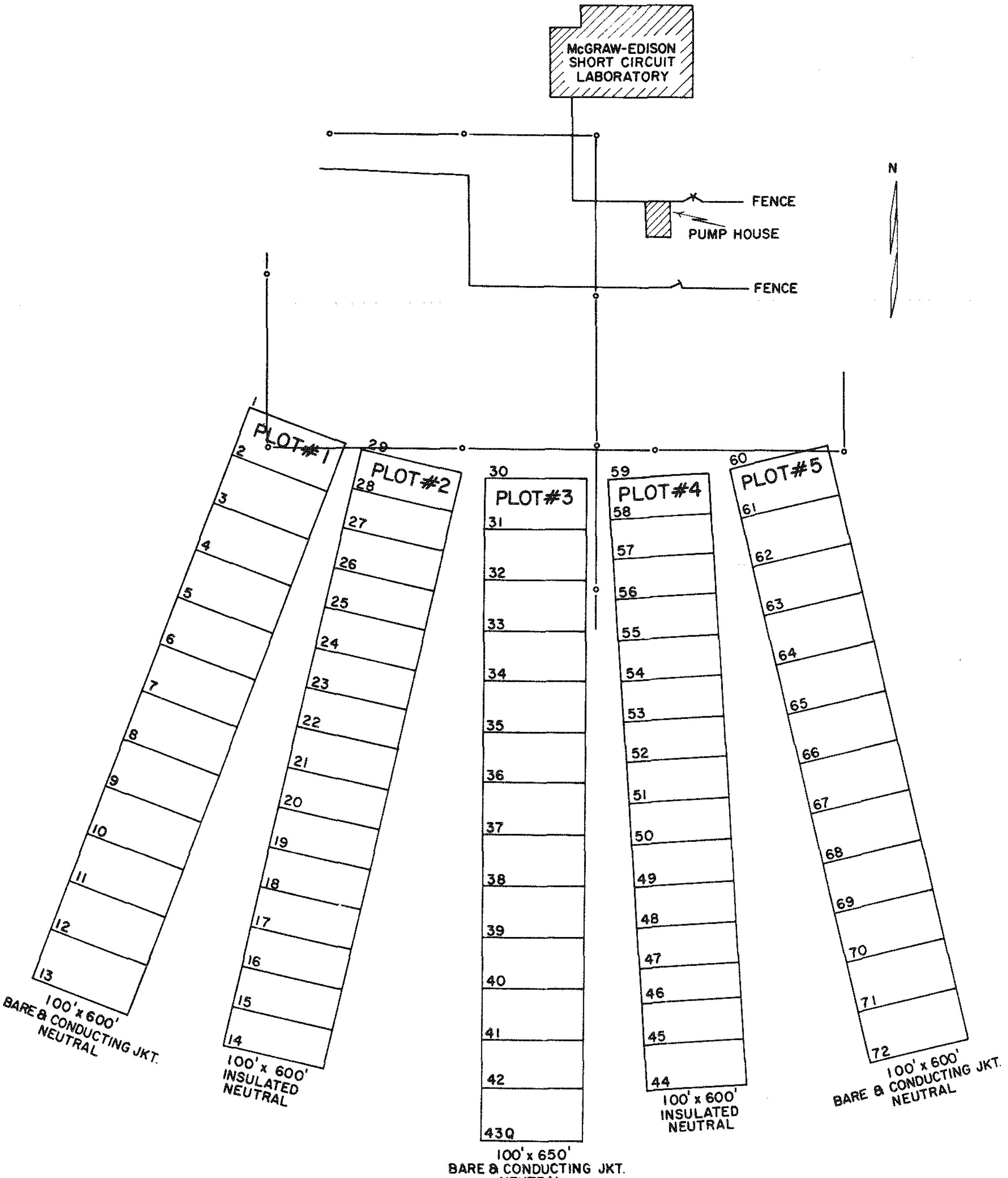


FIGURE 2-2. TEST PLOT LAYOUT.

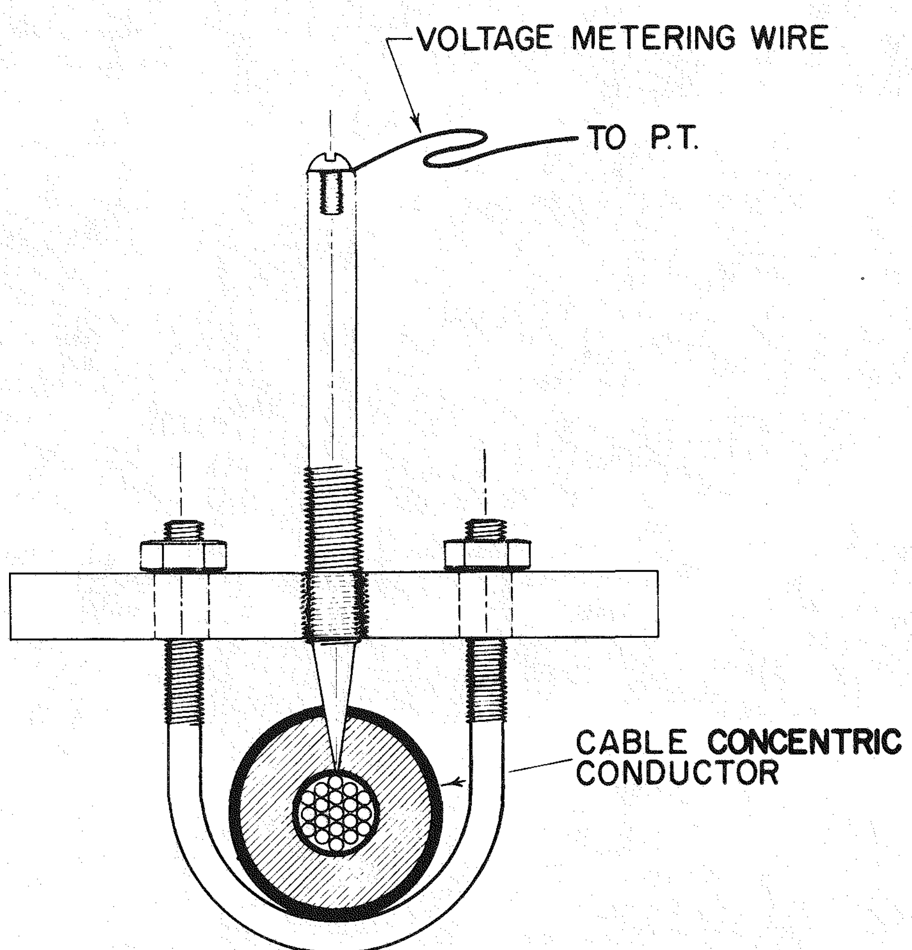


FIGURE 2-3. PRE-STAGED FAULTING DEVICE

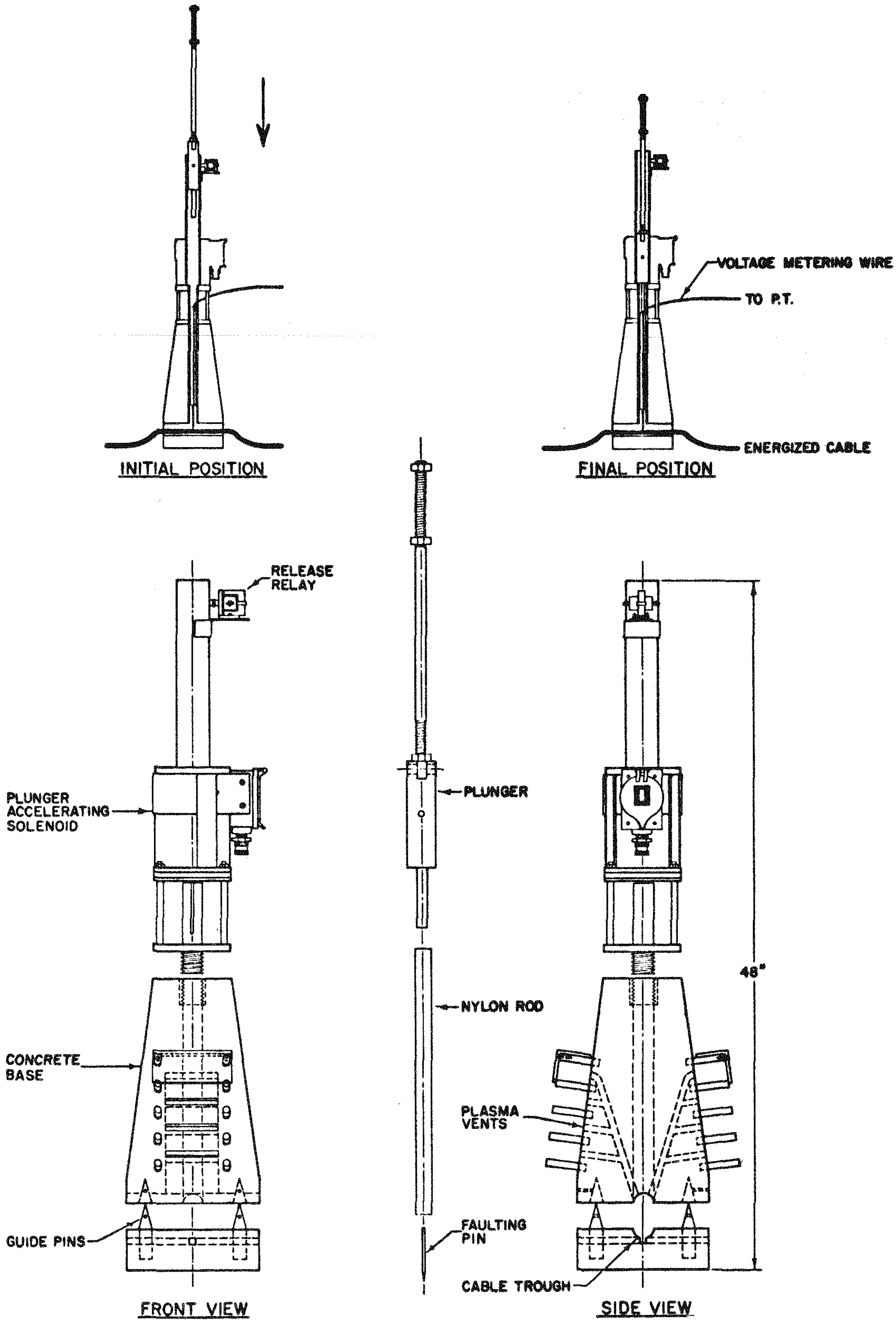


FIGURE 2-4. STAGED FAULTING DEVICE

Installation of Test Cables

The 15kV cable samples were installed in pre-designated trenches with the terminal ends extending approximately 36 inches above grade.

Plastic identification tags were strapped to wooden stakes and installed at the ends of each trench. Matching tags were attached to each cable sample. The backfilling and tamping operations were conducted in accordance with the following procedure:

a) The trench was backfilled with approximately 12 inches of native soil. The backfill was thoroughly compacted by completing two passes along the entire trench with a heavy duty gasoline driven tamper.

b) The trench was flooded with approximately 2 inches of water and the backfill allowed to settle overnight. The back-filling operation was completed late the following day. Twenty-four hours were allowed for water compaction. The final compaction was completed using gasoline driven tampers, as on the previous day, followed by running the heavy digging machine over the trench. Satisfactory compaction was verified by measuring soil density and moisture content with an instrument using radiation scatter techniques. The fact that the trenches were filled to grade with no soil left over was further evidence of adequate compaction.

The 15kV cables designated for pre-staged fault testing were all pre-faulted prior to being installed in their respective trenches. The 15kV cables designated for staged faults were installed in trenches and a small section in the central portion of the trench was left open exposing the cable. This allowed for the installation of the staged faulting device. In order to facilitate the installation of this faulting device, which weighs 250 pounds, a 6-foot long slit trench was dug at a right angle to the cable at the fault point and at the center of the main trench. The additional slit trench greatly facilitated the positioning and assembling of the faulting device, an operation which otherwise would have been strenuous, awkward and time consuming.

The 35kV cable samples were terminated and prepared for burial in the same manner as the 15kV cables except that all 35kV cable samples were pre-faulted using the same type device as was used for pre-faulting the 15kV cables. Based on an analysis of the 15kV staged and pre-staged fault test data associated with short-circuits due to dielectric breakdown, it was determined that staged fault testing of the 35kV cables was not necessary. This change in the program permitted additional and more meaningful tests (described further in this report) without adding to the overall cost of the project.

Test Site Preparation

A remote ground, common to both the 15kV and 35kV testing programs, was installed, as shown in Figure 2-5. It was approximately 1000 yards southwest of the cable test site. A #6AWG solid insulated copper wire of sufficient length to reach any test cable in the five test plots was installed for measuring the potentials between the faulted cables and remote ground.

Instrumentation for the measurement of short circuit currents and ground voltage gradients was mounted on mobile trailers to facilitate movement from one test cable to the next. Ground voltage gradients adjacent to each cable fault were measured by utilizing four 5 inches by 10 inches by 1/4 inch copper plate electrodes. One plate was installed at grade adjacent to the trench and immediately above the staged or pre-staged fault. The other three plate electrodes were installed in a line and at a right angle to the first plate and spaced 3 feet, 6 feet and 12 feet respectively from the trench. Instrument transformers were used to measure the voltage drop between plate electrodes. In order to improve conductivity between plate electrodes and earth, a slurry was produced under each plate electrode. The weight of a man on the plate electrodes was simulated by placing a 100 pound steel weight on each plate electrode. Figures 2-6 and 2-7 are photographs of the instrumentation and plate electrodes as used at the test site.

Cable Impedance and Soil Resistivity Measurements

Soil resistivity measurements were taken at each cable location for the 15kV and 35kV series of tests using a four point Nielssen impedance bridge.[+]

[+]A Method of Measuring Resistivity, F. Wenner, National Bureau of Standards, Scientific Paper 12, No. S258.

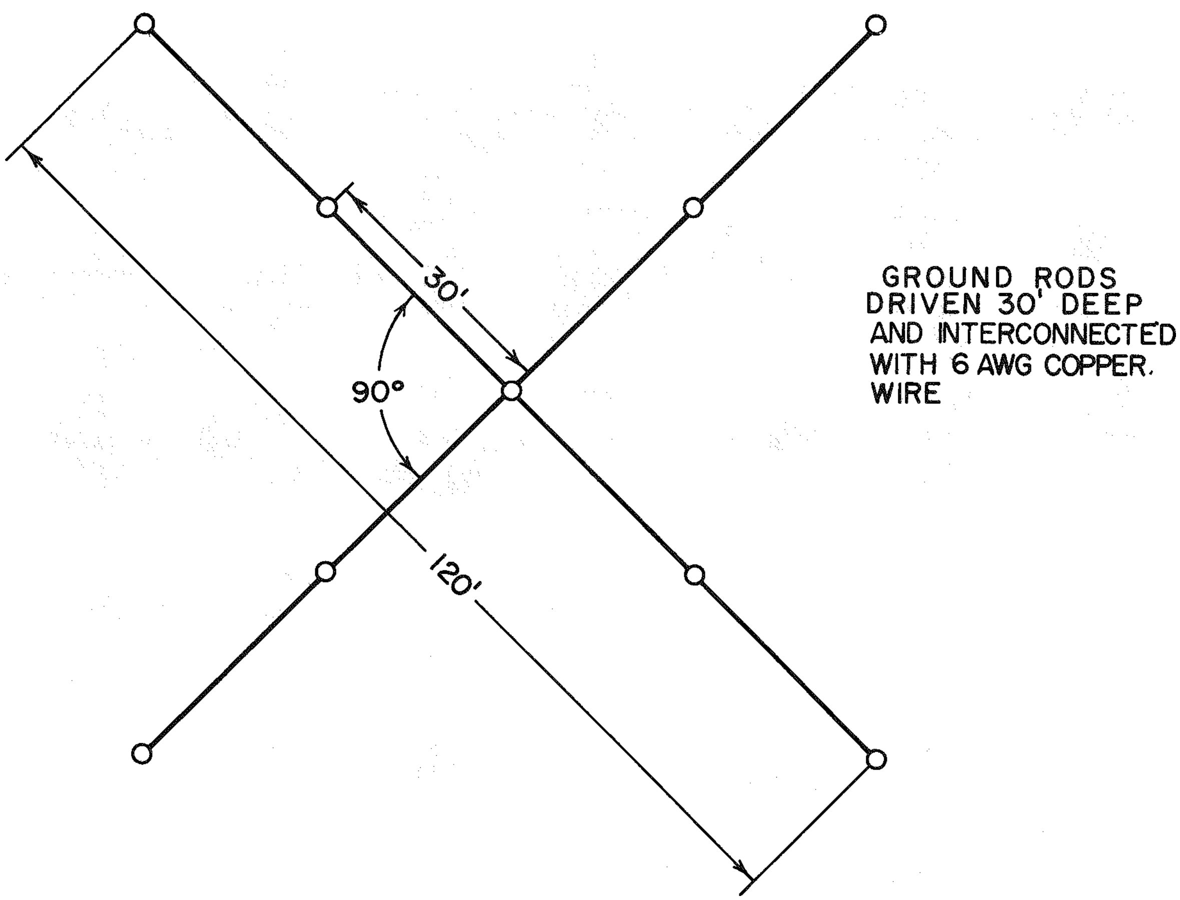


FIGURE 2-5. REMOTE GROUND SYSTEM

Figure 2-6. Instrumentation for Short Circuit Field Measurement.

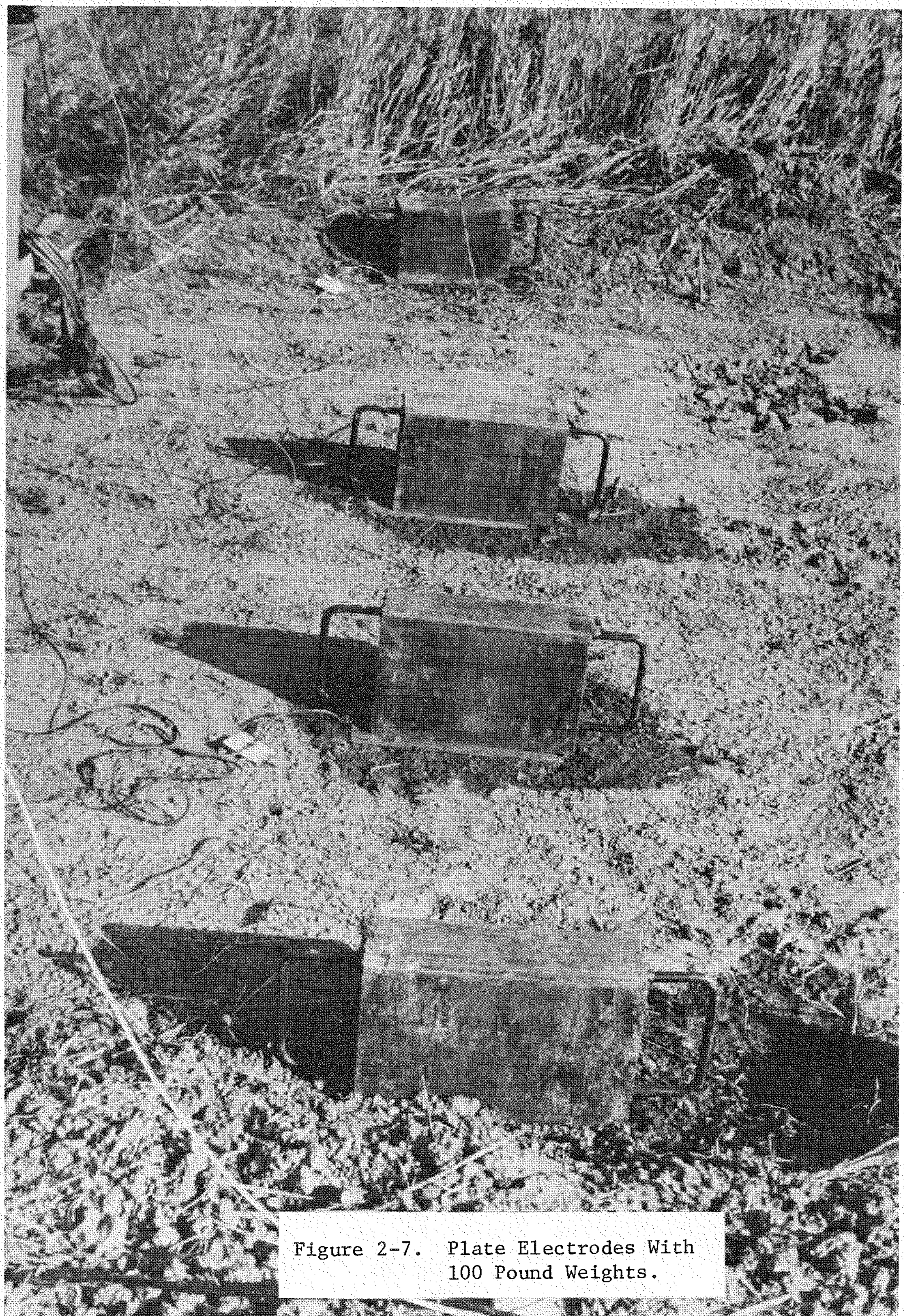


Figure 2-7. Plate Electrodes With 100 Pound Weights.

The electrodes used for these measurements were fabricated of hard copper rod 3/8 inch in diameter by 6 inches long. The four electrodes were driven into the ground starting at the edge of the trench above the fault and extending at right angle to the trench on 5 foot centers. These measurements were taken shortly before each cable was short-circuited.

Numerous soil resistivity measurements were also made contiguous to each test plot to determine if soil layers with different electrical resistivities were present within 100 feet from the surface of the earth. A four terminal impedance megger with four earth electrodes was utilized to measure the earth resistivity at depths from one foot to 100 feet. The data from these tests is shown in Figure 2-8.

Impedance measurements to remote ground and station ground were taken before each 15kV and 35kV cable was short-circuited. The two point method, using the Nielssen bridge, was used for these measurements.

The impedances of remote ground and station ground to earth were measured utilizing a fall of potential method. This measurement technique was selected to achieve the accuracy required to measure the very low impedances of the station and remote grounds at this test site.

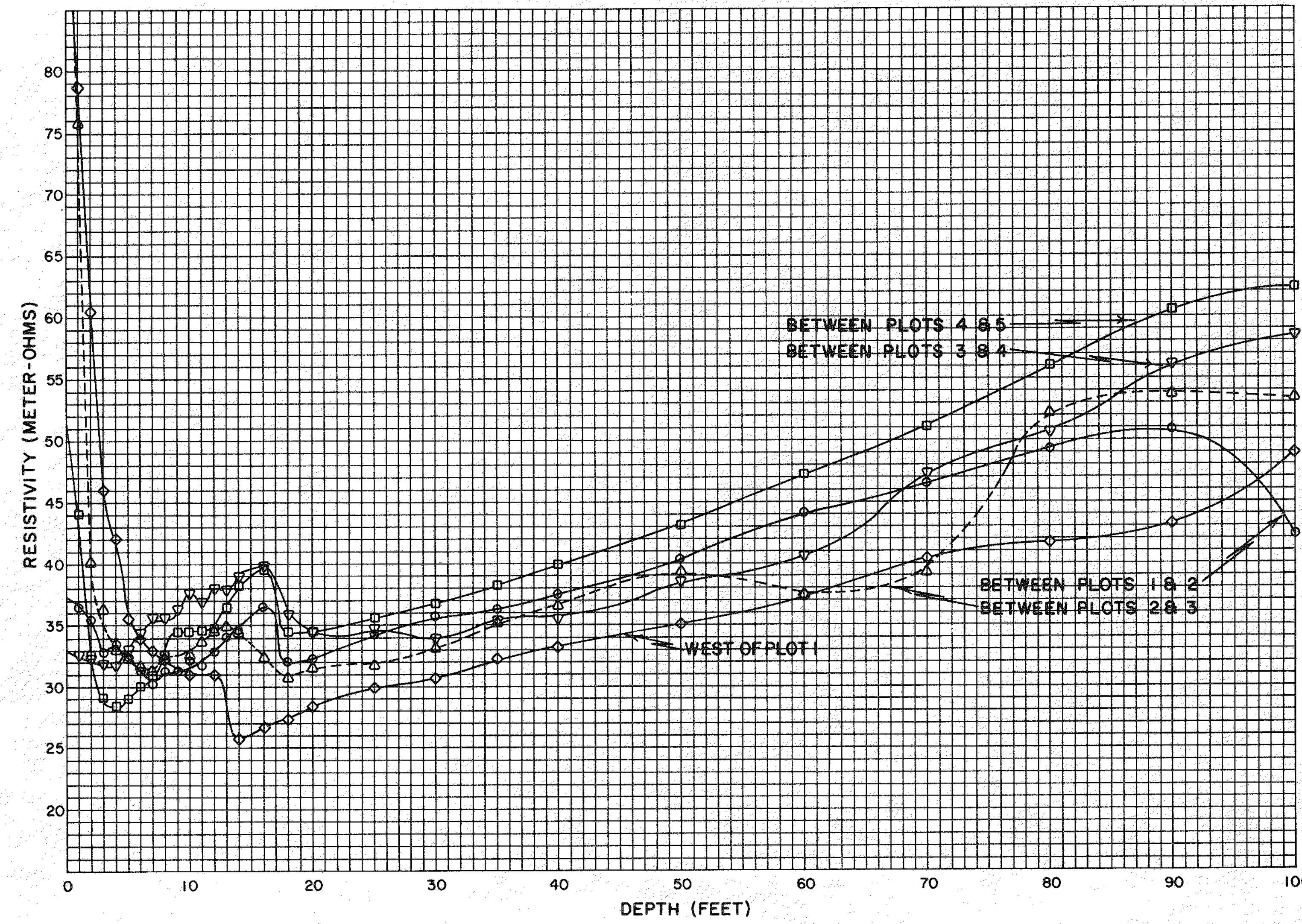


FIGURE 2-8. ELECTRICAL EARTH RESISTIVITY VS. DEPTH

Section 3

FIELD MEASUREMENTS

General

All field measurements were made using conventional techniques and all instruments utilized for the measurements were calibrated prior to each phase of testing. The techniques employed for making all of the soil resistance measurements in the earth are described in the literature.[+]

Soil moisture content and soil density measurements were made using nuclear equipment. The equipment provided a means to measure soil properties from the earth surface down to a depth of six feet.

Preliminary Tests

Due to the magnitude of the test program and the number of cable samples to be tested, preliminary tests were made to determine optimum methods of field measurement and optimum spacing between adjacent cables. During these tests, transient earth voltages were measured with both potential transformers and non-inductive voltage divider circuits. In addition, the voltages were recorded with a light-writing oscillograph and a magnetic tape system with frequency response of 2kHz and 80kHz, respectively.

Conclusions drawn from these preliminary tests indicated that the optimum cable spacing should be 40 feet for insulating jacketed cables and 50 feet for bare and semiconducting jacketed cables. Analyses of the waveforms indicated that the arc voltages present during the tests did not result in erratic voltage excursions beyond 2kHz, thus allowing future measurements to be made satisfactorily with the less expensive lightwriting oscillograph.

[+]Guide for Measuring Ground Resistance and Potential Gradients in the Earth. A.I.E.E. No. 81, May 1962.

Calibration of Metering Circuits

Calibration for high voltage measurements in the field included amplitude and frequency response for the entire measurement system including the metering cables.

Based on the maximum frequencies measured during the preliminary tests in conjunction with arc voltages, all potential transformers were tested for frequency response from 60Hz to 2kHz. The procedure for frequency calibration consisted of applying a constant magnitude sine wave signal to each potential transformer with 1,200 feet of metering cables attached, as shown in Figure 3-1. Additional damping or loading non-inductive resistors were employed to load each potential transformer to improve the frequency response. The frequency was raised in steps up to 2kHz and the voltage ratio error was measured. Upon completion of the tests, the potential transformers showed no error associated with frequencies up to 2kHz. For information purposes additional wavefront rise time tests were performed to determine the maximum response of the potential transformers. The rise time calibration was performed by applying a square wave signal to the potential transformer and measuring the degree of difference in the output waveform. Test results indicated that the potential transformers were capable of measuring wavefronts down to a 50 microsecond rise time, which corresponds to a 5kHz frequency.

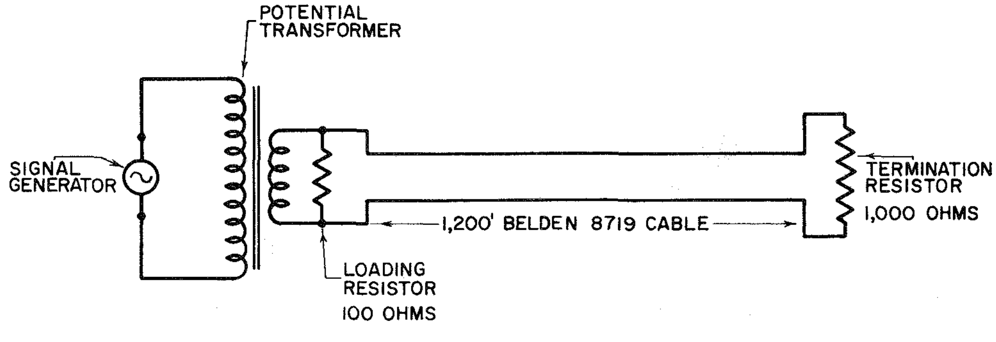


FIGURE 3-1. AMPLITUDE AND FREQUENCY RESPONSE CALIBRATING CIRCUIT FOR FIELD INSTRUMENTATION

Amplitude calibration of the potential transformers, cable and oscillographs was performed by energizing the entire metering system from the field. A regulated 60Hz voltage was supplied to the test site, stepped up to an appropriate level, and applied to the potential transformer system and fed back over the respective shielded metering cable to the oscillograph. The applied voltage at the potential transformer was metered and recorded by a portable standard Systron Donner (.05% accuracy) digital multimeter. This procedure assured that the total metering system, including the oscillographs, was calibrated accurately and operating satisfactorily.

Field Measurement Circuit

Voltages and currents were measured in the field in accordance with the schematic diagram shown in Figure 3-2. Total short-circuit current, cable metallic shield currents and earth current were measured with current transformers designated I_F, I_{FR1}, I_{FR2}, and I_{FR3}, respectively. Ground voltage gradients adjacent to the cable fault were measured with potential transformers designated Vp_1, Vp_2, Vp_3, and Vp_4. Voltages on both ends of the cable shields and voltage to remote ground were measured with potential transformers designated Vs_1, Vs_2, and Vrg, respectively. The experimental error for repetitive tests performed under equivalent conditions did not exceed 2 percent.

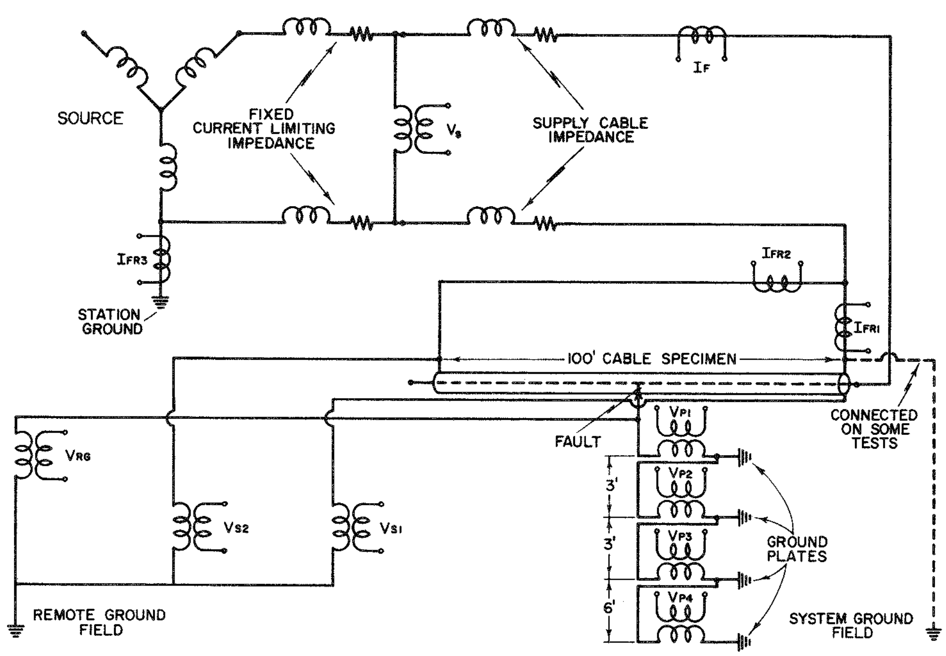


FIGURE 3-2. SCHEMATIC DIAGRAM OF FIELD TEST CIRCUIT

Section 4

SHORT-CIRCUIT TEST PROGRAM

General

Short-circuit tests were performed on direct earth buried 15kV and 35kV cross-linked polyethylene insulated cables of various metallic neutral conductor designs. Designs comprised bare as well as insulating type and semiconducting jacketed cables. A detailed description of the test cables is included in Appendix A.

Testing of 15kV and 35kV Cables

The 15kV cables were subjected to the staged and pre-staged faults with 8.66kV between line and concentric neutral conductor. The tests were performed at fault currents of 5000 and 10,000 amperes. The 35kV cables were subjected to pre-staged faults at 20.2kV between phase and concentric neutral conductor at a fault current level of 10,000 amperes. The time duration for sustained fault current; ie, the time between circuit breaker reclosures and the sequence of occurrences, which are typical of all circuit reclosers, are indicated below:

5000 Amperes	10,000 Amperes
5 cycles "on"	3 cycles "on"
90 cycles "off"	90 cycles "off"
5 cycles "on"	3 cycles "on"
90 cycles "off"	90 cycles "off"
10 cycles "on"	6 cycles "on"

The 15kV cables were buried in their respective trenches and tested during the fourth quarter of 1975. Following the completion of these tests, all 15kV cables were removed and the 34kV cables were installed in their respective trenches during November of 1975. In view of the approaching severe winter weather and the desirability to perform detailed analysis of the test data obtained on the 15kV cables prior to proceeding with testing of the 35kV cables, approval was requested and obtained from the EPRI Project Manager to delay fault testing of the 35kV cables until June of the following year. Based on analysis and evaluation of the test data obtained on the 15kV cables, it was recommended, and subsequently approved by the EPRI Project Manager that the test program for the 35kV cables would be modified as indicated herein.

A) Six trenches were partially backfilled and tamped with sand having high electrical resistivity. The tamped sand backfill encompassed a radius of approximately twelve inches around the cable for a distance of 5 feet on each side of the pre-staged fault. The remainder of each of these trenches was backfilled and tamped with native soil. Three of the trenches had cables with full size bare copper concentric neutral conductors and three had cables with semiconducting jackets that covered the neutral wires.

B) Six trenches were carefully backfilled with native soil utilizing extremely uniform compaction techniques to achieve uniform soil density adjacent to the cable fault. The uniform soil compaction encompassed the entire 36 inch depth of backfill for 5 feet on both sides of the fault. Two of the trenches had cables with full size bare concentric copper conductor. One of the trenches contained a cablewith bare concentric neutral and the second contained a cable with a semiconducting jacket over the neutral. Four of the trenches had cables with half size concentric copper conductor; two cables with bare neutrals and two with a semiconducting polyethylene jacket over the neutral.

C) Ground rods were driven at both ends of eight cable lengths and connected to the cable concentric conductor/shield. The cable types that were tested and the test conditions are as listed below:

1. Full size longitudinally folded corrugated copper tape with semiconducting jacket.

   a) Two cables were tested with the total impedance proportioned so that 60% of the impedance was represented in the circuit from the voltage source to the point of fault (high side) and 40% in the return path from the fault to the source (low side).

   b) Two cables were tested with approximately 97% of the impedance in the high side.

2. Full size longitudinally folded corrugated aluminum tape with insulated jacket.

   a) Two cables were tested with the total impedance proportioned so that 60% of the impedance was represented in the circuit from the voltage source to the point of fault (high side) and 40% in the return path from the fault to the source (low side).

   b) Two cables were tested with approximately 97% of the impedance in the high side.

D) A simulated system ground, comprised of 16-foot ground rods and connecting conductors, was installed at a convenient location near the test area. The simulated system ground was established in the form of two 150 foot lines crossing at right angles with ground rods driven at the intersection and at the extremities of the lines as shown in Figure 4-1. A ground grid was formed by interconnecting all the driven ground rods with a #4AWG stranded insulated copper cable. A 1,000 foot length of #4AWG stranded insulated copper lead was connected to the center of the grid and was used to connect designated test cables to the simulated system ground.

Test Circuit Arrangement

The circuits shown in Figures 4-2, 4-3, 4-4 and 4-5, represent the series equivalent test circuits that were utilized during the 15kV, 5 and 10kA and the 35kV, 10kA test programs, respectively. The low side impedances represent the parallel return paths for the flow of fault current consisting of the following four elements: (1) the metallic neutral shield of the tested cable, (2) the return leg of the portable power supply cable, (3) the fixed low side impedance (inserted in the return leg at the generator room) and (4) the impedance of the earth circuit. The high side impedances represent (1) the impedance of the generator, (2) the fixed impedance (inserted in the supply leg of the circuit at the generator), (3) the impedance of the portable power supply cable and (4) the impedance of the line conductor of the tested cable. The impedance values used in the test program are shown in the schematic diagrams and are also tabulated on the data sheets. The resultant ratios of high side to total circuit impedances of approximately 0.97 and 0.60 are considered to be the extreme values likely to be encountered in a typical utility multi-grounded power distribution circuit.

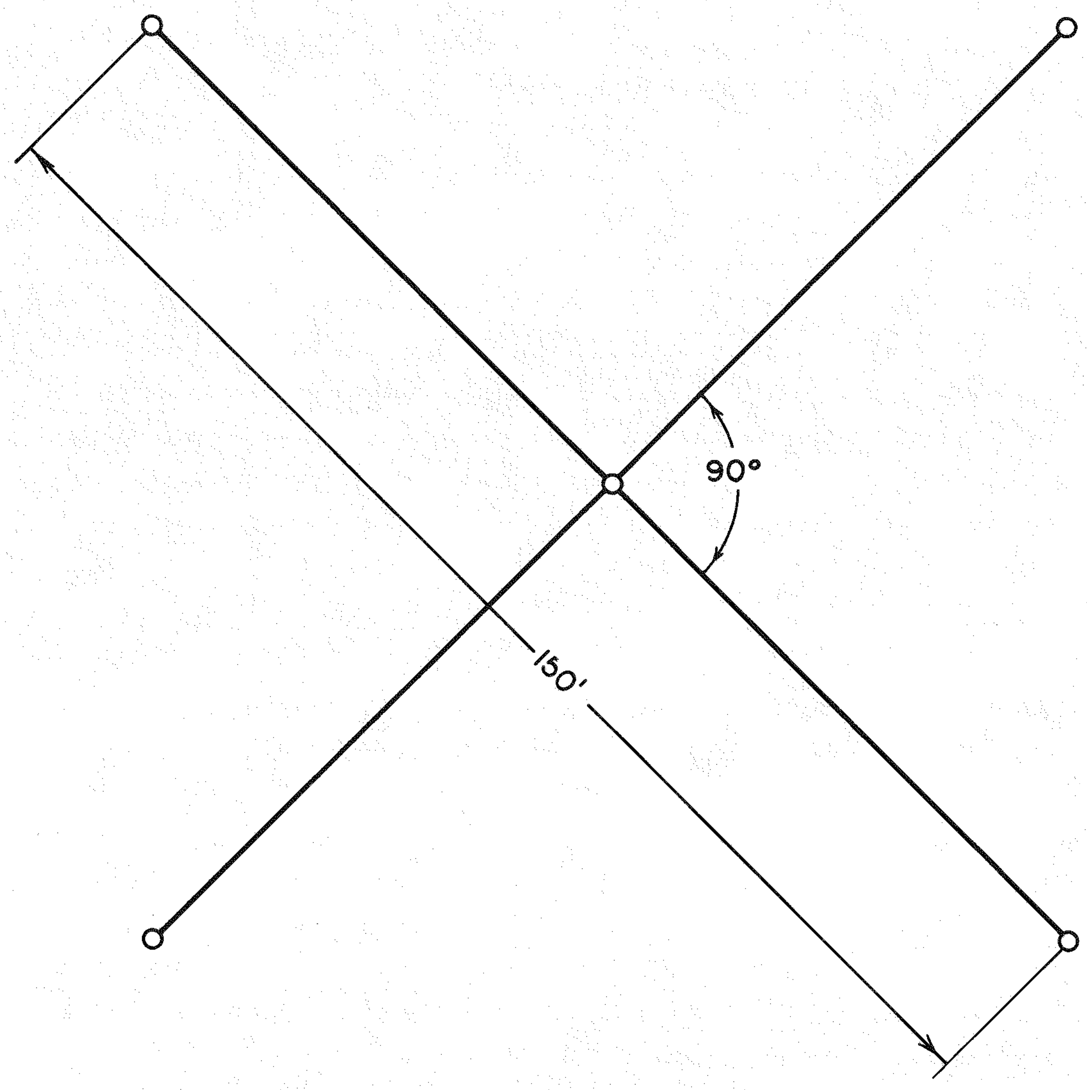
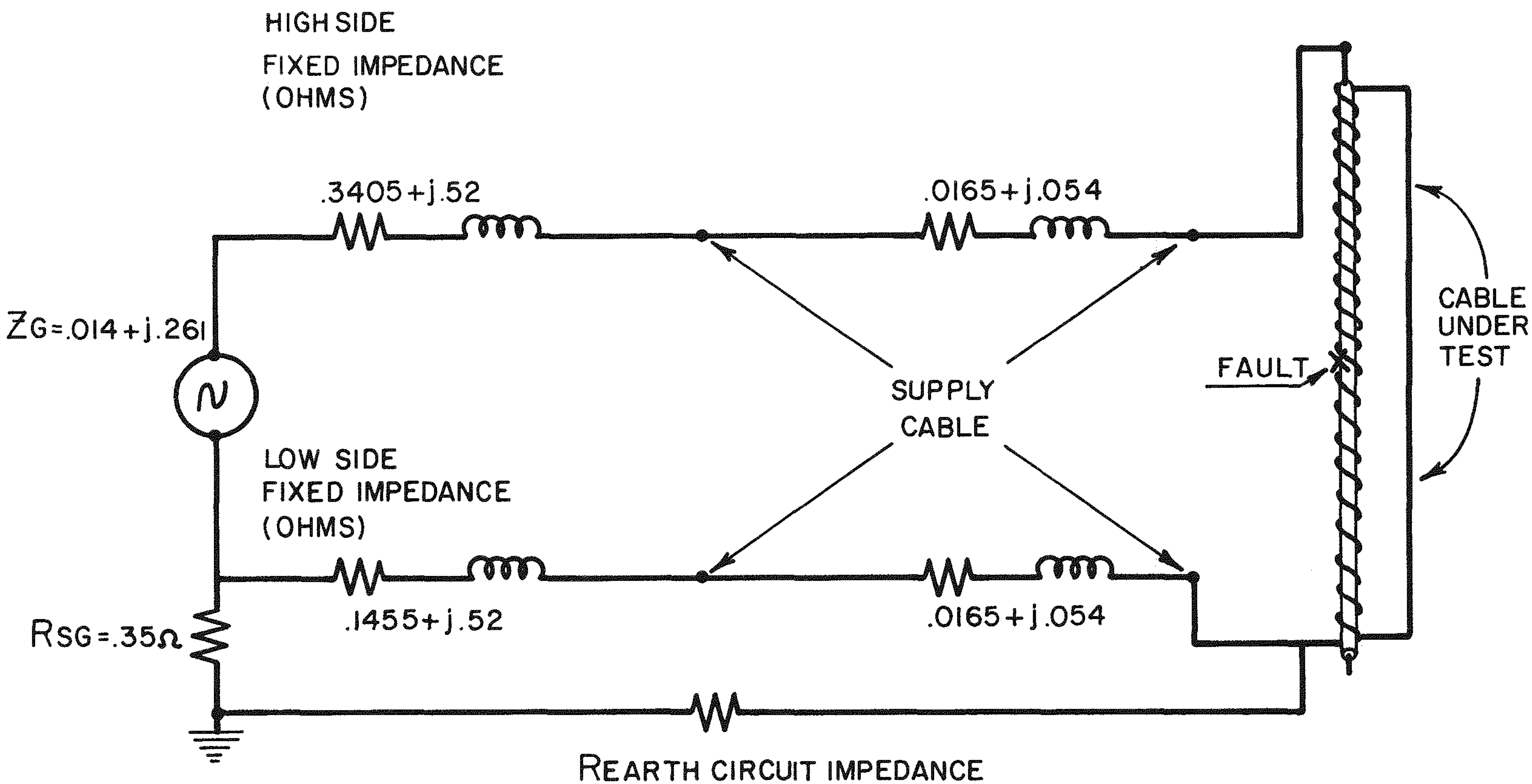
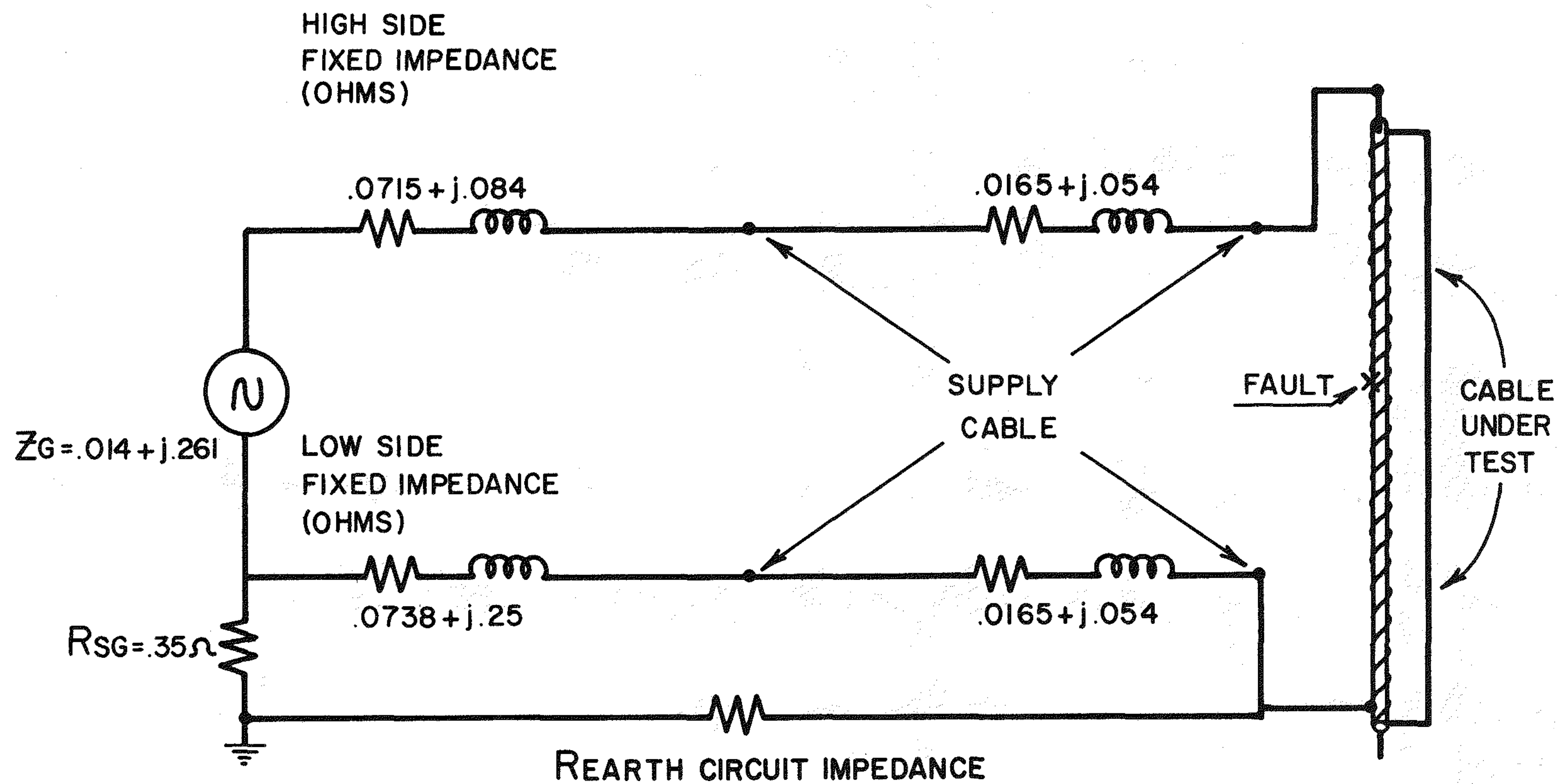


FIGURE 4-1. SIMULATED SYSTEM GROUND FOR 35 kV TEST PROGRAM



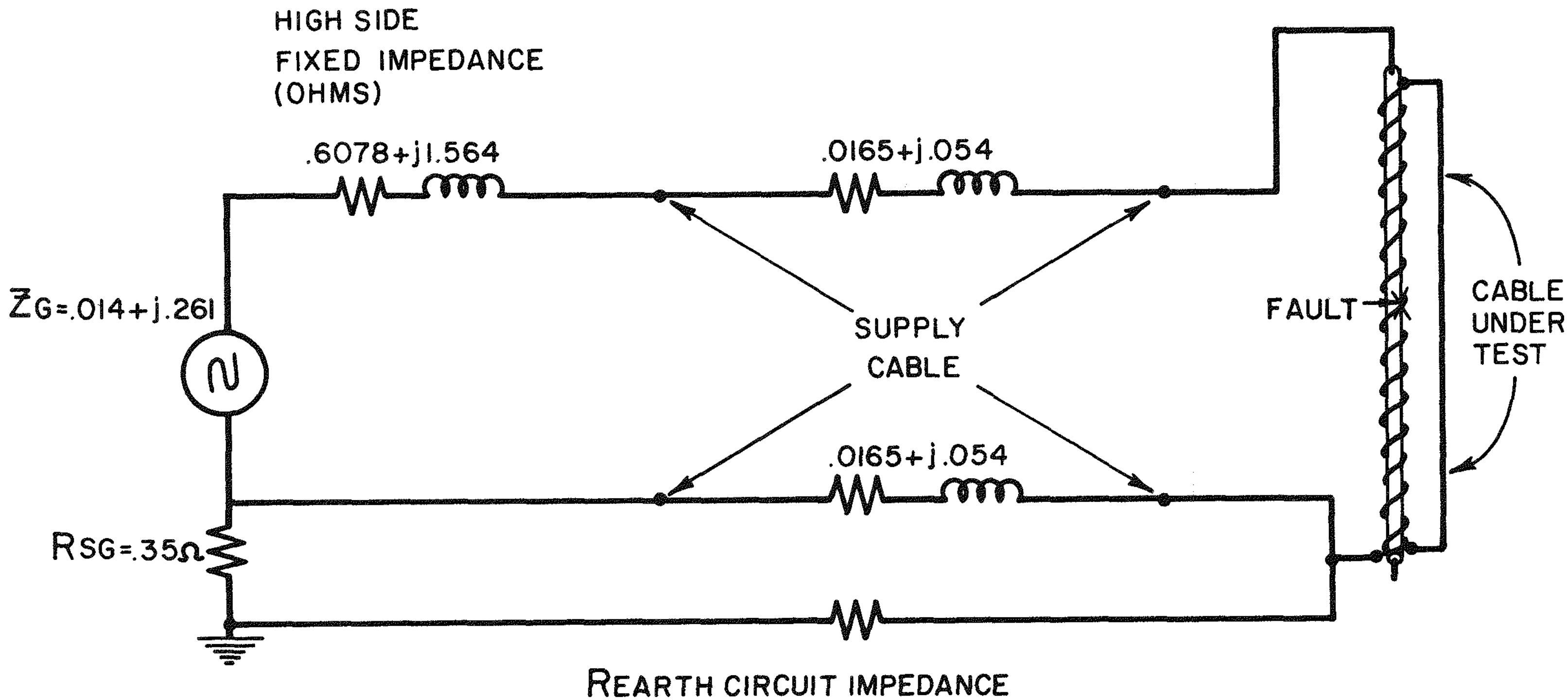
RATIO OF HIGH SIDE TO TOTAL CIRCUIT IMPEDANCE–.61

FIGURE 4-2. SERIES EQUIVALENT TEST CIRCUIT. SUPPLY VOLTAGE 8.3kV. SHORT CIRCUIT CURRENT 5kA.



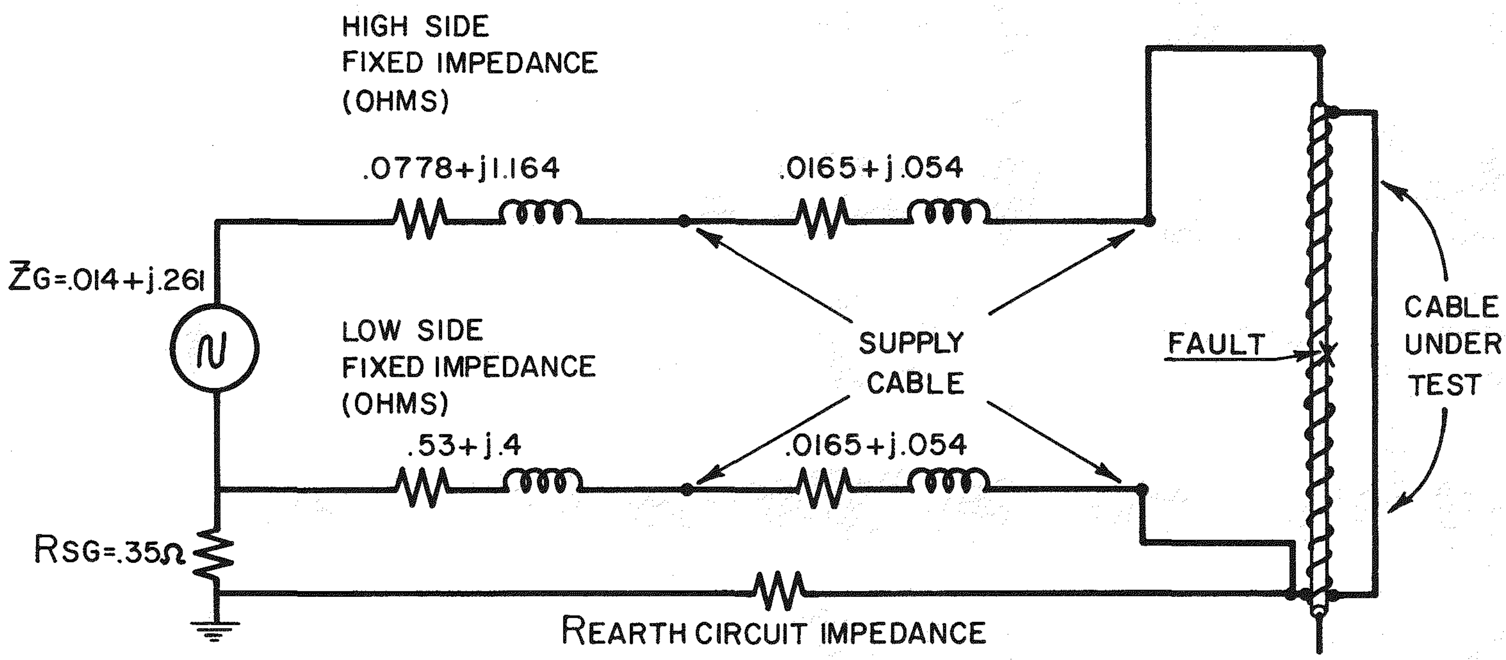
RATIO OF HIGH SIDE TO TOTAL CIRCUIT IMPEDANCE - .57

FIGURE 4-3. SERIES EQUIVALENT TEST CIRCUIT. SUPPLY VOLTAGE 8.3kV. SHORT CIRCUIT CURRENT 10kA.



RATIO OF HIGH SIDE TO TOTAL CIRCUIT IMPEDANCE .97

FIGURE 4-4. SERIES EQUIVALENT TEST CIRCUIT. SUPPLY VOLTAGE 20.2 kV. SHORT CIRCUIT CURRENT 10 kA.



RATIO OF HIGH SIDE TO TOTAL CIRCUIT IMPEDANCE .6

FIGURE 4-5. SERIES EQUIVALENT TEST CIRCUIT. SUPPLY VOLTAGE 20.2 kV. SHORT CIRCUIT CURRENT 10 kA.

Section 5

CRITERIA FOR ANALYSIS AND PRESENTATION OF TEST DATA

Wave form analyses were made to determine the maximum zero to peak voltages during any part of the short-circuit test sequence. The maximum touch voltage occurred during the first full half cycle of power current. This was attributed to the asymmetry of the sine wave and the minimum current flow in the earth during the initial portion of the short circuit. With increasing duration of short-circuit current and subsequent reclosures, the arc plasma increased in size and resulted in a greater flow of current in the earth thereby decreasing the touch voltages.

The voltages measured during the staged and pre-staged faults were tabulated and the earth equipotential lines calculated and plotted as a percentage of the supply voltage, as shown in Appendix B, Figures 5-2 to 5-16. Similar plots were made using the percentage of individual voltages to remote ground as shown in Appendix B, Graphs 16 to 30. The equipotential lines were calculated employing the formulae indicated herein. The identification of the symbols used is indicated in Figure 5-1.

$V_{RG}/V_S \times 100$ = Voltage at fault as a percent of supply voltage

$\frac{V_{RG}-V_{p1}}{V_S} \times 100$ = Voltage at grade above fault (at 0 feet) as percent of supply voltage

$\frac{V_{RG} - V_{P1} - V_{P2}}{V_S} \times 100$ = Voltage at 3 feet as a percent supply voltage

$\frac{V_{RG} - V_{P1} - V_{P2} - V_{P3}}{V_S} \times 100$ = Voltage at 6 feet percent of supply voltage

$\frac{V_{RG} - V_{P1} - V_{P2} - V_{P3} - V_{P4}}{V_S} \times 100$ = Voltage at 12 feet percent of supply voltage

V_{RG} = Voltage to remote ground (100%)

$$\frac{V_{RG} - V_{P1}}{V_{RG}} \times 100 = \text{Voltage at grade above fault (at 0 feet) as a percent of voltage to remote ground}$$

$$\frac{V_{RG} - V_{P_1} - V_{P_2}}{V_{RG}} \times 100 = \text{Voltage at 3 feet as a percent of voltage to remote ground}$$

$$\frac{V_{RG} - V_{P_1} - V_{P_2} - V_{P_3}}{V_{RG}} \times 100 = \text{Voltage at 6 feet as a percent of voltage to remote ground}$$

$$\frac{V_{RG} - V_{P_1} - V_{P_2} - V_{P_3} - V_{P_4}}{V_{RG}} \times 100 = \text{Voltage at 12 feet as a percent of voltage to remote ground}$$

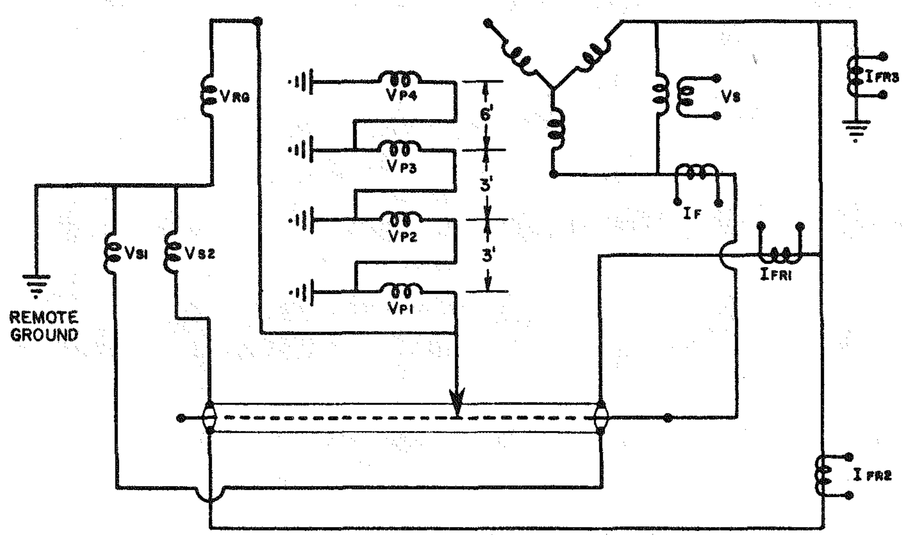


FIGURE 5-1. IDENTIFICATION OF VOLTAGES AND CURRENTS IN TEST CIRCUIT

The data plotted in Figures 5-2 to 5-16 represent the measured voltages at the fault and earth potential lines at 0, 3, 6 and 12 feet from the fault as a ratio of the supply voltage. Therefore the difference between the potential "at fault" and at any distance from the fault multiplied by the supply voltage is the touch voltage at that point. However, in this report, the term "touch voltage" refers specifically to the difference in potential between the fault and the surface of the earth directly above fault. The difference between the equipotential lines at any two points multiplied by the supply voltage is the step voltage between the two points during the fault, i.e. the potential difference between the two points at the earth's surface perpendicular to the equipotential lines.

The data plotted in Figures 5-17 to 5-31 represent the measured voltages at the fault and earth potential lines at 0, 3, 6 and 12 feet from the fault as a ratio of the voltage to remote ground. The curves in Figures 5-2 to 5-16 have, in effect been normalized in Figures 5-17 to 5-31 with respect to the "at fault" voltage assuming an "at fault" voltage of 100 percent.

The abbreviated cable types indicated under "Test" in Figures 5-2 through 5-31 are defined as follows:

<u>Concentric Neutral Conductor Material</u>

Al	Aluminum
Cu	Copper

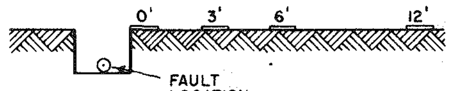
<u>Concentric Neutral Conductor Design</u>

CW	Concentric Wire
CT	Longitudinally Folded Corrugated Metal Tape
FS	Flat Strap (Ribbon)

<u>Concentric Neutral Conductor Type Covering, If Any</u>

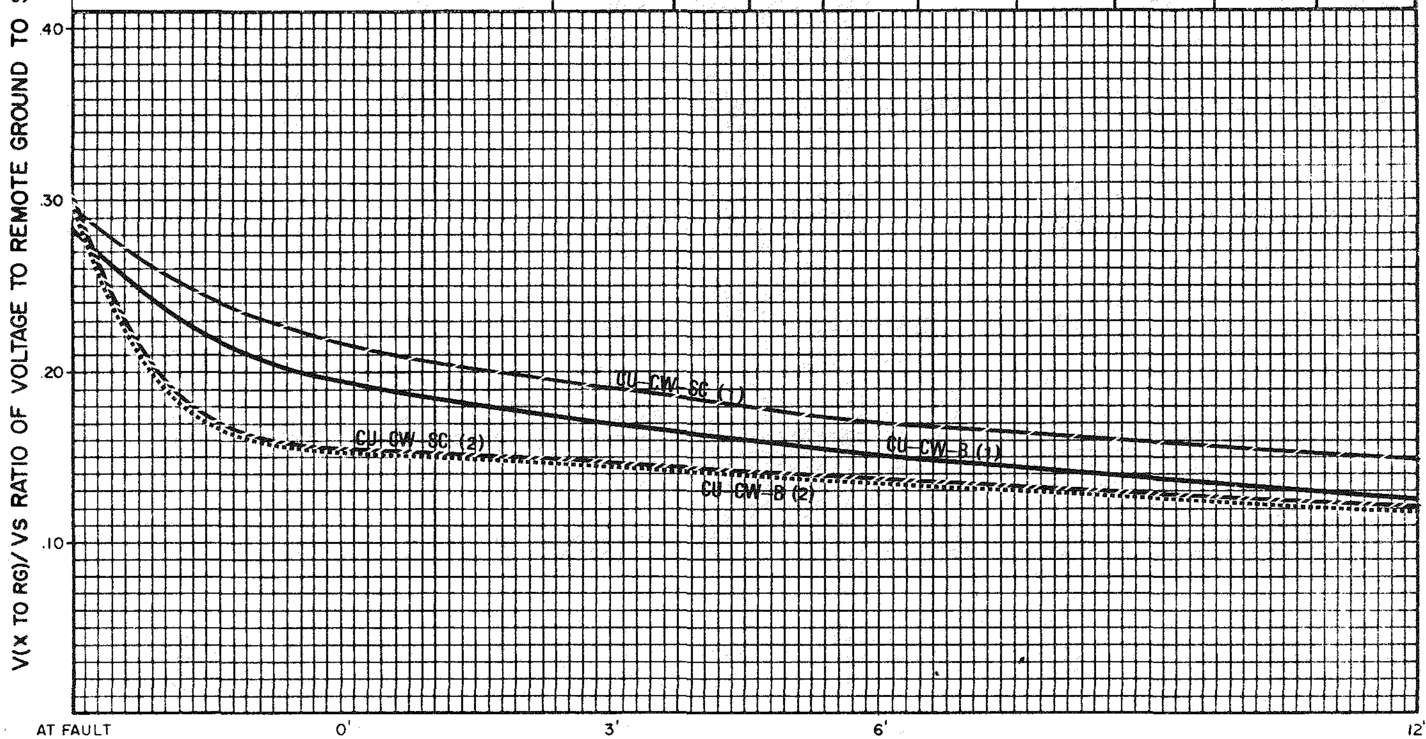
B	Bare
SC	Semiconducting
I	Insulating Type

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE(1) SAND(2)



EARTH EQUIPOTENTIAL LINE VALUES

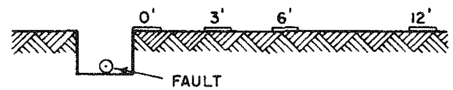
TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
CU-CW-B(1)	15414	3971	22.56	1.48∠86°	.71∠40°	2.60	NO	NO
CU-CW-B(2)	14747	3872	32.74	1.48∠86°	.71∠40°	2.59	NO	NO
CU-CW-SC(1)	15562	4218	24.19	1.48∠86°	.71∠40°	2.62	NO	NO
CU-CW-SC(2)	15488	3979	31.20	1.48∠86°	.71∠40°	2.77	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

FIGURE 5-2.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITED IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
CU-CW-B	15414	3971	22.56	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.60	NO	NO
CU-CW-SC	15562	4218	24.19	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.62	NO	NO
CU-CW-I	15167	387	26.72	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	165	NO	NO
CU-CT-SC(1)	15377	4255	24.48	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.62	NO	NO
CU-CT-SC(2)	14191	552	26.64	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	2.74	NO	NO
CU-CT-I	14080	86.5	28.90	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	111	NO	NO
AL-FS-SC	15612	4216	24.06	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.63	NO	NO
AL-FS-I	14376	300	27.36	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	143	NO	NO

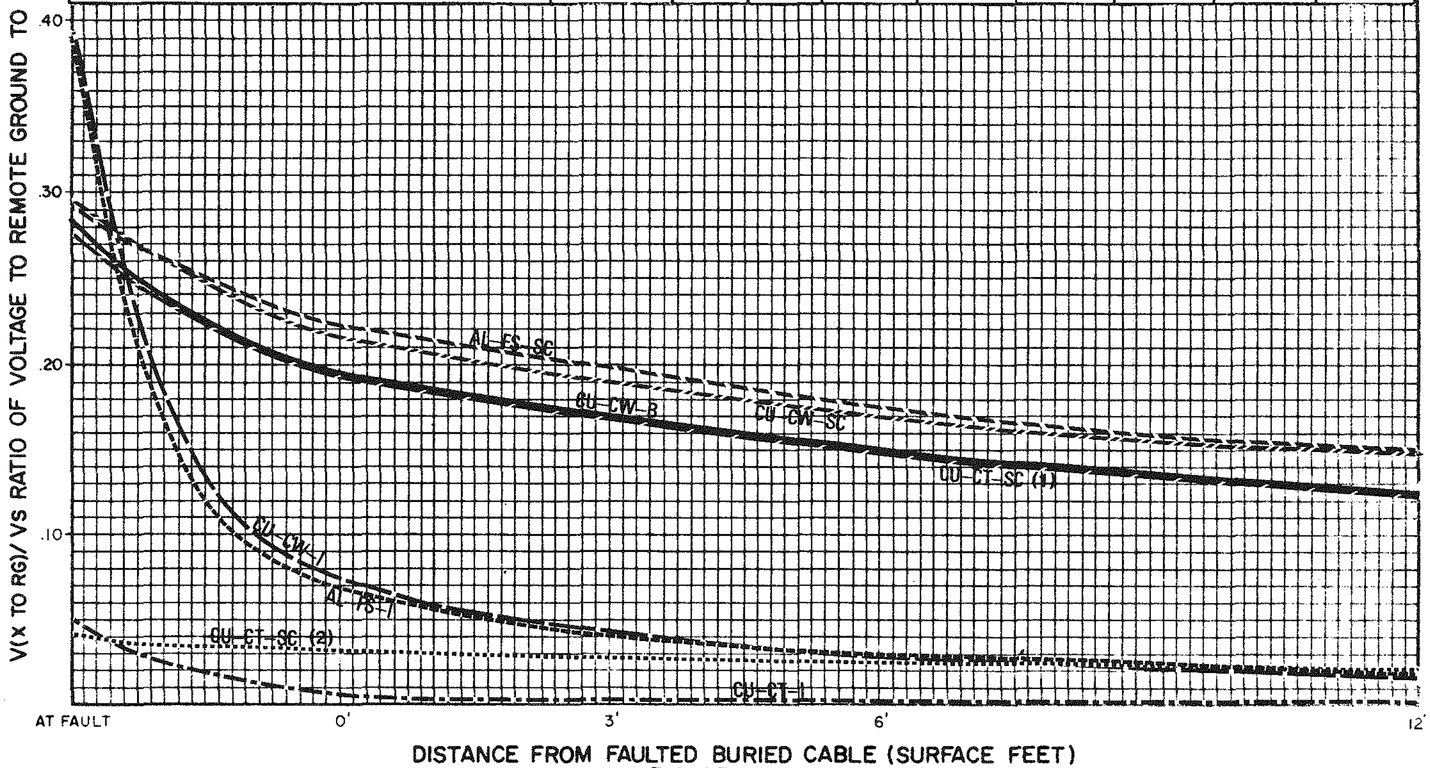
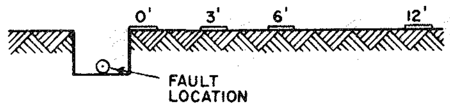


FIGURE 5-3.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
CU-CW-1	15414	4347	30.24	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.29	NO	YES
AL-FS-SC	16451	6617	31.30	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	1.59	NO	YES
AL-FS-1	15710	4588	26.88	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.19	NO	YES
AL-CT-SC(1)	16118	6528	29.47	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	1.62	YES	YES
AL-CT-SC(2)	14414	888	25.59	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	1.40	YES	YES
AL-CT-1(1)	16007	5318	29.67	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	1.95	YES	YES
AL-CT-1(2)	14079	740	31.20	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	1.93	YES	YES

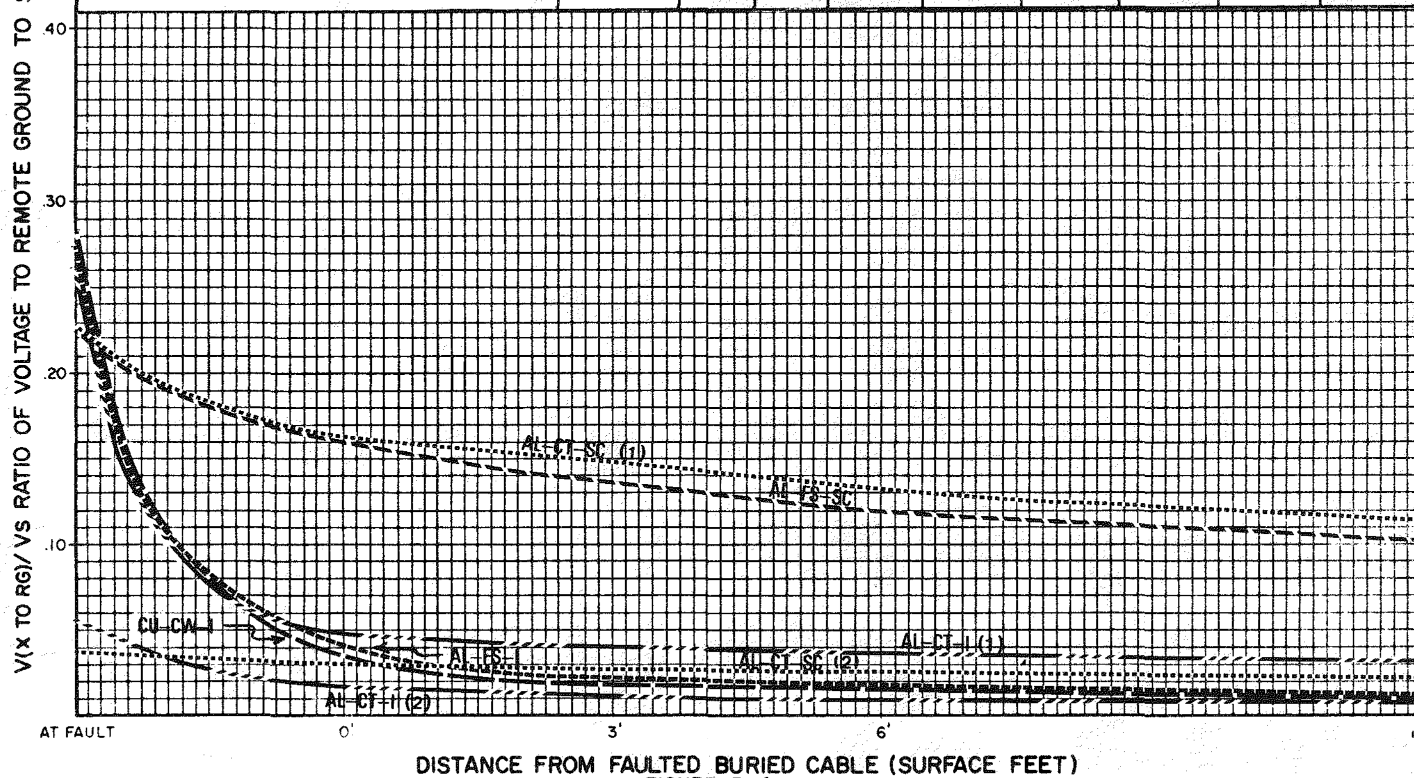
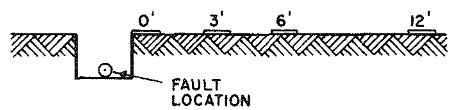


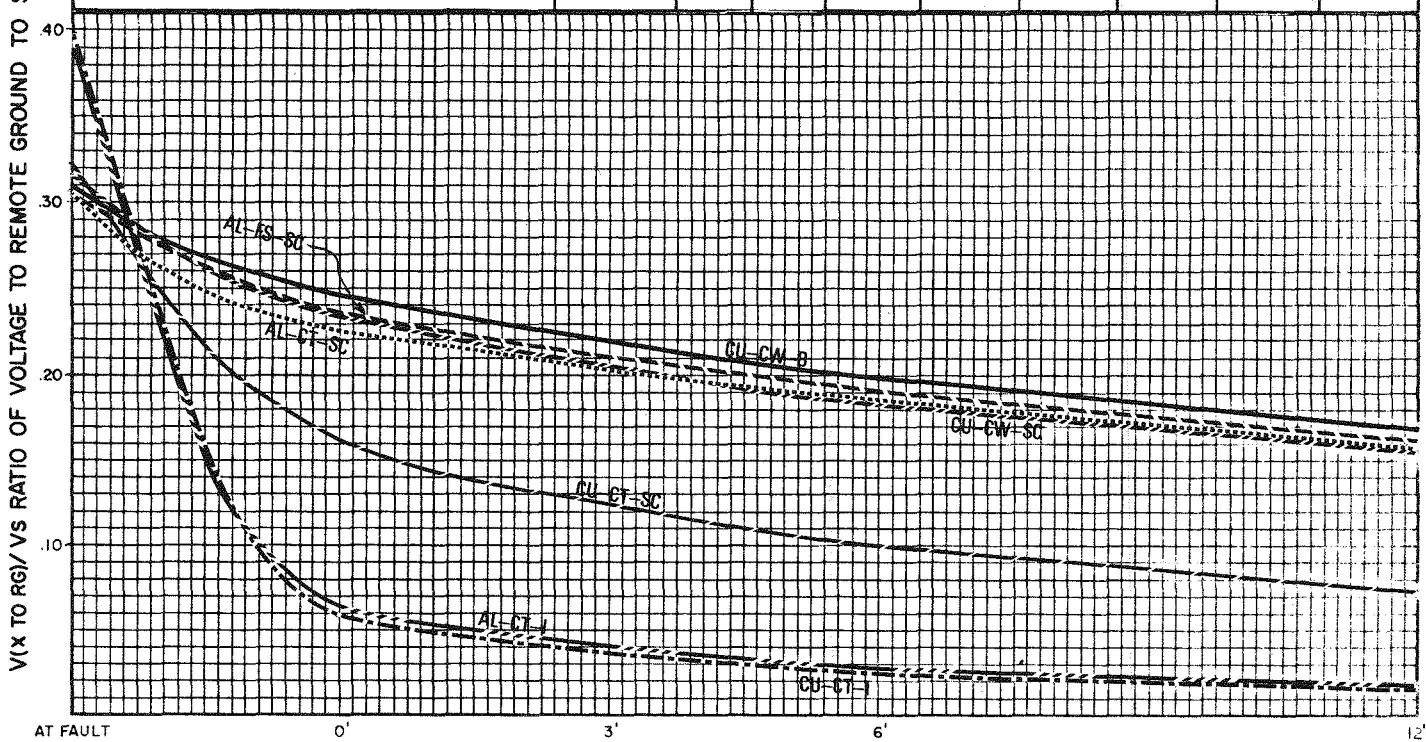
FIGURE 5-4.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE ONE-HALF
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

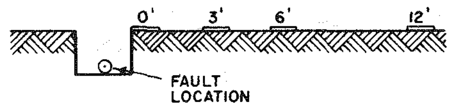
TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITED IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
	O-PEAK	O-PEAK	M-OHMS	HIGH SIDE	LOW SIDE			
CU-CW-B	15600	4742	23.04	1.48∠46°	.71∠40°	2.26	NO	NO
CU-CW-SC	15636	4218	27.24	1.48∠46°	.71∠40°	2.43	NO	NO
CU-CT-SC	15191	3441	47.04	1.48∠46°	.71∠40°	3.23	NO	NO
CU-CT-I	14228	286	27.77	1.48∠46°	.71∠40°	119	NO	NO
AL-FS-SC	15970	4452	22.30	1.48∠46°	.71∠40°	2.25	NO	NO
AL-CT-SC	15859	4680	31.27	1.48∠46°	.71∠40°	2.18	NO	NO
AL-CT-I	14321	296	26.83	1.48∠46°	.71∠40°	110	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

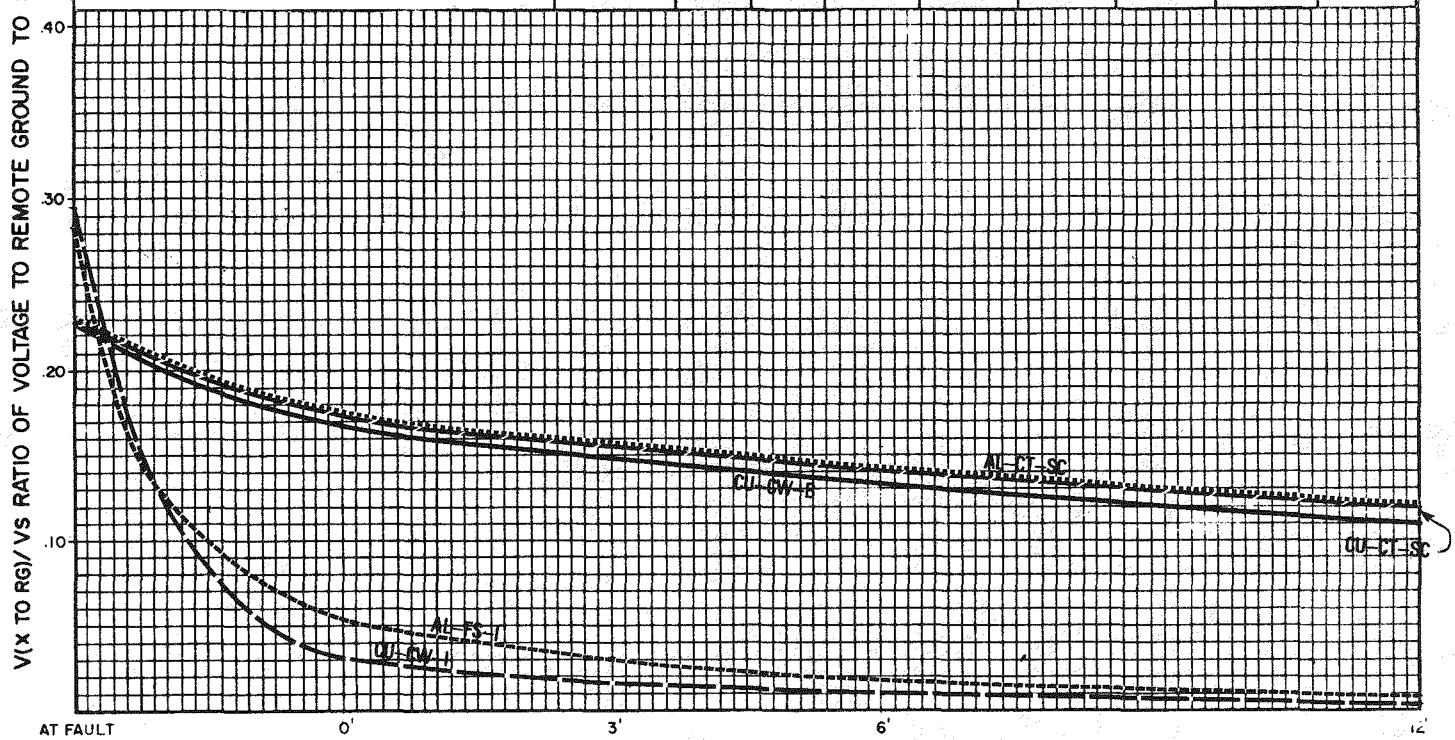
FIGURE 5-5.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE ONE-HALF
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

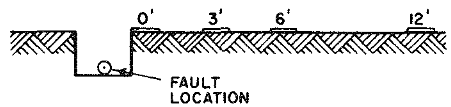
TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITED IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
	O-PEAK	O-PEAK	M-OHMS	HIGH SIDE	LOW SIDE			
CU-CW-B	16563	6967	22.37	1.48∠86°	.71∠40°	1.24	NO	YES
CU-CT-SC	16698	6920	23.78	1.48∠86°	.71∠40°	1.32	NO	YES
AL-CT-SC	16748	6905	22.71	1.48∠86°	.71∠40°	1.28	NO	YES
CU-CW-1	15784	4708	27.50	1.48∠86°	.71∠40°	2.27	NO	YES
AL-FS-1	15766	4680	30.36	1.48∠86°	.71∠40°	2.25	NO	YES



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

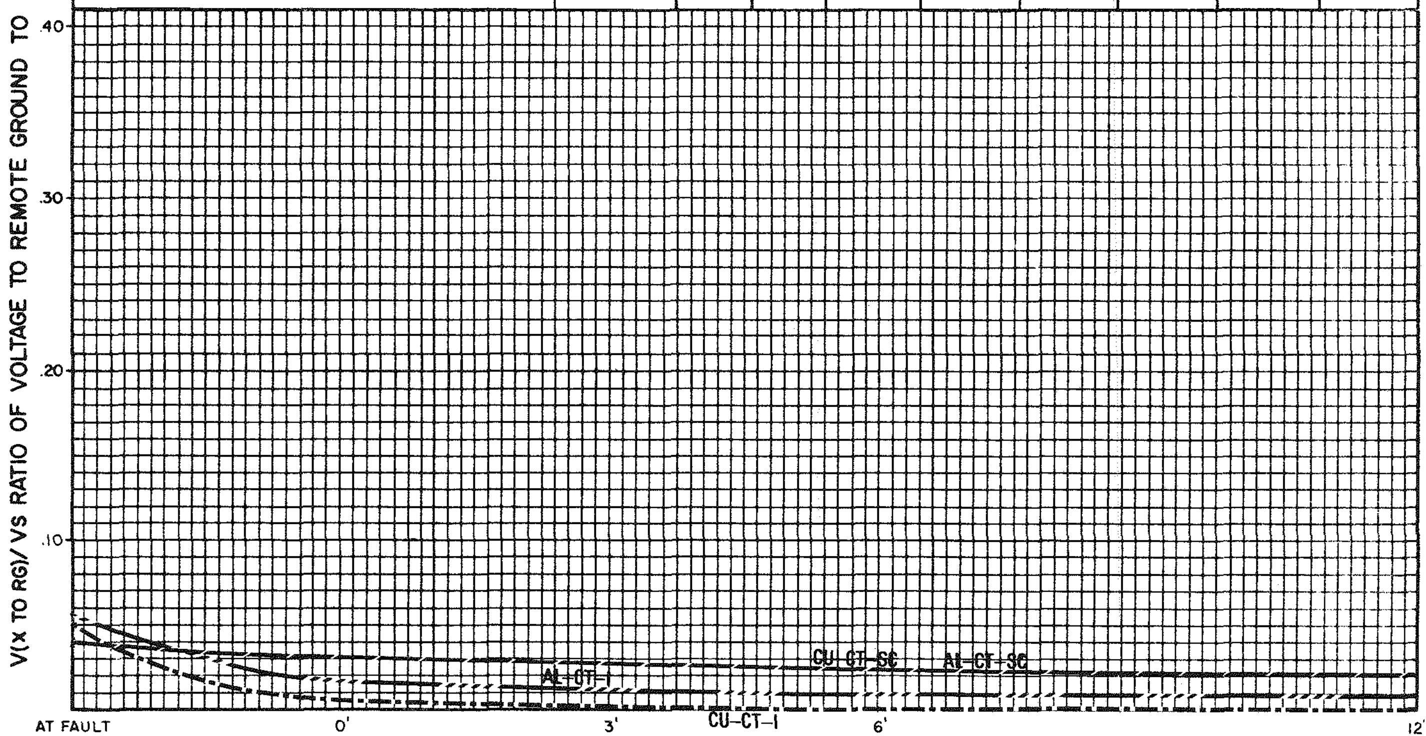
FIGURE 5-6.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

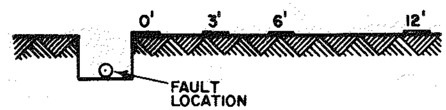
TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITED IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
CU-CT-1	14080	86.5	28.90	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	$111\angle 0$	NO	NO
AL-CT-1	14079	740	31.20	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	$1.93\angle 0$	YES	YES
CU-CT-SC	14191	552	26.64	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	$2.74\angle 0$	NO	NO
AL-CT-SC	14414	888	25.59	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	$1.40\angle 0$	YES	YES



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

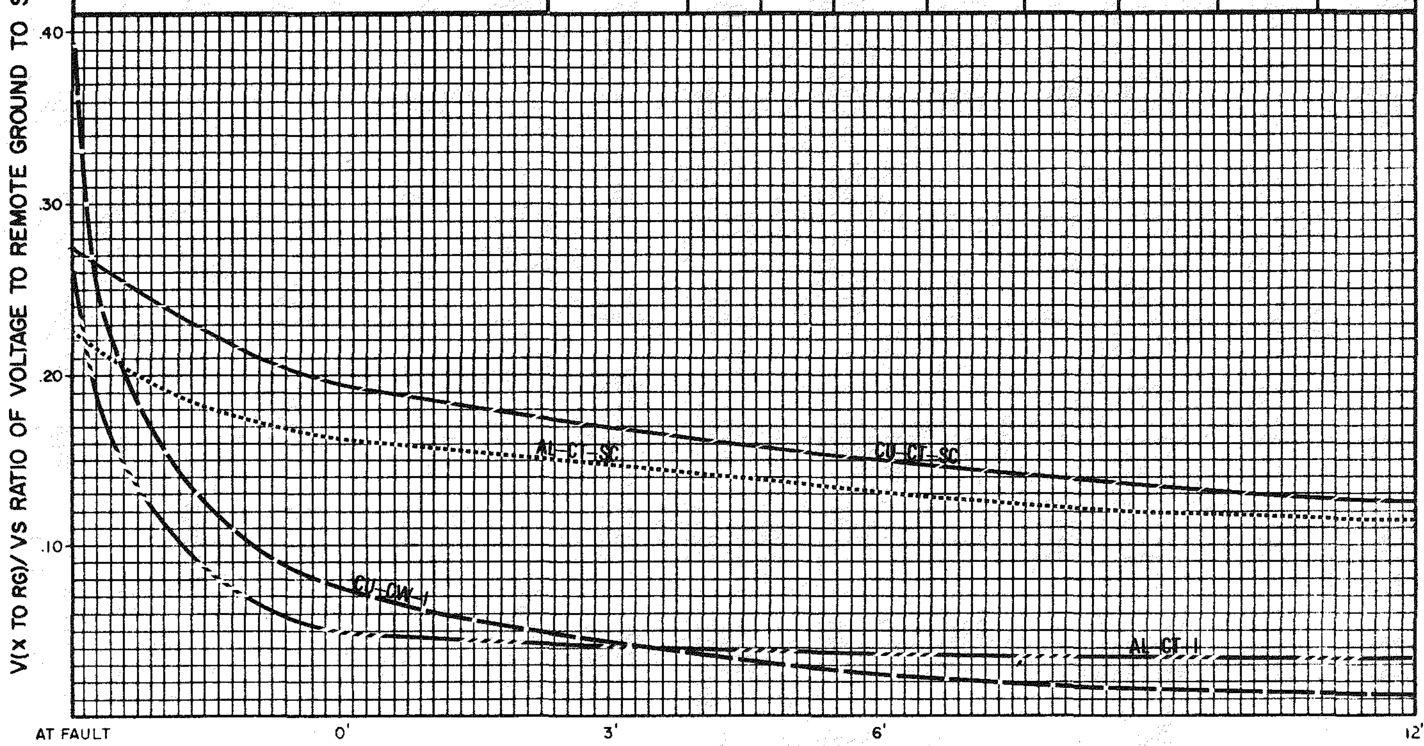
FIGURE 5-7.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

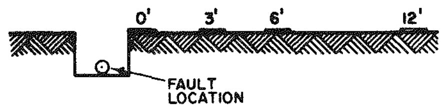
TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
AL-CT-SC	16118	6528	29.47	1.48∠86°	.71∠40°	1.62∠0°	YES	YES
CU-CT-SC	15377	4255	24.48	1.48∠86°	.71∠40°	2.62∠0°	NO	NO
AL-CT-I	16007	5318	29.67	1.48∠86°	.71∠40°	1.95∠0°	YES	YES
CU-CW-I	15711	411	26.88	1.48∠86°	.71∠40°	165∠0°	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

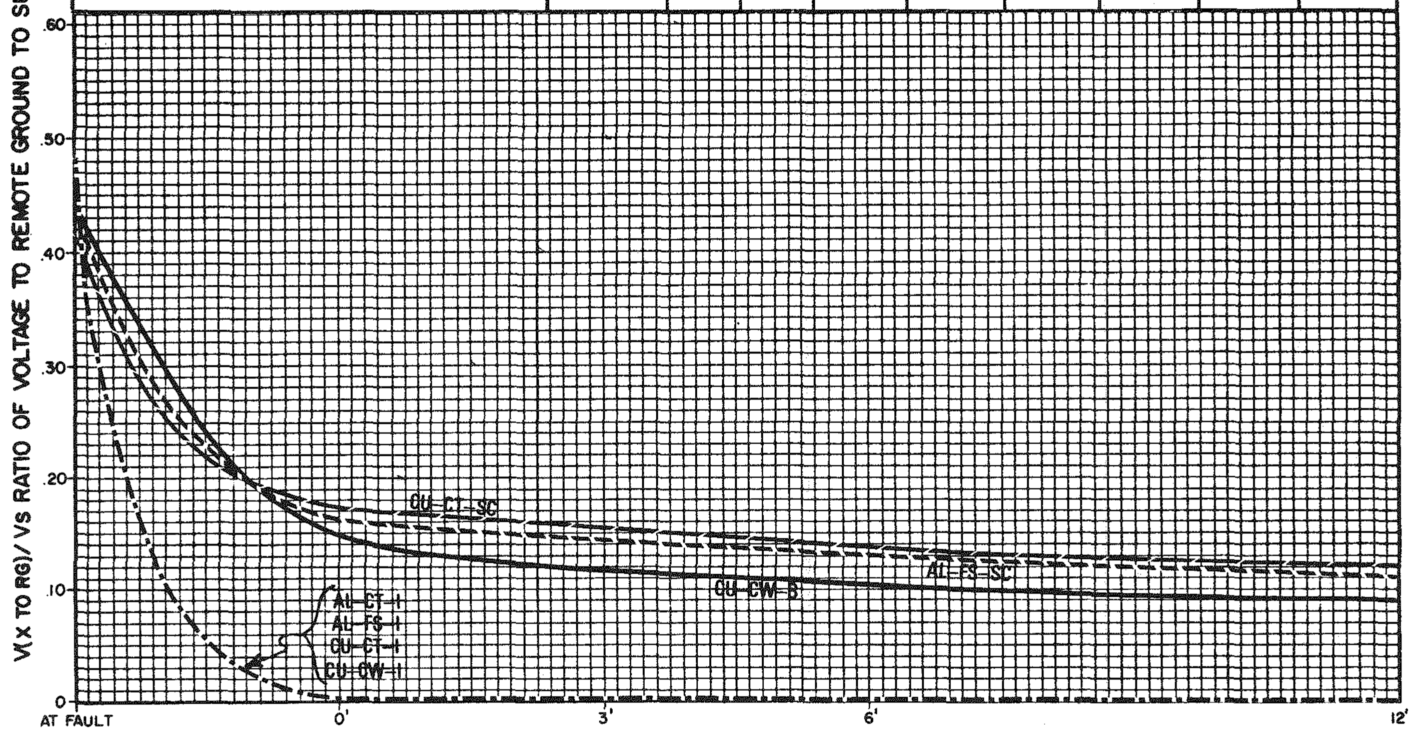
FIGURE 5-8.

SUPPLY CURRENT 5000 AMPERES RMS
SUPPLY VOLTAGE 10731 VOLTS O-PEAK
TYPE OF FAULT STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

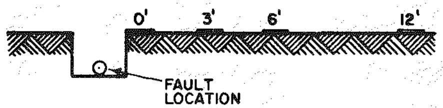
TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
CU-CW-B	10693	1019	47.5	.91∠66°	.60∠74°	5.8∠0°	NO	NO
CU-CT-SC	9100	1480	30.7	.91∠66°	.60∠74°	6.9∠0°	NO	NO
AL-FS-SC	9100	1233	30.7	.91∠66°	.60∠74°	7.5∠0°	NO	NO
AL-CT-I	9100	0	33.6	.91∠66°	.60∠74°	140k∠0°	NO	NO
AL-FS-I	9100	6	27.8	.91∠66°	.60∠74°	30k∠0°	NO	NO
CU-CT-I	8439	0	28.8	.91∠66°	.60∠74°	145k∠0°	NO	NO
CU-CW-I	9266	0	26.9	.91∠66°	.60∠74°	50k∠0°	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

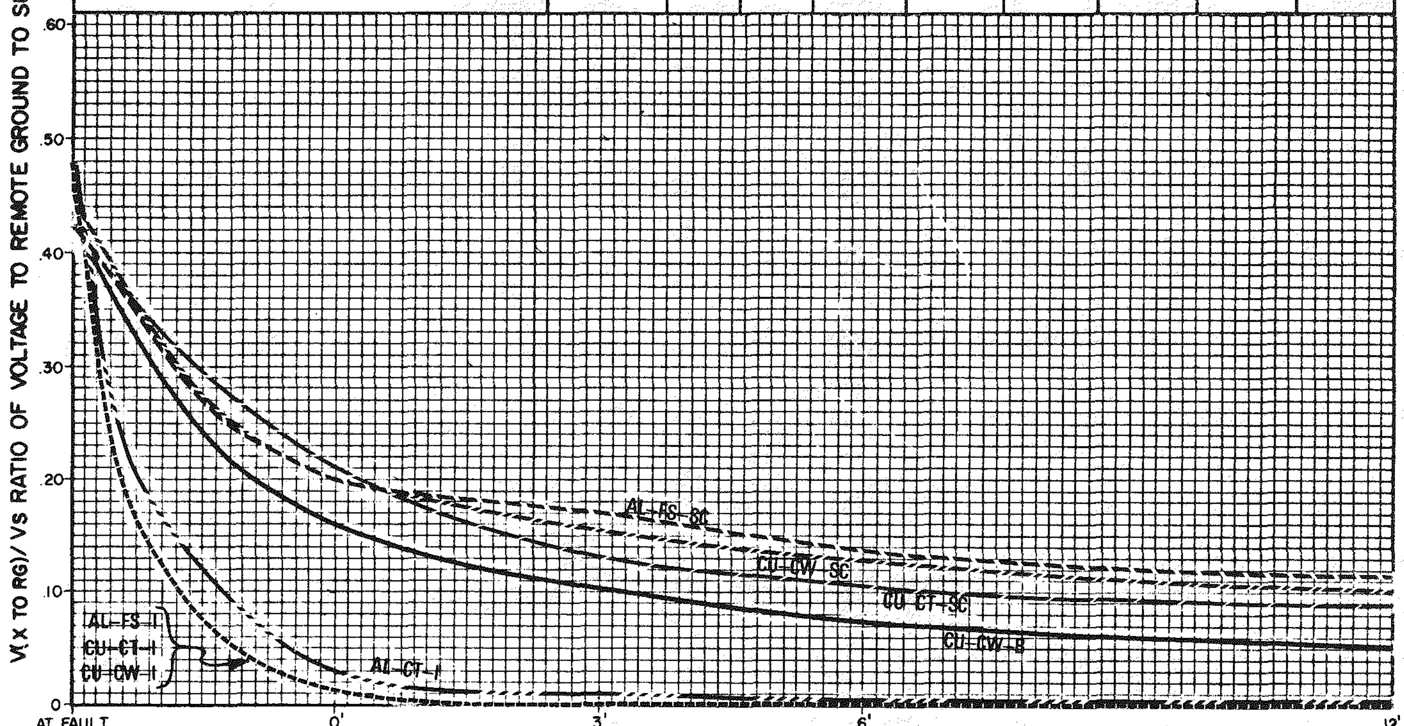
FIGURE 5-9.

SUPPLY CURRENT 5000 AMPERES RMS
SUPPLY VOLTAGE 10731 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

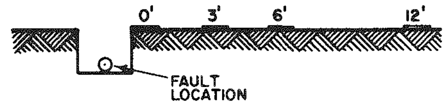
TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITED IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
	O-PEAK	O-PEAK	M-OHMS	HIGH SIDE	LOW SIDE			
CU-CW-B	9266	1041	33.6	.91∠66°	.60∠74°	6.6∠0°	NO	NO
CU-CW-SC	7942	1233	47.0	.91∠66°	.60∠74°	8.1∠0°	NO	NO
CU-CT-SC	8770	1387	30.2	.91∠66°	.60∠74°	7.6∠0°	NO	NO
AL-FS-SC	8604	1326	42.2	.91∠66°	.60∠74°	7.0∠0°	NO	NO
AL-CT-I	8273	37	31.9	.91∠66°	.60∠74°	350∠0°	NO	NO
AL-FS-I	8273	31	26.9	.91∠66°	.60∠74°	485∠0°	NO	NO
CU-CT-I	8273	12	27.8	.91∠66°	.60∠74°	1500∠0°	NO	NO
CU-CW-I	8273	19	24.0	.91∠66°	.60∠74°	2000∠0°	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

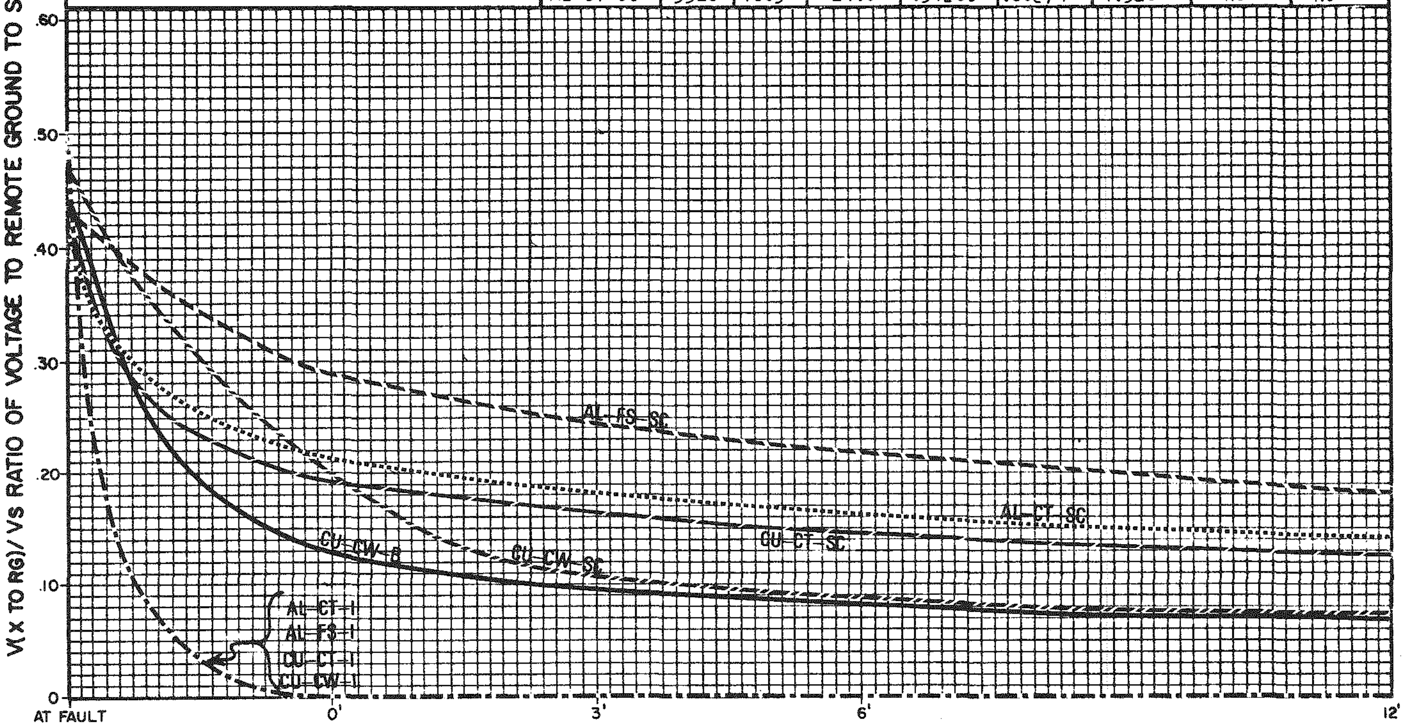
FIGURE 5-10.

SUPPLY CURRENT 5000 AMPERES RMS
SUPPLY VOLTAGE 10731 VOLTS O-PEAK
TYPE OF FAULT STAGED
NEUTRAL SIZE ONE-HALF
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

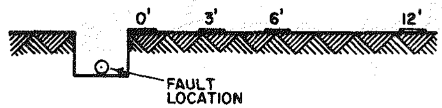
TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITED IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
CU-CW-B	9928	894	26.9	.91∠66°	.60∠74°	8.5∠0°	NO	NO
CU-CW-SC	8770	987	54.7	.91∠66°	.60∠74°	7.2∠0°	NO	NO
CU-CT-SC	8687	1418	38.4	.91∠66°	.60∠74°	6.0∠0°	NO	NO
AL-CT-I	9762	0	35.5	.91∠66°	.60∠74°	40k∠0°	NO	NO
AL-FS-I	8604	0	49.9	.91∠66°	.60∠74°	50k∠0°	NO	NO
CU-CT-I	9597	0	42.2	.91∠66°	.60∠74°	50k∠0°	NO	NO
CU-CW-I	9266	0	32.6	.91∠66°	.60∠74°	190k∠0°	NO	NO
AL-FS-SC	9597	2035	28.3	.91∠66°	.60∠74°	3.2∠0°	NO	NO
AL-CT-SC	9928	1603	24.0	.91∠66°	.60∠74°	4.9∠0°	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

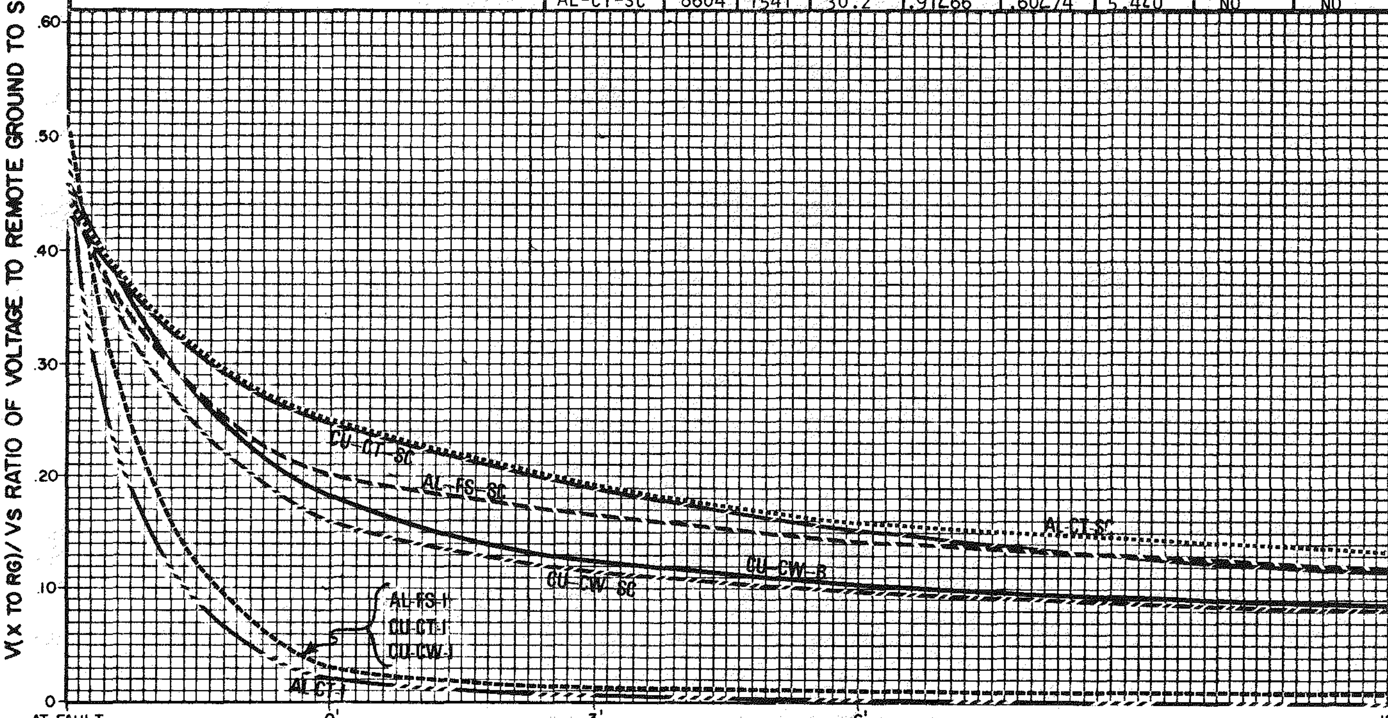
FIGURE 5-11.

SUPPLY CURRENT	5,000 AMPERES RMS
SUPPLY VOLTAGE	10,731 VOLTS O-PEAK
TYPE OF FAULT	PRE-STAGED
NEUTRAL SIZE	ONE-HALF
BACKFILL MATERIAL	NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

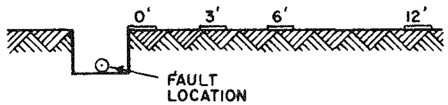
TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITED IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
CU-CW-B	8273	1017	26.9	.91∠66°	.60∠74°	7.6∠0°	NO	NO
CU-CW-SC	8439	925	32.6	.91∠66°	.60∠74°	9.3∠0°	NO	NO
CU-CT-SC	8439	1264	52.8	.91∠66°	.60∠74°	5.5∠0°	NO	NO
AL-FS-SC	8273	1418	29.8	.91∠66°	.60∠74°	4.5∠0°	NO	NO
AL-CT-I	8273	34	34.6	.91∠66°	.60∠74°	400∠0°	NO	NO
AL-FS-I	8190	25	34.6	.91∠66°	.60∠74°	700∠0°	NO	NO
CU-CT-I	8025	22	32.2	.91∠66°	.60∠74°	1100∠0°	NO	NO
CU-CW-I	8273	31	29.8	.91∠66°	.60∠74°	600∠0°	NO	NO
AL-CT-SC	8604	1541	30.2	.91∠66°	.60∠74°	5.4∠0°	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

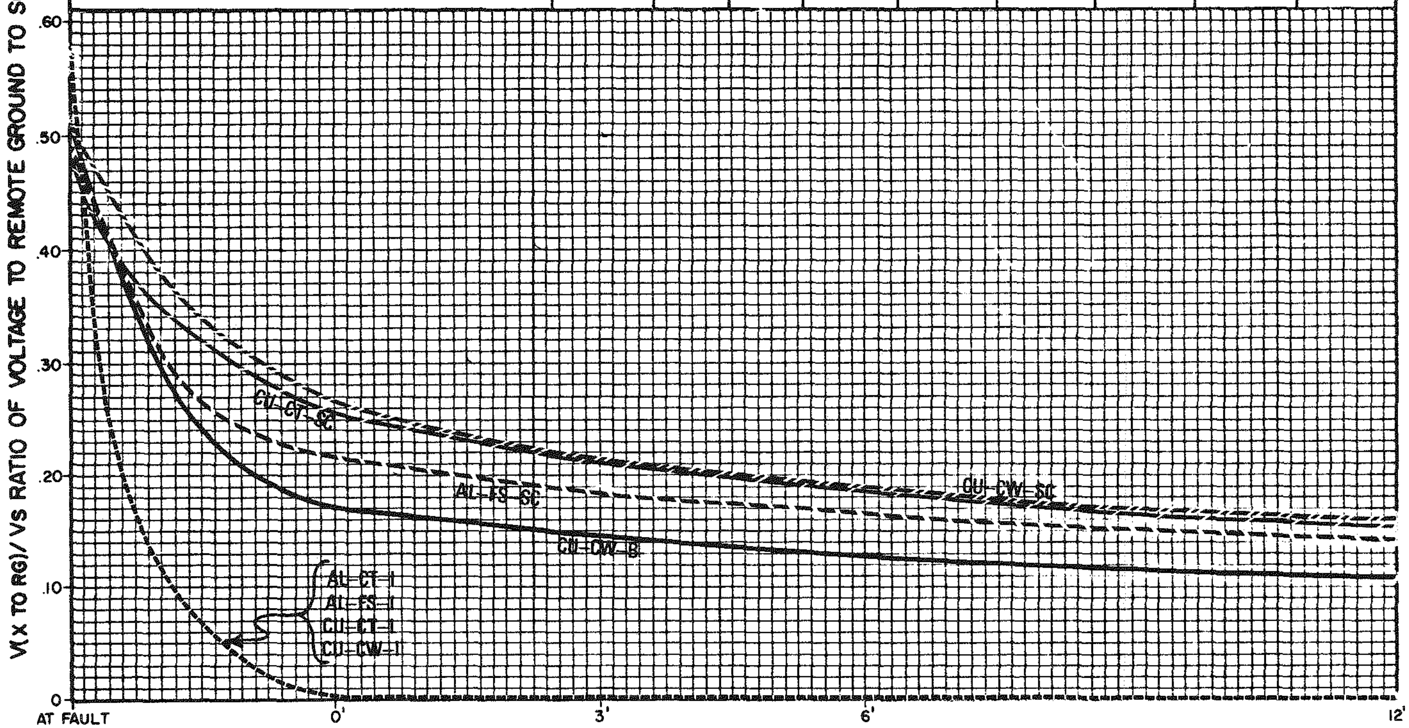
FIGURE 5-12.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

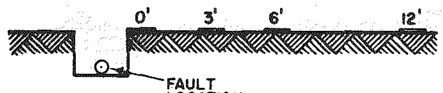
TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M-OHMS	FIXED CURRENT LIMITED IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITED IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
CU-CW-B	20670	1588	31.2	.41∠76°	.32∠74°	5.0∠0°	NO	NO
AL-CT-1	19194	0	33.6	.41∠76°	.32∠74°	∞ ∠0°	NO	NO
AL-FS-1	19932	0	32.7	.41∠76°	.32∠74°	∞ ∠0°	NO	NO
CU-CT-1	17717	0	31.7	.41∠76°	.32∠74°	400k∠0°	NO	NO
CU-CW-1	19194	0	33.6	.41∠76°	.32∠74°	80k∠0°	NO	NO
CU-CW-SC	18086	1911	23.0	.41∠76°	.32∠74°	4.9∠0°	NO	NO
CU-CT-SC	14764	1788	39.4	.41∠76°	.32∠74°	5.2∠0°	NO	NO
AL-FS-SC	20486	1726	31.7	.41∠76°	.32∠74°	5.1∠0°	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

FIGURE 5-13.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITED IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
	O-PEAK	O-PEAK	M-OHMS	HIGH SIDE	LOW SIDE			
CU-CW-B	16241	1649	25.9	$.41\angle 76^\circ$	$.32\angle 74^\circ$	$4.5\angle 0^\circ$	NO	NO
CU-CW-SC	16979	709	33.6	$.41\angle 76^\circ$	$.32\angle 74^\circ$	$8.2\angle 0^\circ$	NO	NO
AL-CT-I	16241	62	25.0	$.41\angle 76^\circ$	$.32\angle 74^\circ$	$920\angle 0^\circ$	NO	NO
AL-FS-I	16241	19	26.9	$.41\angle 76^\circ$	$.32\angle 74^\circ$	$1550\angle 0^\circ$	NO	NO
CU-CT-I	16241	19	24.0	$.41\angle 76^\circ$	$.32\angle 74^\circ$	$510\angle 0^\circ$	NO	NO
CU-CW-I	16240	44	30.2	$.41\angle 76^\circ$	$.32\angle 74^\circ$	$800\angle 0^\circ$	NO	NO
CU-CT-SC	16610	2004	36.5	$.41\angle 76^\circ$	$.32\angle 74^\circ$	$4.6\angle 0^\circ$	NO	NO
AL-FS-SC	16610	1572	36.5	$.41\angle 76^\circ$	$.32\angle 74^\circ$	$5.7\angle 0^\circ$	NO	NO

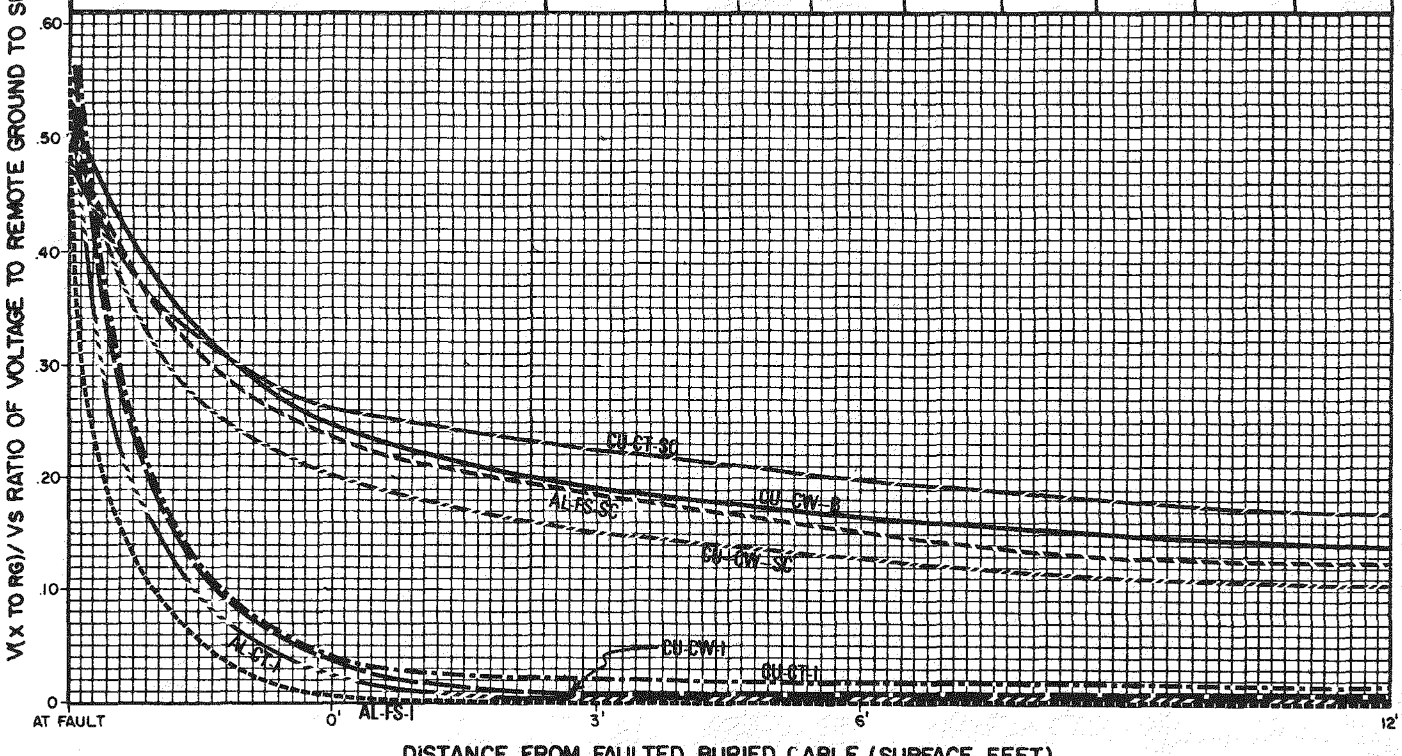
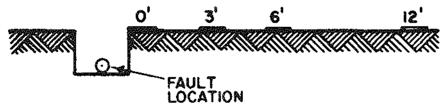


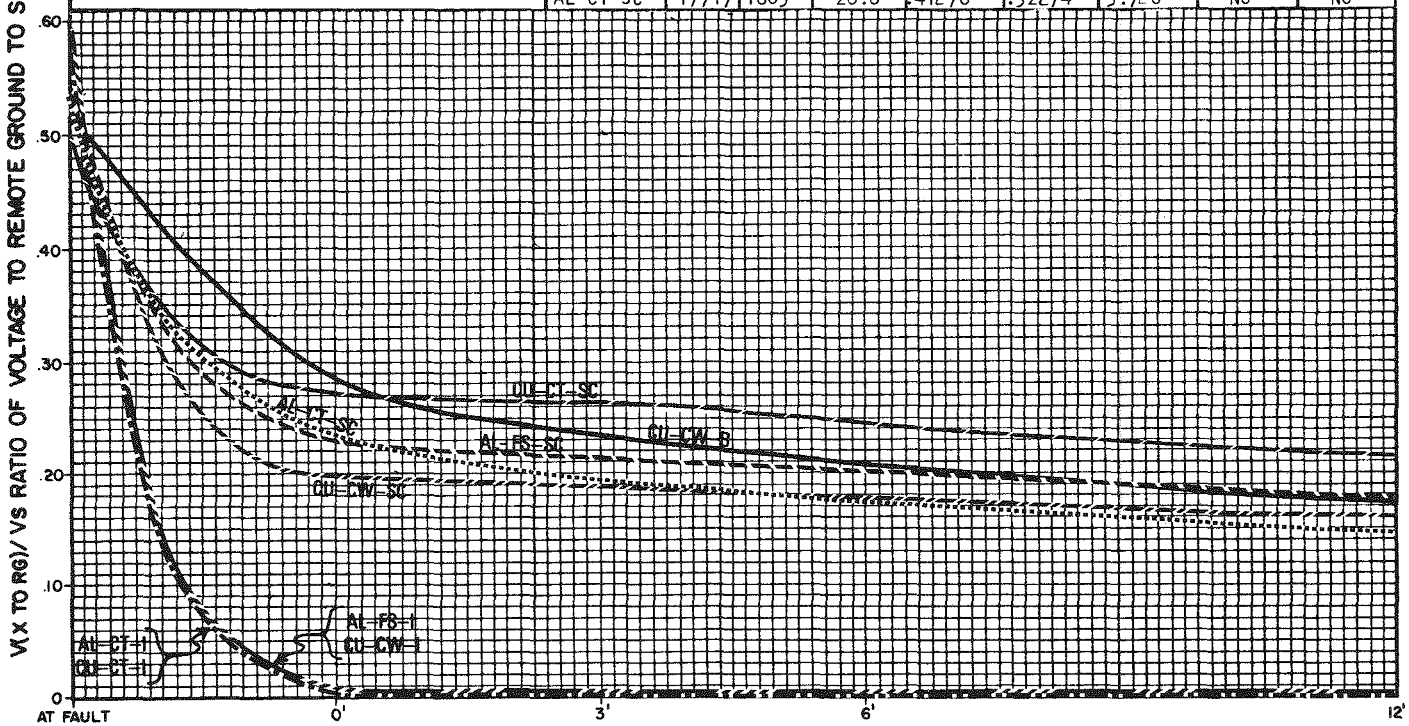
FIGURE 5-14.

SUPPLY CURRENT	10,000 AMPERES RMS
SUPPLY VOLTAGE	10,731 VOLTS O-PEAK
TYPE OF FAULT	STAGED
NEUTRAL SIZE	ONE-HALF
BACKFILL MATERIAL	NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

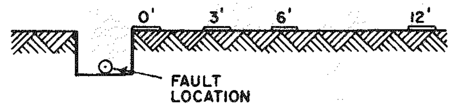
TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITED IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
	O-PEAK	O-PEAK	M-OHMS	HIGH SIDE	LOW SIDE			
AL-CT-1	19378	0	51.4	.41∠76°	.32∠74°	90k∠0°	NO	NO
AL-FS-1	18825	18	34.6	.41∠76°	.32∠74°	12.5k∠0°	NO	NO
CU-CT-1	14026	0	34.6	.41∠76°	.32∠74°	50k∠0°	NO	NO
CU-CW-1	18086	19	37.4	.41∠76°	.32∠74°	140k∠0°	NO	NO
CU-CW-B	19932	2035	25.9	.41∠76°	.32∠74°	3.8∠0°	NO	NO
CU-CW-SC	16979	1665	19.2	.41∠76°	.32∠74°	5.1∠0°	NO	NO
CU-CT-SC	20670	2158	25.0	.41∠76°	.32∠74°	4.0∠0°	NO	NO
AL-FS-SC	16241	1726	25.0	.41∠76°	.32∠74°	5.0∠0°	NO	NO
AL-CT-SC	17717	1603	28.8	.41∠76°	.32∠74°	5.7∠0°	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

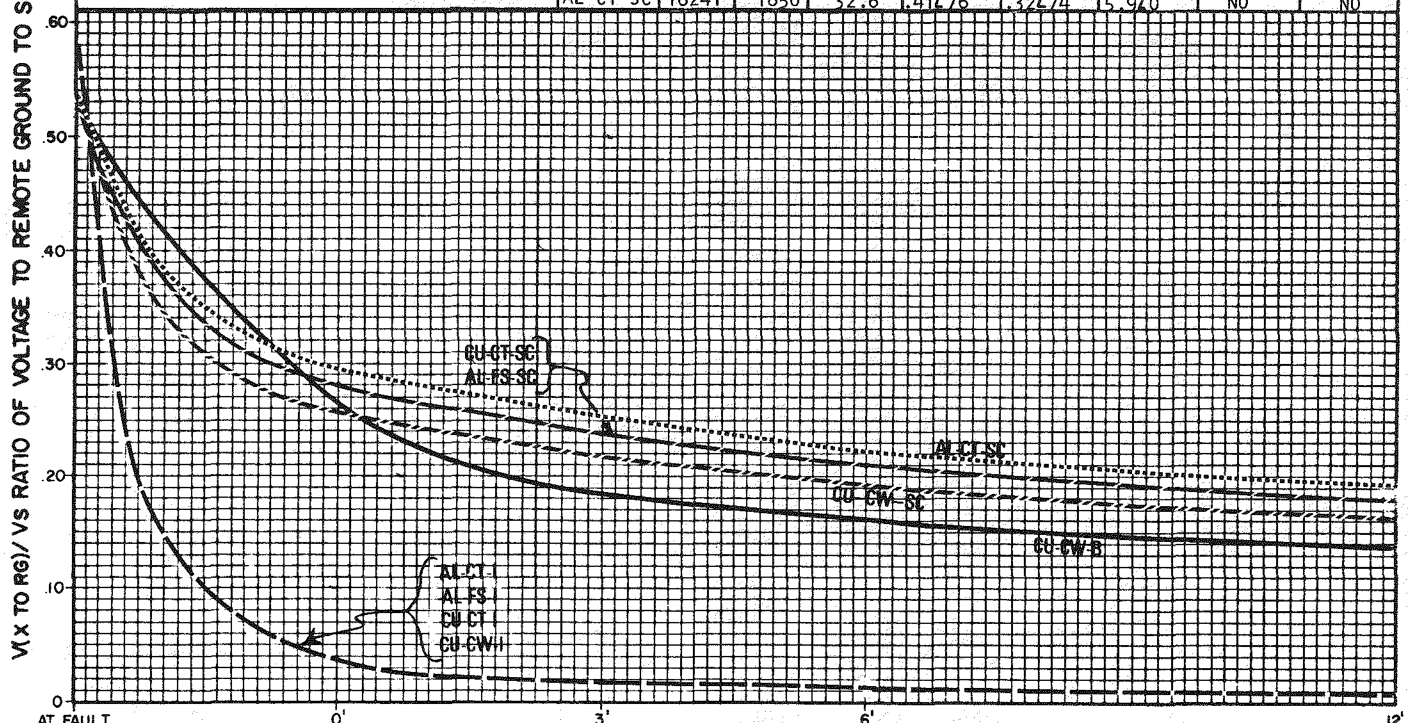
FIGURE 5-15.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE ONE-HALF
BACKFILL MATERIAL NATIVE



EARTH EQUIPOTENTIAL LINE VALUES

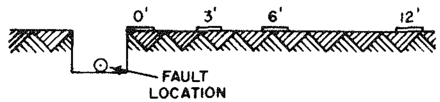
TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITED IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	GROUND RODS CONNECTED	SYSTEM GROUND CONNECTED
	O-PEAK	O-PEAK	M-OHMS	HIGH SIDE	LOW SIDE			
AL-CT-I	16241	31	29.8	.41∠76°	.32∠74°	8250∠0°	NO	NO
AL-FS-I	15687	56	33.6	.41∠76°	.32∠74°	480∠0°	NO	NO
CU-CT-I	15872	75	28.8	.41∠76°	.32∠74°	700∠0°	NO	NO
CU-CW-I	15503	62	28.8	.41∠76°	.32∠74°	950∠0°	NO	NO
CU-CW-B	16241	1588	26.9	.41∠76°	.32∠74°	4.8∠0°	NO	NO
CU-CW-SC	16795	1788	21.1	.41∠76°	.32∠74°	4.6∠0°	NO	NO
CU-CT-SC	16241	1834	11.5	.41∠76°	.32∠74°	4.7∠0°	NO	NO
AL-FS-SC	16610	1865	24.0	.41∠76°	.32∠74°	4.7∠0°	NO	NO
AL-CT-SC	16241	1850	32.6	.41∠76°	.32∠74°	5.9∠0°	NO	NO



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

FIGURE 5-16.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE(1) SAND(2)



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M - OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
CU-CW-B(1)	15414	3971	22.56	1.48∠86°	.71∠40°	2.60	.58∠31.7	1.88∠71.5
CU-CW-B(2)	14747	3872	32.74	1.48∠86°	.71∠40°	2.59	.58∠31.7	1.88∠71.5
CU-CW-SC(1)	15562	4218	24.19	1.48∠86°	.71∠40°	2.62	.58∠31.8	1.88∠71.5
CU-CW-SC(2)	15488	3979	31.20	1.48∠86°	.71∠40°	2.77	.59∠32.2	1.89∠71.4

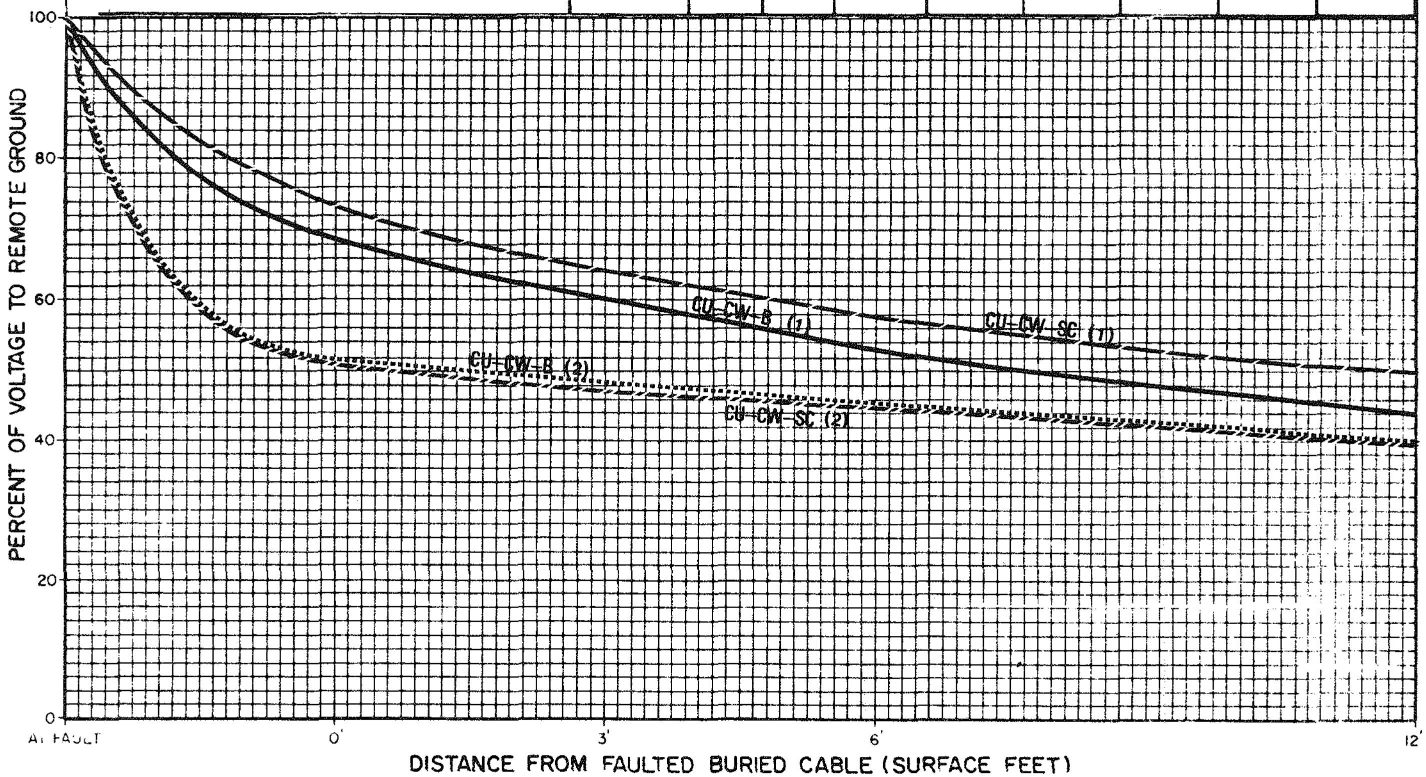
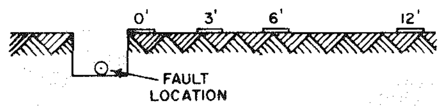


FIGURE 5-17.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITING IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
	O-PEAK	O-PEAK	M – OHMS	HIGH SIDE	LOW SIDE			
CU-CW-B	15414	3971	22.56	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.60	$.58\angle 31.7$	$1.88\angle 71.5$
CU-CW-SC	15562	4218	24.19	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.62	$.58\angle 31.8$	$1.88\angle 71.5$
CU-CW-I	15167	387	26.72	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	165	$.71\angle 39.8$	$2.04\angle 71.5$
CU-CT-SC(1)	15377	4255	24.48	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.62	$.58\angle 31.8$	$1.88\angle 71.5$
CU-CT-SC(2)	14191	552	26.64	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	2.74	$.057\angle 71.9$	$2.04\angle 71.0$
CU-CT-I	14080	86.5	28.90	$1.98\angle 71^\circ$	$.057\angle 73^\circ$	111	$.057\angle 73.0$	$2.04\angle 71.1$
AL-FS-SC	15612	4216	24.06	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	2.63	$.58\angle 31.8$	$1.88\angle 71.5$
AL-FS-I	14376	300	27.36	$1.48\angle 86^\circ$	$.71\angle 40^\circ$	143	$.71\angle 39.8$	$2.03\angle 71.5$

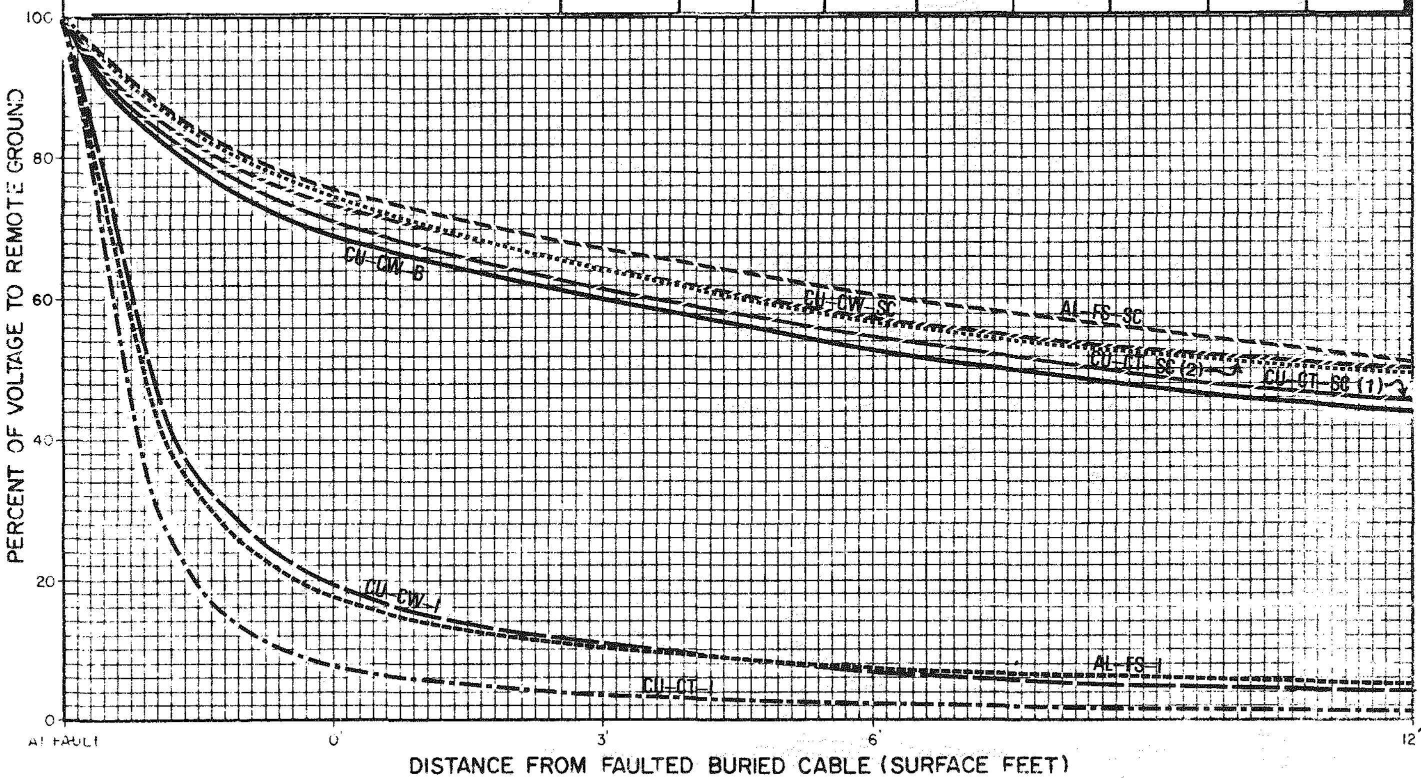


FIGURE 5-18.

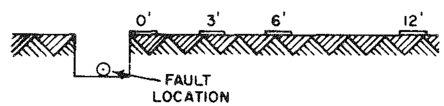
SUPPLY CURRENT 10,000 AMPERES RMS

SUPPLY VOLTAGE 27,263 VOLTS O-PEAK

TYPE OF FAULT PRE-STAGED

NEUTRAL SIZE FULL

BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M - OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITING IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
CU-CW-I	15414	4347	30.24	1.48∠86°	.71∠40°	2.29	.57∠30.9	1.86∠71.6
AL-FS-SC	16451	6617	31.30	1.48∠86°	.71∠40°	1.59	.52∠27.9	1.81∠71.9
AL-FS-I	15710	4588	26.88	1.48∠86°	.71∠40°	2.19	.56∠30.5	1.86∠71.6
AL-CT-SC(1)	16118	6528	29.47	1.48∠86°	.71∠40°	1.62	.52∠28.1	1.81∠71.9
AL-CT-SC(2)	14414	888	25.59	1.98∠71°	.057∠73°	1.40	.056∠70.8	2.04∠71.0
AL-CT-I(1)	16007	5318	29.67	1.48∠86°	.71∠40°	1.95	.55∠29.6	1.84∠71.7
AL-CT-I(2)	14079	740	31.20	1.98∠71°	.057∠73°	1.93	.056∠71.4	2.04∠71.0

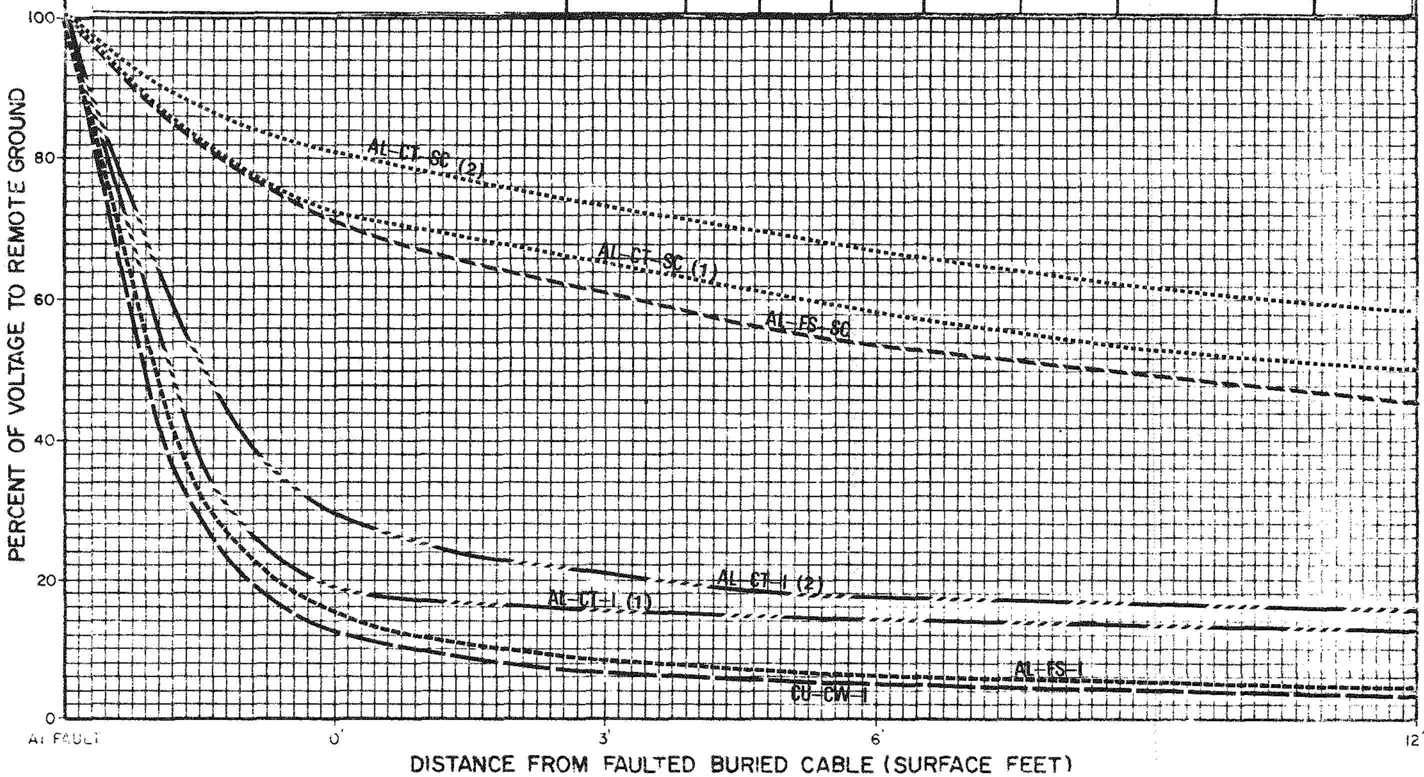
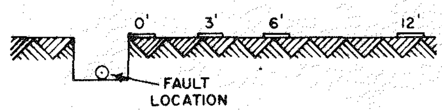


FIGURE 5-19.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE ONE-HALF
BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M - OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITING IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
CU-CW-B	15600	4742	23.04	1.48∠46°	.71∠40°	2.26	.56∠30.8	1.86∠71.6
CU-CW-SC	15636	4218	27.24	1.48∠46°	.71∠40°	2.43	.57∠31.3	1.87∠71.5
CU-CT-SC	15191	3441	47.04	1.48∠46°	.71∠40°	3.23	.60∠33.1	1.91∠71.4
CU-CT-I	14228	286	27.77	1.48∠46°	.71∠40°	119	.71∠39.8	2.03∠71.9
AL-FS-SC	15970	4452	22.30	1.48∠46°	.71∠40°	2.25	.56∠30.9	1.86∠71.6
AL-CT-SC	15859	4680	31.27	1.48∠46°	.71∠40°	2.18	.56∠30.5	1.86∠71.6
AL-CT-I	14321	296	26.83	1.48∠46°	.71∠40°	110	.71∠39.8	2.03∠71.9

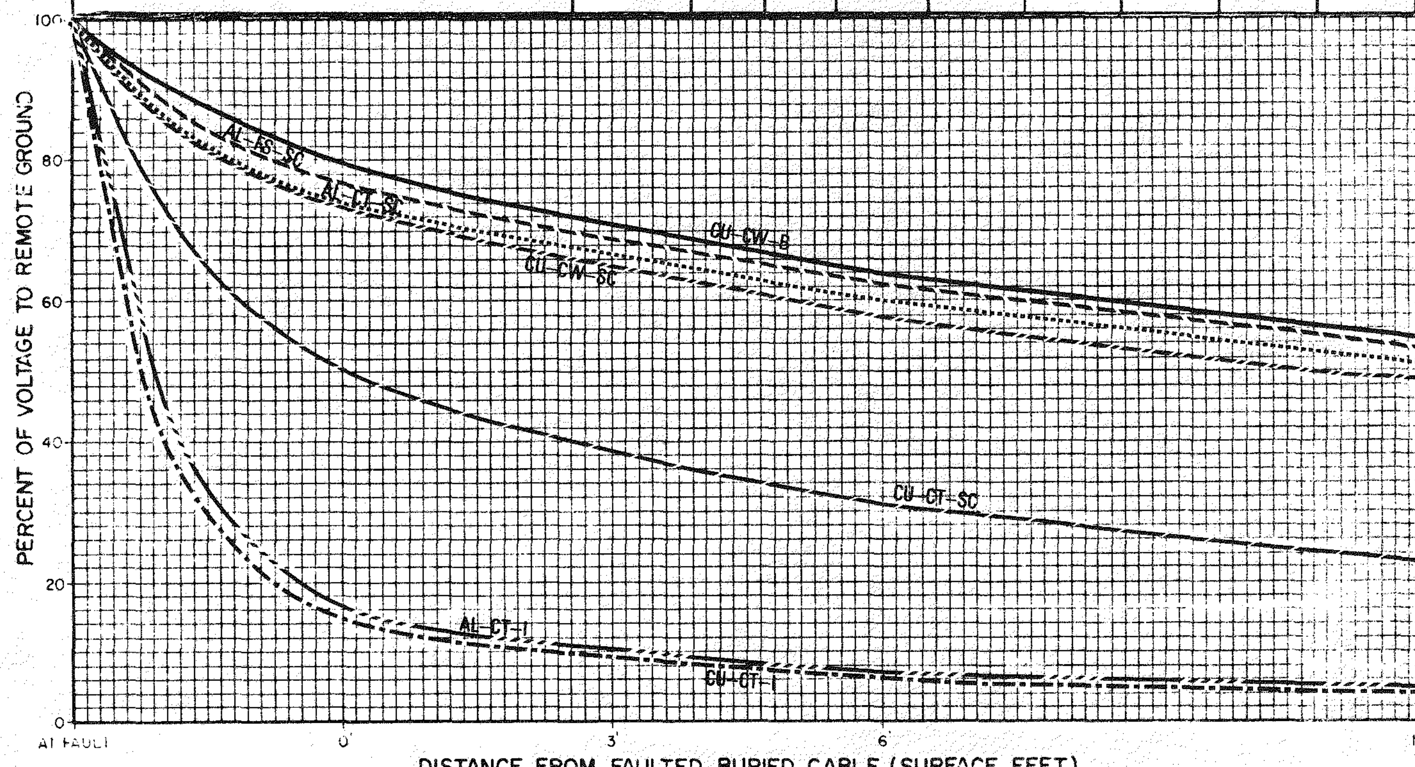
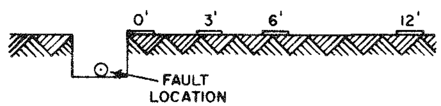


FIGURE 5-20.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE ONE-HALF
BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITING IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
	O-PEAK	O-PEAK	M – OHMS	HIGH SIDE	LOW SIDE			
CU-CW-B	16563	6967	22.37	1.48∠86°	.71∠40°	1.24	.48∠25.7	1.77∠72.4
CU-CT-SC	16698	6920	23.78	1.48∠86°	.71∠40°	1.32	.49∠26.2	1.78∠72.3
AL-CT-SC	16748	6905	22.71	1.48∠86°	.71∠40°	1.28	.48∠26.0	1.77∠72.3
CU-CW-I	15784	4708	27.50	1.48∠86°	.71∠40°	2.27	.57∠30.8	1.86∠71.6
AL-FS-I	15766	4680	30.36	1.48∠86°	.71∠40°	2.25	.56∠30.7	1.86∠71.6

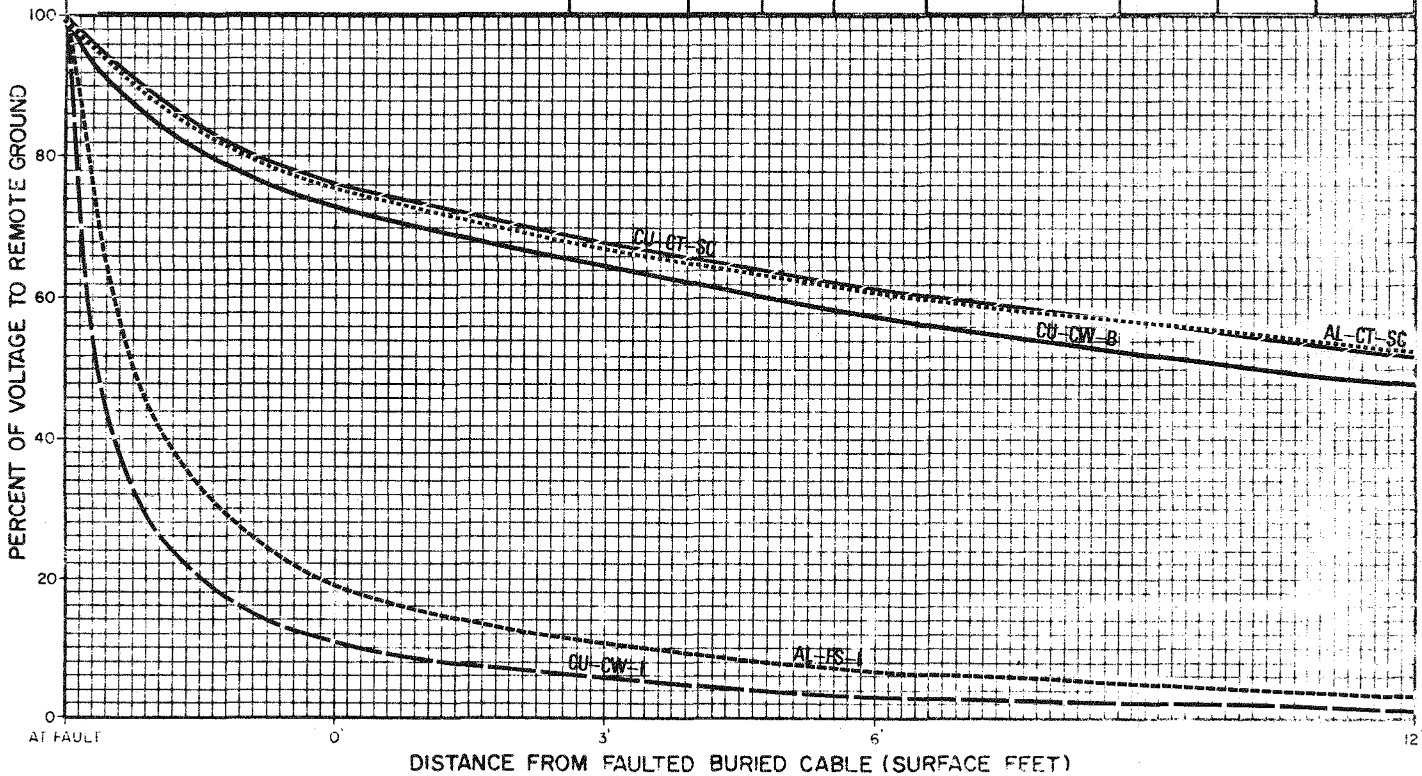
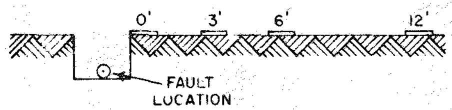


FIGURE 5-21.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 27,263 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITING IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
	O-PEAK	O-PEAK	M - OHMS	HIGH SIDE	LOW SIDE			
CU-CT-I	14080	86.5	28.90	1.98∠71°	.057∠73°	111∠0	.06∠73.0	2.04∠71.1
AL-CT-I	14079	740	31.20	1.98∠71°	.057∠73°	1.93∠0	.06∠71.4	2.04∠71.0
CU-CT-SC	14191	552	26.64	1.98∠71°	.057∠73°	2.74∠0	.06∠71.9	2.04∠71.0
AL-CT-SC	14414	888	25.59	1.98∠71°	.057∠73°	1.40∠0	.06∠70.8	2.04∠71.0

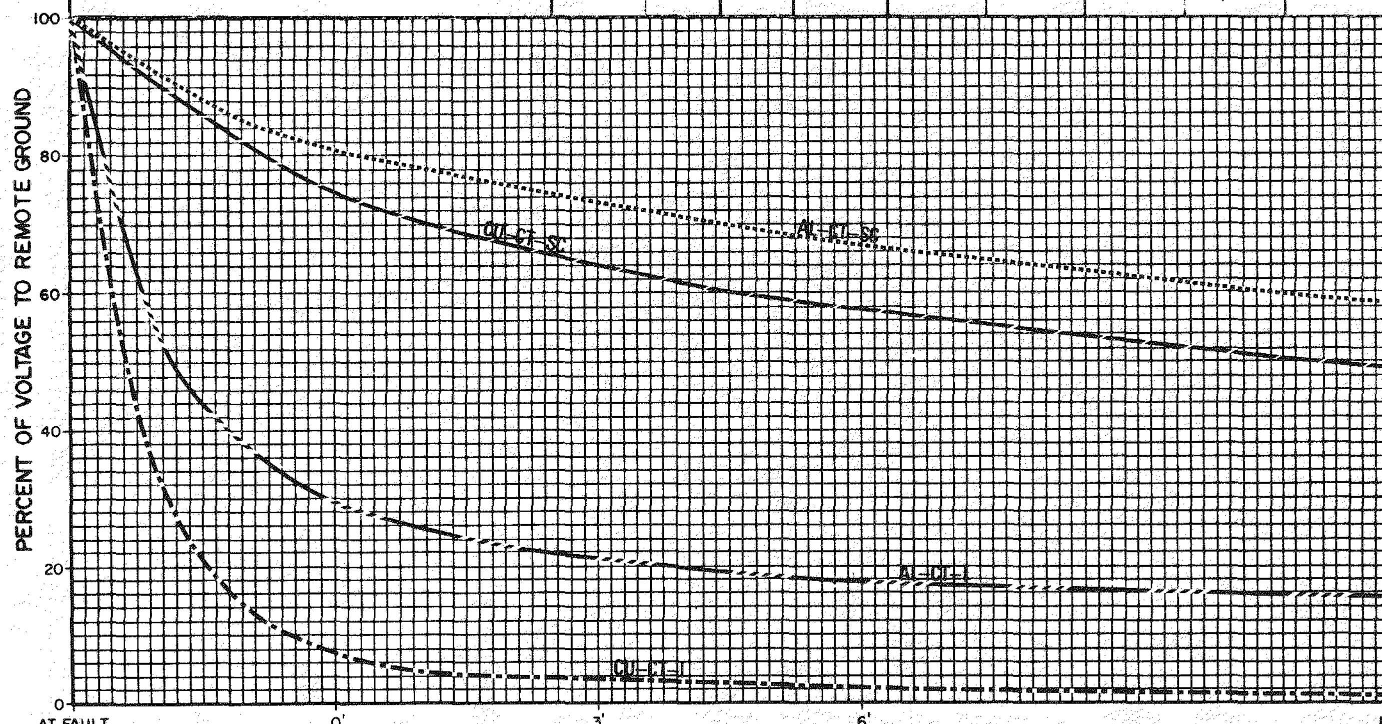
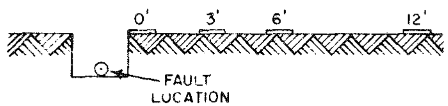


FIGURE 5-22.

SUPPLY CURRENT	10,000 AMPERES RMS
SUPPLY VOLTAGE	27,263 VOLTS O-PEAK
TYPE OF FAULT	PRE-STAGED
NEUTRAL SIZE	FULL
BACKFILL MATERIAL	NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M - OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITING IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
AL-CT-SC	16118	6528	29.47	1.48∠86°	.71∠40°	1.62∠0°	.52∠28.1°	1.81∠71.9
CU-CT-SC	15377	4255	24.48	1.48∠86°	.71∠40°	2.62∠0°	.58∠31.8°	1.88∠71.5
AL-CT-I	16007	5318	29.67	1.48∠86°	.71∠40°	1.95∠0°	.55∠29.6°	1.84∠71.7
CU-CW-I	15711	411	26.88	1.48∠86°	.71∠40°	165∠0°	.71∠39.8°	2.04∠71.5

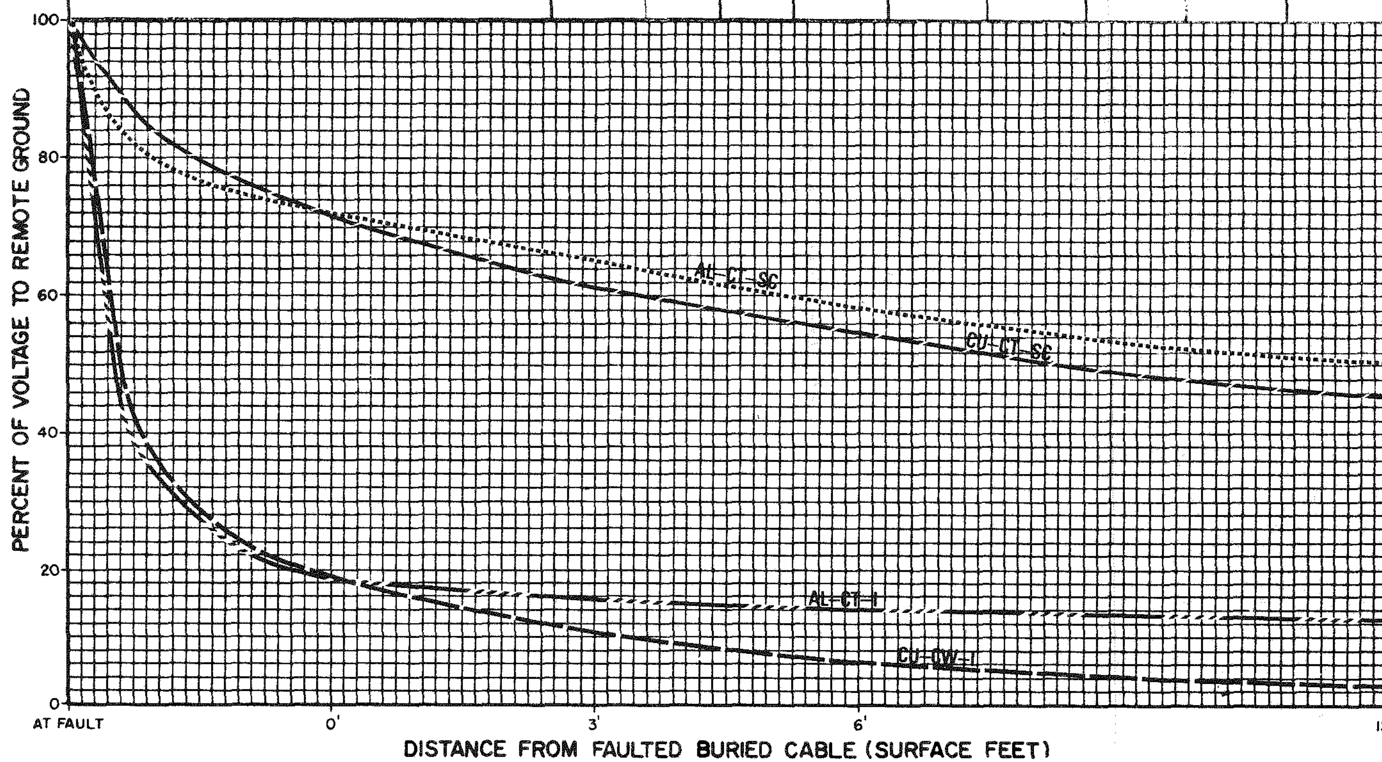
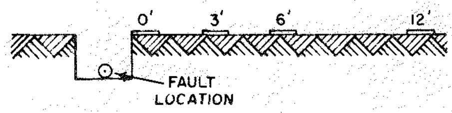


FIGURE 5-23.

SUPPLY CURRENT 5,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M - OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITING IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
CU-CW-B	10693	1019	47.5	.91∠66°	.60∠74°	5.8∠0°	58∠68.5	.49∠67.0
CU-CT-SC	9100	1480	30.7	.91∠66°	.60∠74°	6.9∠0°	58∠69.3	.49∠67.3
AL-FS-SC	9100	1233	30.7	.91∠66°	.60∠74°	7.5∠0°	59∠69.7	.49∠67.5
AL-CT-I	9100	0	33.6	.91∠66°	.60∠74°	140k∠0°	60∠74.0	.51∠69.2
AL-FS-I	9100	6	27.8	.91∠66°	.60∠74°	30k∠0°	60∠74.0	.51∠69.2
CU-CT-I	8439	0	28.8	.91∠66°	.60∠74°	145k∠0°	60∠74.0	.51∠69.2
CU-CW-I	9266	0	26.9	.91∠66°	.60∠74°	50k∠0°	60∠74.0	.51∠69.2

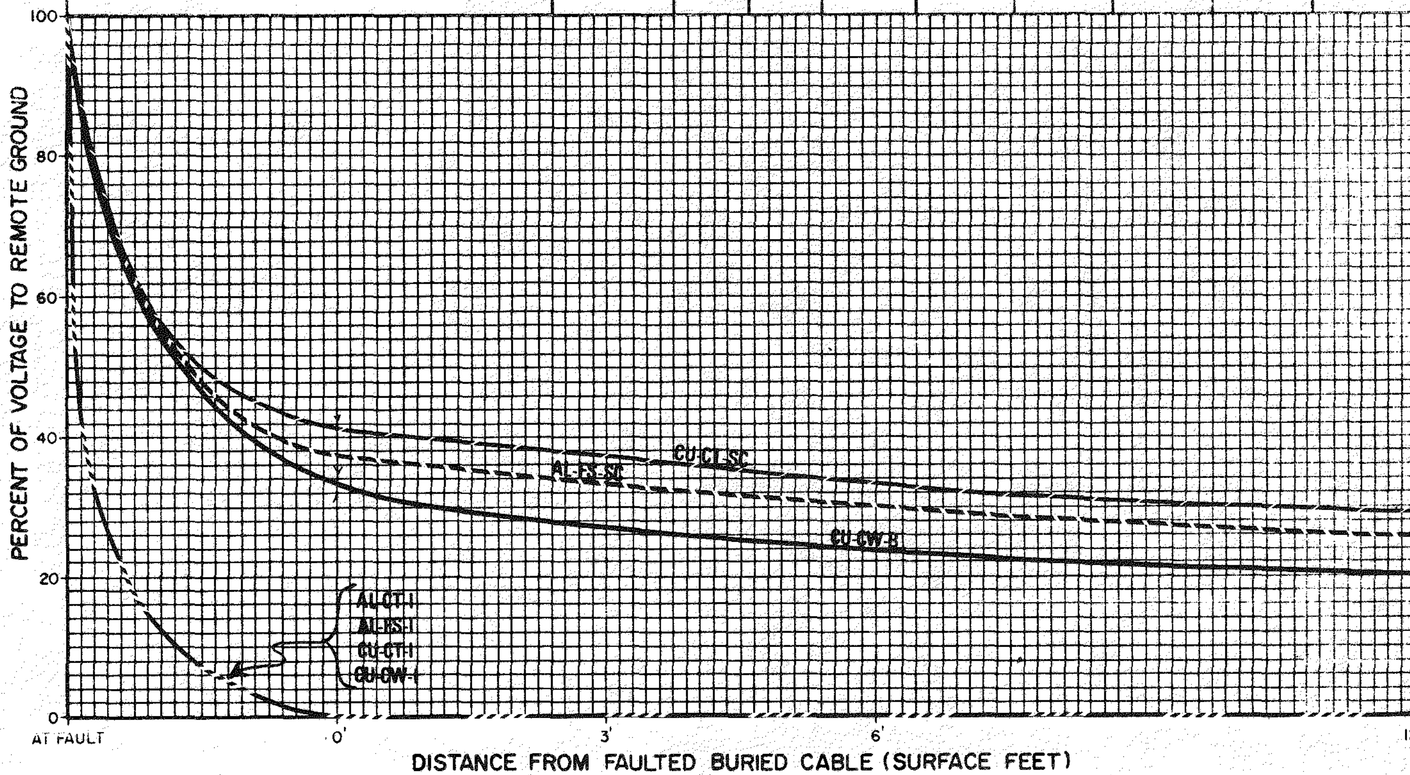
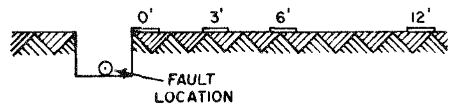


FIGURE 5-24.

SUPPLY CURRENT 5,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M - OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITING IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
CU-CW-B	9266	1041	33.6	.91∠66°	.60∠74°	6.6∠0°	.60∠73.95	1.51∠69.2
CU-CW-SC	7942	1233	47.0	.91∠66°	.60∠74°	8.1∠0°	.59∠70.01	1.50∠67.6
CU-CT-SC	8770	1387	30.2	.91∠66°	.60∠74°	7.6∠0°	.59∠69.75	1.49∠67.5
AL-FS-SC	8604	1326	42.2	.91∠66°	.60∠74°	7.0∠0°	.58∠69.40	1.49∠67.3
AL-CT-I	8273	37	31.9	.91∠66°	.60∠74°	350∠0°	.60∠73.91	1.51∠69.1
AL-FS-I	8273	31	26.9	.91∠66°	.60∠74°	485∠0°	.60∠73.93	1.51∠69.2
CU-CT-I	8273	12	27.8	.91∠66°	.60∠74°	1500∠0°	.60∠73.98	1.51∠67.2
CU-CW-I	8273	19	24.0	.91∠66°	.60∠74°	2000∠0°	.60∠73.98	1.51∠69.2

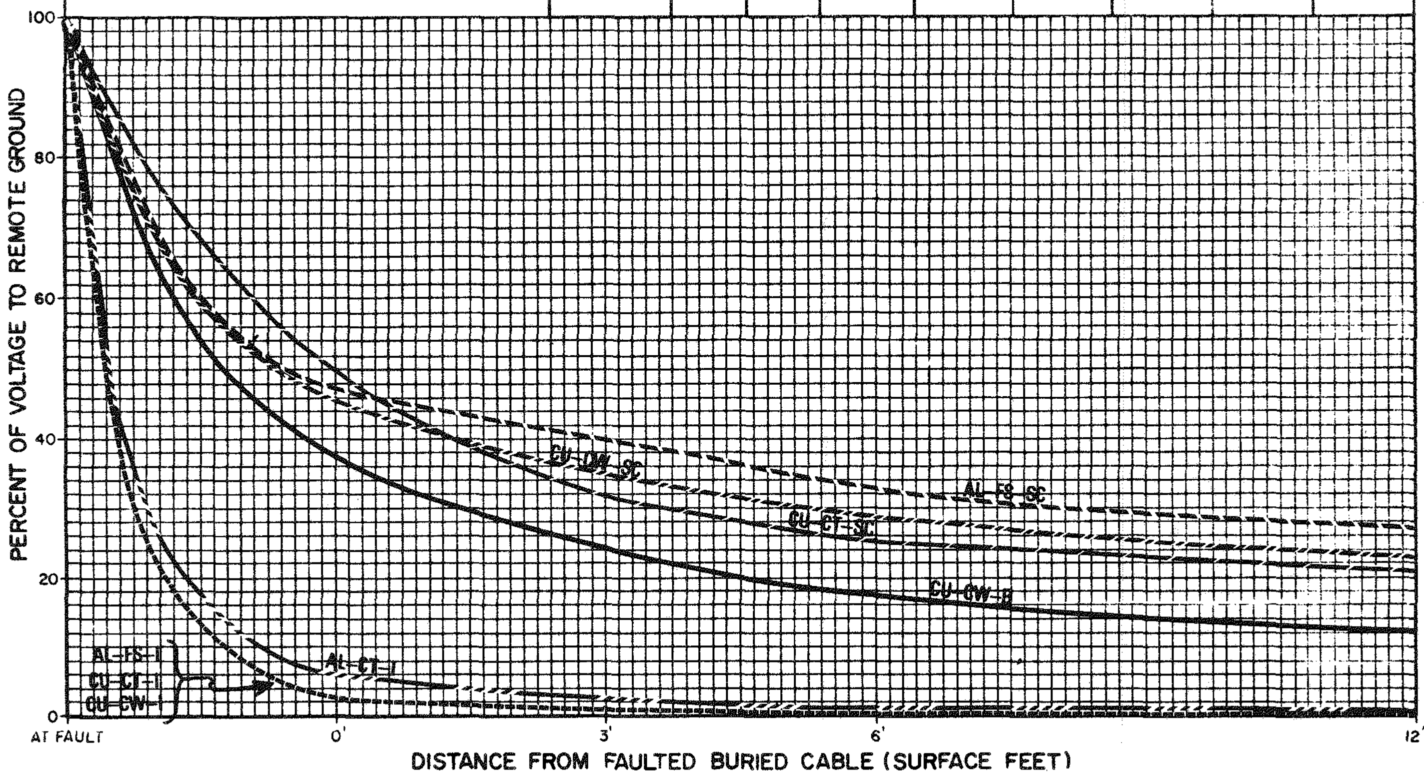
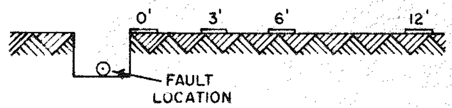


FIGURE 5-25.

SUPPLY CURRENT 5,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT STAGED
NEUTRAL SIZE ONE-HALF
BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITING IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
	O-PEAK	O-PEAK	M - OHMS	HIGH SIDE	LOW SIDE			
CU-CW-B	9928	894	26.9	.91∠66°	.60∠74°	8.5∠0°	.59∠70.19	1.5∠67.64
CU-CW-SC	8770	987	54.7	.91∠66°	.60∠74°	7.2∠0°	.58∠69.52	1.49∠67.4
CU-CT-SC	8687	1418	38.4	.91∠66°	.60∠74°	6.0∠0°	.58∠68.66	1.49∠67.0
AL-CT-1	9762	0	35.5	.91∠66°	.60∠74°	40k∠0°	.60∠74.00	1.51∠69.2
AL-FS-1	8604	0	49.9	.91∠66°	.60∠74°	50k∠0°	.60∠74.00	1.51∠69.2
CU-CT-1	9597	0	42.2	.91∠66°	.60∠74°	50k∠0°	.60∠74.00	1.51∠69.2
CU-CW-1	9266	0	32.6	.91∠66°	.60∠74°	190k∠0°	.60∠74.00	1.51∠69.2
AL-FS-SC	9597	2035	28.3	.91∠66°	.60∠74°	3.2∠0°	.56∠64.28	1.47∠65.3
AL-CT-SC	9928	1603	24.0	.91∠66°	.60∠74°	4.9∠0°	.58∠67.50	1.49∠66.6

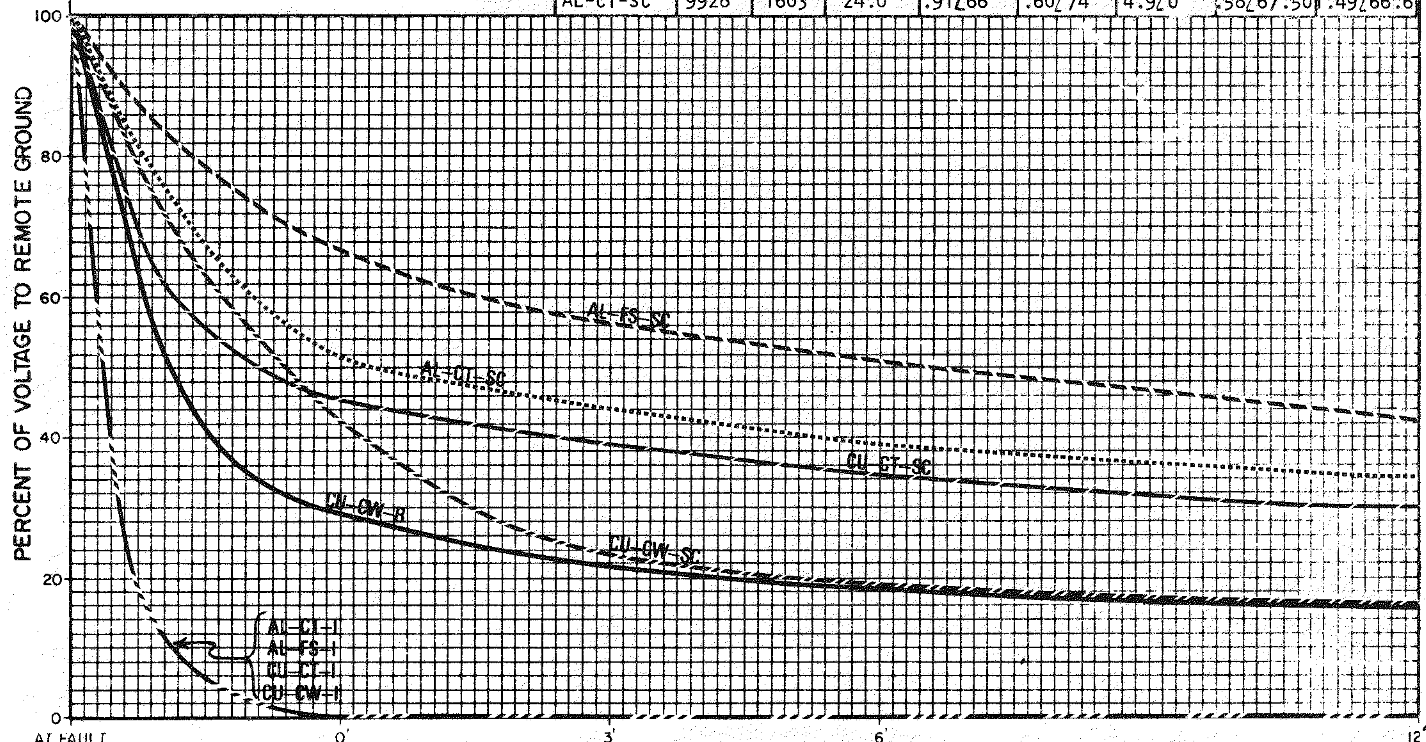
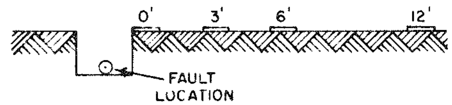


FIGURE 5-26.

SUPPLY CURRENT	5,000 AMPERES RMS
SUPPLY VOLTAGE	10,731 VOLTS O-PEAK
TYPE OF FAULT	PRE-STAGED
NEUTRAL SIZE	ONE-HALF
BACKFILL MATERIAL	NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M – OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITING IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
CU-CW-B	8273	1017	26.9	.91∠66°	.60∠74°	7.6∠0°	.59∠69.75	1.49∠67.5
CU-CW-SC	8439	925	32.6	.91∠66°	.60∠74°	9.3∠0°	.59∠70.51	1.50∠67.8
CU-CT-SC	8439	1264	52.8	.91∠66°	.60∠74°	5.5∠0°	.58∠68.19	1.49∠66.9
AL-FS-SC	8273	1418	29.8	.91∠66°	.60∠74°	4.5∠0°	.57∠66.95	1.48∠66.4
AL-CT-I	8273	34	34.6	.91∠66°	.60∠74°	400∠0°	.60∠73.92	1.51∠69.1
AL-FS-I	8190	25	34.6	.91∠66°	.60∠74°	700∠0°	.60∠73.95	1.51∠69.2
CU-CT-I	8025	22	32.2	.91∠66°	.60∠74°	1100∠0°	.60∠73.97	1.51∠69.2
CU-CW-I	8273	31	29.8	.91∠66°	.60∠74°	600∠0°	.60∠73.94	1.51∠69.2
AL-CT-SC	8604	1541	30.2	.91∠66°	.60∠74°	5.4∠0°	.58∠68.08	1.49∠66.8

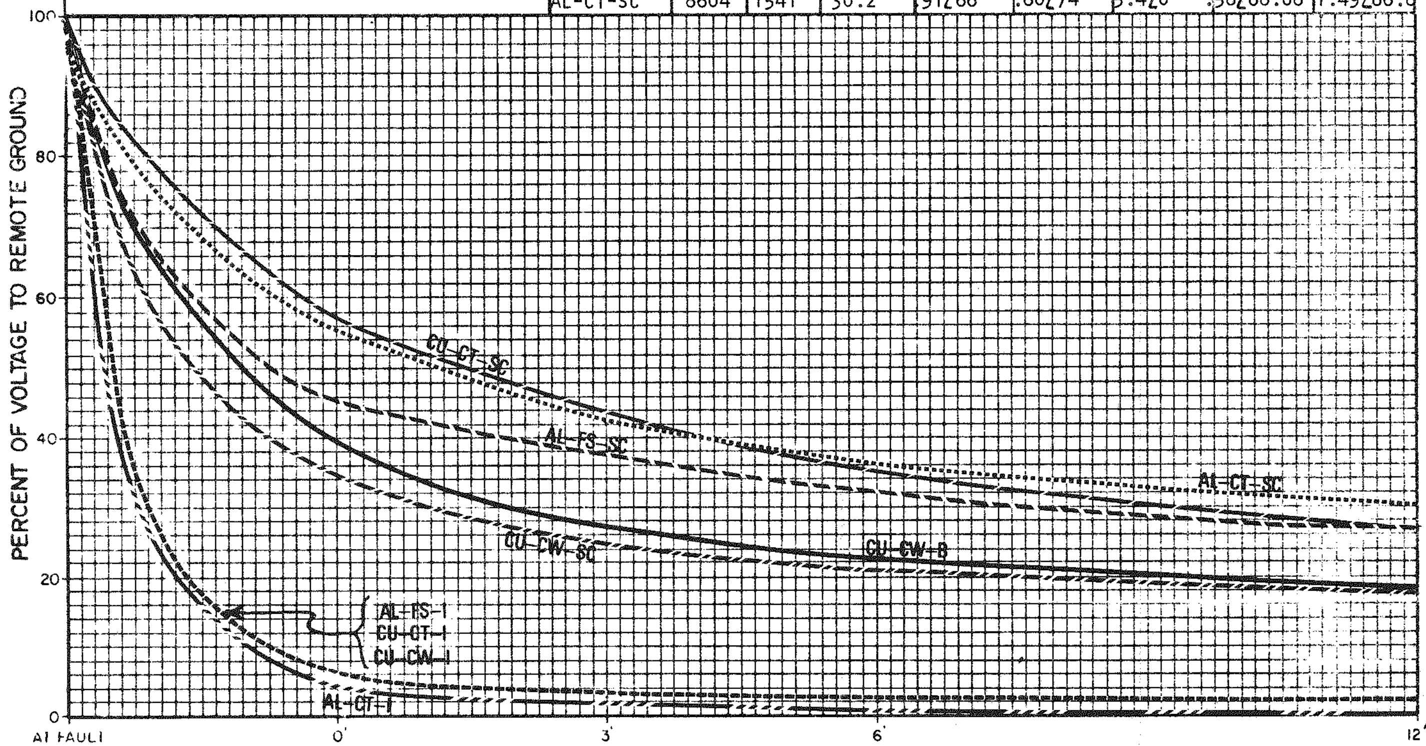
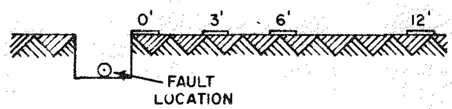


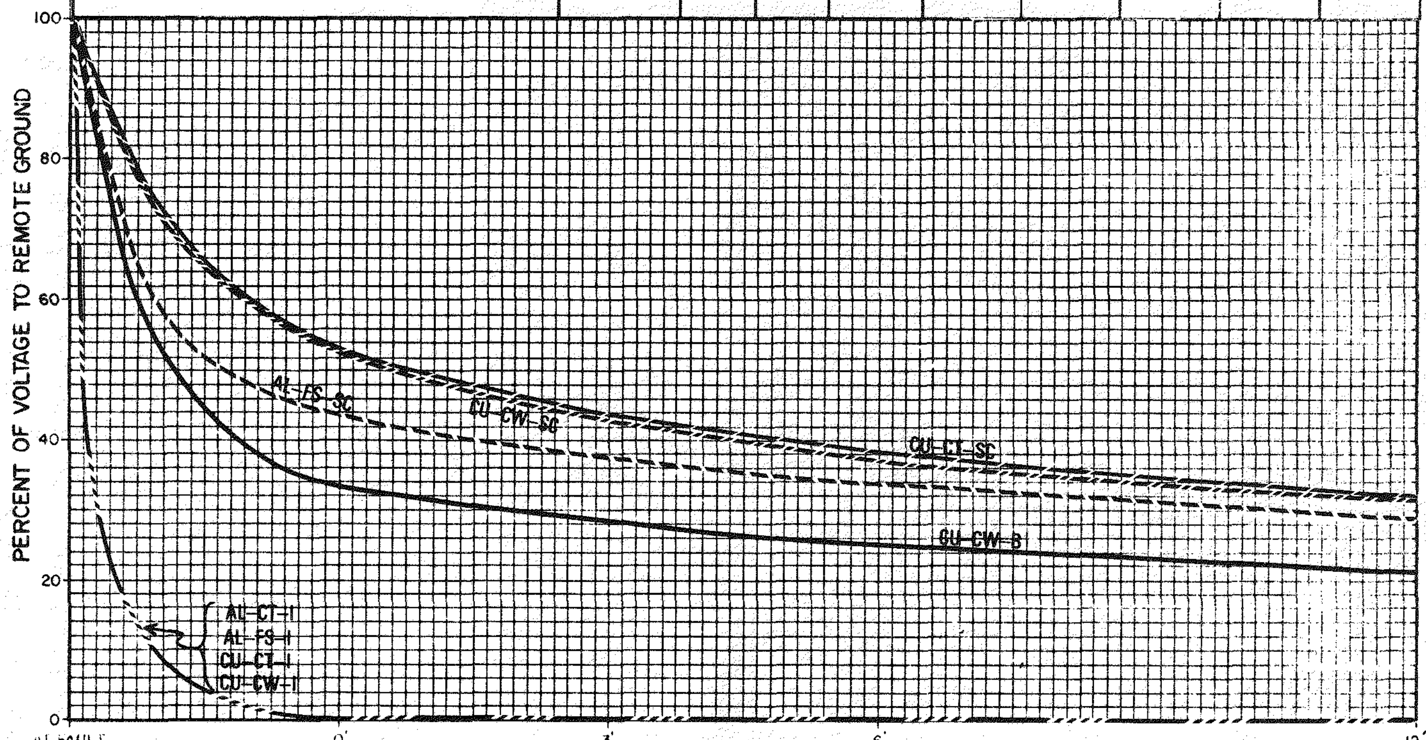
FIGURE 5-27.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

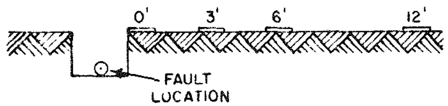
TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M – OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITING IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
CU-CW-B	20670	1588	31.2	.41∠76°	.32∠74°	5.0∠0°	.31∠70.54	.72∠73.63
AL-CT-1	19194	0	33.6	.41∠76°	.32∠74°	∞ ∠0°	.32∠74.00	.73∠75.12
AL-FS-1	19932	0	32.7	.41∠76°	.32∠74°	∞ ∠0°	.32∠74.00	.73∠75.12
CU-CT-1	17717	0	31.7	.41∠76°	.32∠74°	400k∠0°	.32∠74.00	.73∠75.12
CU-CW-1	19194	0	33.6	.41∠76°	.32∠74°	80k∠0°	.32∠74.00	.73∠75.12
CU-CW-SC	18086	1911	23.0	.41∠76°	.32∠74°	4.9∠0°	.31∠70.47	.72∠73.60
CU-CT-SC	14764	1788	39.4	.41∠76°	.32∠74°	5.2∠0°	.31∠70.67	.72∠73.69
AL-FS-SC	20486	1726	31.7	.41∠76°	.32∠74°	5.1∠0°	.31∠70.61	.72∠73.66



DISTANCE FROM FAULTED BURIED CABLE (SURFACE FEET)

FIGURE 5-28.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT PRE-STAGED
NEUTRAL SIZE FULL
BACKFILL MATERIAL NATIVE

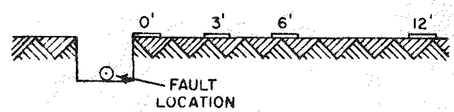


VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M - OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	FIXED CURRENT LIMITING IMPEDANCES (OHMS) LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
CU-CW-B	16241	1649	25.9	.41∠76°	.32∠74°	4.5∠0°	.31∠70.16	.72∠73.47
CU-CW-SC	16979	709	33.6	.41∠76°	.32∠74°	8.2∠0°	.32∠71.87	.73∠74.2
AL-CT-I	16241	62	25.0	.41∠76°	.32∠74°	920∠0°	.32∠73.98	.73∠75.11
AL-FS-I	16241	19	26.9	.41∠76°	.32∠74°	1550∠0°	.32∠73.99	.73∠75.12
CU-CT-I	16241	19	24.0	.41∠76°	.32∠74°	510∠0°	.32∠73.97	.73∠75.11
CU-CW-I	16240	44	30.2	.41∠76°	.32∠74°	800∠0°	.32∠73.98	.73∠75.11
CU-CT-SC	16610	2004	36.5	.41∠76°	.32∠74°	4.6∠0°	.31∠70.25	.72∠73.51
AL-FS-SC	16610	1572	36.5	.41∠76°	.32∠74°	5.7∠0°	.31∠70.96	.72∠73.81

FIGURE 5-29.

SUPPLY CURRENT 10,000 AMPERES RMS
SUPPLY VOLTAGE 10,731 VOLTS O-PEAK
TYPE OF FAULT STAGED
NEUTRAL SIZE ONE-HALF
BACKFILL MATERIAL NATIVE

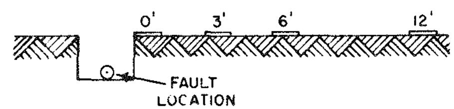


VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT	GROUND CURRENT	EARTH RESISTIVITY AT FAULT	FIXED CURRENT LIMITING IMPEDANCES (OHMS)		PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
	O-PEAK	O-PEAK	M - OHMS	HIGH SIDE	LOW SIDE			
AL-CT-I	19378	0	51.4	.41∠76°	.32∠74°	90k∠0°	.32∠74.00	.73∠75.12
AL-FS-I	18825	18	34.6	.41∠76°	.32∠74°	12.5k∠0°	.32∠74.00	.73∠75.12
CU-CT-I	14026	0	34.6	.41∠76°	.32∠74°	50k∠0°	.32∠74.00	.73∠75.12
CU-CW-I	18086	19	37.4	.41∠76°	.32∠74°	140k∠0°	.32∠74.00	.73∠75.12
CU-CW-B	19932	2035	25.9	.41∠76°	.32∠74°	3.8∠0°	.31∠69.48	.72∠73.18
CU-CW-SC	16979	1665	19.2	.41∠76°	.32∠74°	5.1∠0°	.31∠70.61	.72∠73.66
CU-CT-SC	20670	2158	25.0	.41∠76°	.32∠74°	4.0∠0°	.31∠69.70	.72∠73.28
AL-FS-SC	16241	1726	25.0	.41∠76°	.32∠74°	5.0∠0°	.31∠70.54	.72∠73.63
AL-CT-SC	17717	1603	28.8	.41∠76°	.32∠74°	5.7∠0°	.31∠70.96	.72∠73.81

FIGURE 5-30.

SUPPLY CURRENT	10,000 AMPERES RMS
SUPPLY VOLTAGE	10,731 VOLTS O-PEAK
TYPE OF FAULT	PRE-STAGED
NEUTRAL SIZE	ONE-HALF
BACKFILL MATERIAL	NATIVE



VOLTAGE GRADIENT TO REMOTE GROUND

TEST	TOTAL CURRENT O-PEAK	GROUND CURRENT O-PEAK	EARTH RESISTIVITY AT FAULT M - OHMS	FIXED CURRENT LIMITING IMPEDANCES (OHMS) HIGH SIDE	LOW SIDE	PARALLEL EARTH LOW SIDE IMPEDANCE (OHMS)	TOTAL LOW SIDE IMPEDANCE (OHMS)	TOTAL CIRCUIT IMPEDANCE (OHMS)
AL-CT-I	16241	31	29.8	.41$\angle$76°	.32$\angle$74°	8250$\angle$0°	.32$\angle$74.00	.73$\angle$75.12
AL-FS-I	15687	56	33.6	41$\angle$76°	.32$\angle$74°	480$\angle$0°	.32$\angle$73.96	.73$\angle$75.11
CU-CT-I	15872	75	28.8	41$\angle$76°	.32$\angle$74°	700$\angle$0°	.32$\angle$73.97	.73$\angle$75.11
CU-CW-I	15503	62	28.8	41$\angle$76°	.32$\angle$74°	950$\angle$0°	.32$\angle$73.98	.73$\angle$75.12
CU-CW-B	16241	1588	26.9	41$\angle$76°	.32$\angle$74°	4.8$\angle$0°	.31$\angle$70.40	.72$\angle$73.57
CU-CW-SC	16795	1788	21.1	41$\angle$76°	.32$\angle$74°	4.6$\angle$0°	.31$\angle$70.25	.72$\angle$73.51
CU-CT-SC	16241	1834	11.5	41$\angle$76°	.32$\angle$74°	4.7$\angle$0°	.31$\angle$70.32	.72$\angle$73.54
AL-FS-SC	16610	1865	24.0	41$\angle$76°	.32$\angle$74°	4.7$\angle$0°	.31$\angle$70.32	.72$\angle$73.54
AL-CT-SC	16241	1850	32.6	41$\angle$76°	.32$\angle$74°	5.9$\angle$0°	.31$\angle$71.06	.72$\angle$73.85

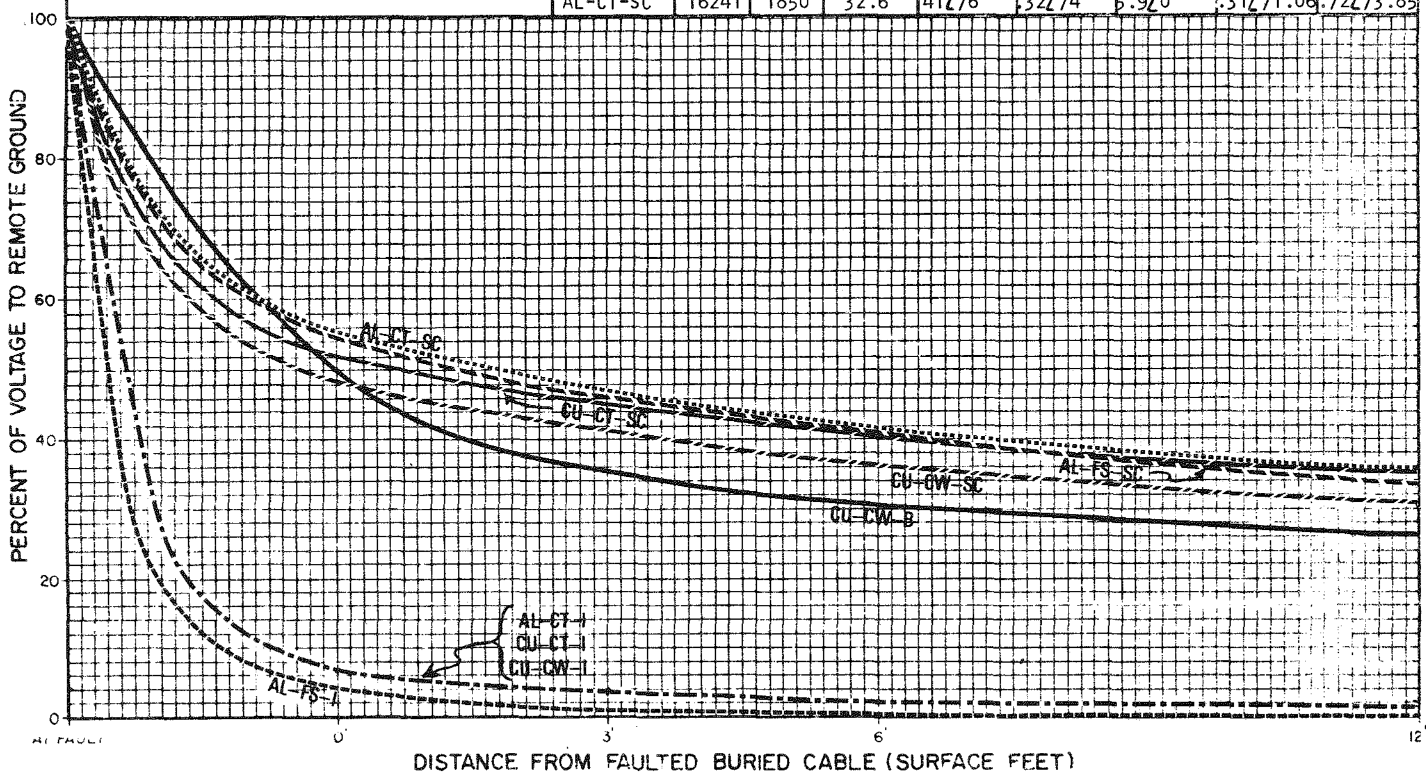


FIGURE 5-31.

Section 6

DISCUSSION OF TEST RESULTS

Analyses of the data shown in the graphs for 15kV and 35kV cables indicate that the touch and step voltages measured for the bare and semiconducting jacketed concentric neutral cables are essentially the same when tested under equivalent conditions. The most significant factor that affected the spread in the voltage gradient measurements between the bare and semiconducting jacketed 15kV cables was the variation in contact resistance at the cable earth interface. This is evident from the tabular data shown in the graphs under "Parallel Earth low Side Impedance" (to station ground). The spread in the voltage gradient measurements between the bare and semiconducting jacketed 35kV cables is significantly less than for the 15kV cables. This is attributed to the longer time (7 months versus 7 days) that the 35kV cables were buried in the earth resulting in lower and more uniform contact resistance at the cable earth interface. This is also evident from the tabular data shown in the graphs under "Parallel Earth Low Side Impedance" (to station ground). Other factors that contributed to the spread in the voltage gradient measurements between the bare and semiconducting jacketed 15 cables are (1) the tests were performed under staged and pre-staged fault conditions, and (2) the small diameter of the cable influenced the degree of contact resistance with the earth.

Comparison of the test data for bare and semiconducting jacketed cables with insulating type jacketed cables indicates that for equivalent circuit impedances and earth resistivities the touch voltages for cables with the insulating type jacket are higher. The step voltages are higher for the bare and semiconducting jacketed cables. When comparing the test data for insulating type jacketed cables in a circuit with a high ratio ($\sim .97$) of high side to total circuit impedance with bare and semiconducting jacketed cables in a circuit with a low ratio (~ 0.6) of high side to total circuit impedance, it will be noted that the touch voltages are now lower for the insulating type jacketed cables. The step voltages are also lower for the insulating type jacketed cables.

For a given cable design, the voltage gradient in the earth during short circuit conditions is a function of the voltage at the point of fault and the conductance from the surface of the cable to remote ground. This conductance consists of the conductance of the earth backfill and the conductance of the surrounding undisturbed soil. Within the voltage test limit of approximately 8kV conductor to ground, the conductance of the earth backfill and conductance of the surrounding undisturbed soil are linear with voltage. In this regard, see Figures B-2 through B-11. Figures B-2 and B-7 are composites of the data shown in Figures B-2 through B-6 and B-8 through B-11, respectfully. While the conductance of the earth backfill and the conductance of the surrounding undisturbed soil are the same, which is not expected to be experienced in practice, the voltage gradient, for a given cable design, would not depend on the conductance between the surface of the cable and remote ground. In this regard, it should be recognized that the conductance of the earth does not depend only on the nature of the soil, but also on its moisture content and density.

The ratios of high side to total circuit impedances employed in this test program, and for which the data are included in this report, are considered as the two extreme values likely to be encountered on a power utility system. Therefore, the absolute values of these touch and step voltages are not necessarily indicative of the voltages that may be experienced on a typical power distribution system under fault conditions.

During the 15kV test program, staged and pre-staged short-circuit tests were performed. Both types of cable faults were considered in this phase of the test program to simulate a dig-in to an energized cable and a cable failure due to mechanical damage during installation or dielectric imperfection, respectively. During the staged faults, faulting of the cable was initiated at random with respect to the instantaneous value of the sinusoidal voltage. For the pre-staged faults, the voltage was applied at the peak value of the sine wave. It was found during the staged faults that 35 percent of the cable faults occurred at less than half of the peak voltage, 29 percent occurred at or near peak voltage and the remainder between half and 90 percent of peak voltage. See Figure 6-1. The significance of these test results is that during a dig-in fault the touch voltage may be influenced by the $\frac{x}{r}$ ratio of the power system. The higher the $\frac{x}{r}$ ratio, the greater will be the touch voltage during the first half cycle. The staged faults were not performed on 35kV cables since it was considered that the same conditions would exist as for the 15kV cables. It was deemed more desirable to employ these cables to establish the repeatability of the test results and to perform tests on cables in a different environment.

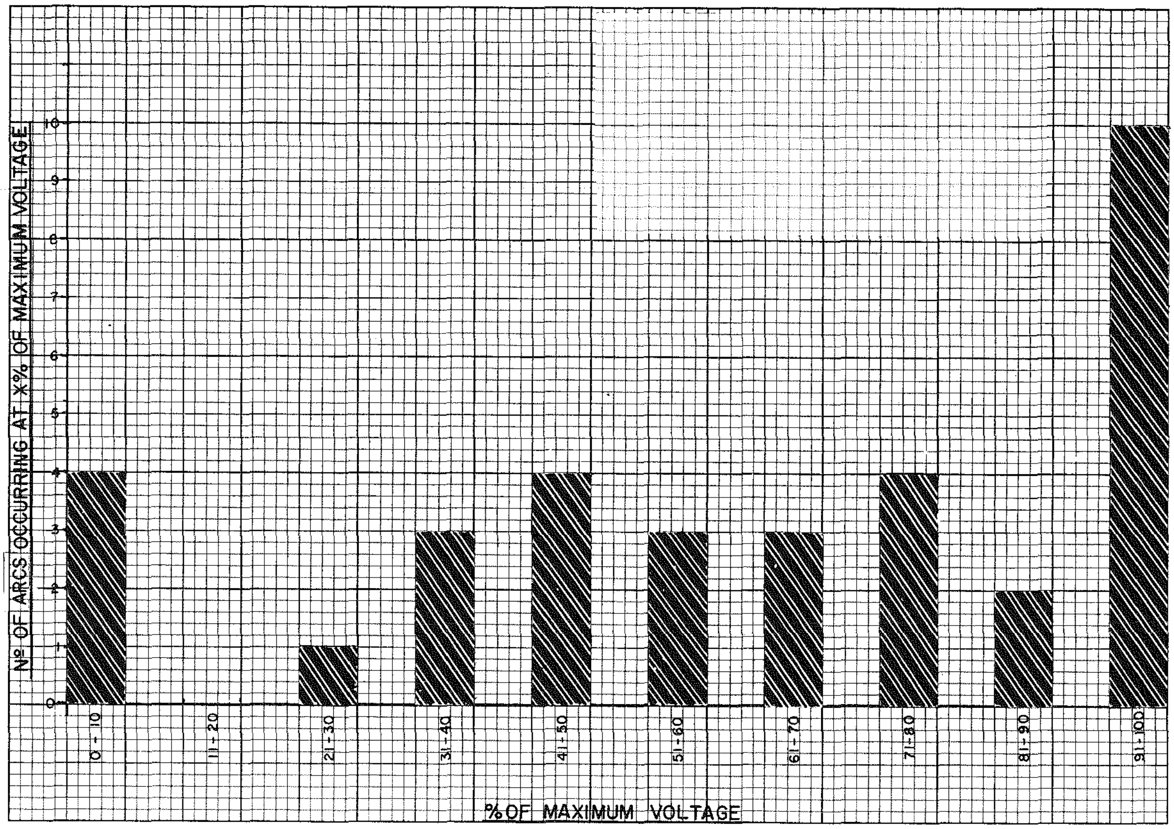


FIGURE 6-1. DIELECTRIC BREAKDOWN VALUES AS A PERCENT OF PEAK VOLTAGE DURING STAGED FAULTS

A comparison of the test results on the pre-staged short-circuit tests on 35kV bare and semiconducting jacketed cables buried in the native soil in Franksville, Wisconsin with the test results obtained on the same cables embedded in a high resistivity soil (ρ_e = 700 meter-ohms) at the point of fault, indicates that the touch voltages in the latter case were increased by a factor of 2. The step voltages were lower, also by a factor of 2. This is indicative of the influence of high resistivity soil in close proximity to the cable on touch and step voltages on bare and semiconducting jacketed cables. The effect of high resistivity soil would be much less, but in the same direction, for insulating type jacketed cables as previously discussed in this report. Cables in 15kV and 35kV ratings in various concentric neutral conductor designs, as shown in Appendix A, were subjected to the short-circuit program. No significant differences in touch and step voltages were observed for the various concentric neutral conductor designs. This can be attributed to the levels of fault current employed in this test program and the ability of the concentric neutral conductors, designed for equal and half conductance of that of the inner conductors, to accommodate these fault currents. In a significant number of the short-circuit tests there was no re-strike on the third circuit breaker reclosure and for several tests there was no re-strike on the second circuit breaker reclosure. These occurrences were caused by burn-back of the inner aluminum conductors rather than burn-back of any of the concentric neutral conductors. This is probably due to poor heat dissipating capability of the inner conductors.

The 35kV cables were short-circuit tested with and without ground rods and/or system ground. The heat effect of the ground rods and/or system ground was an increase in the conductance of the concentric neutral conductor to ground. This resulted in some reduction of the voltage at the point of fault and a more significant reduction in touch voltages. The effect of the addition of the ground rods and/or system ground was greater for cables with the insulating jacket when compared to the bare and semiconducting jacketed cables. However, in no case was the effect of such a magnitude as to reduce the touch voltage for the insulating type jacketed cables to the levels obtained for the bare and semiconducting jacketed cables with or without equivalent grounds.

The physical damage to all cables tested varied due to the degree of burn-back of the line conductor and affect on re-strike pattern and was generally restricted to the vicinity of the fault. Burn-back of the line conductor was as much as 4.8 in. (12.3cm). Burn-back of the concentric conductor was as much as 11.8 in. (30cm).

A limited comparison can be made between the test results developed in this investigation and the data obtained in 1959 by the Joint EEI-Bell Systems Subcommittee to Study Buried Distribution Systems. Refer to the reference on Page 1 of this report. A valid comparison can only be made for the bare concentric neutral conductor cables. Although there were significant differences in the test circuit and the burial depths of the cables, the test results are essentially in agreement when expressed as a percentage of voltage to remote ground.

Section 7

CONCLUSIONS

The following conclusions are based on analyses of the test data obtained in this investigation:

1. The voltage at the fault is determined by the supply voltage and circuit impedances and is a dominant factor in determination of touch and step voltages.

2. Bare and semiconducting jacketed concentric neutral cables exhibit approximately the same touch and step voltages when tested under equivalent conditions. The equivalent performance of the bare and semiconducting jacketed cables is contingent on the radial resistivity of the semiconducting jacket being comparable to that of the earth and remaining essentially stable in service.

3. When tested under equivalent conditions, the touch voltage for a concentric neutral cable with insulating type jacket will be higher than for a bare or semiconducting jacketed concentric neutral cable. For the same location with respect to the cable, the step voltages will be higher for the bare and semiconducting jacketed cables.

4. The touch voltage for an insulating type jacketed cable can be lower than for bare and semiconducting jacketed cables if the circuit conditions are such that the voltage at the fault, in the case of insulating type jacketed cable is significantly lower than in the case of bare and semiconducting jacketed cables.

5. The difference in touch voltage for insulating type as compared to bare and semiconducting jacketed cables diminishes with increase in resistivity of the backfill soil in the area of the fault. The step voltages decrease and tend to approach the same value for the three cable types with increase in backfill soil resistivity in the area of the fault.

6. For a given cable design, voltage gradient in the earth during short-circuit conditions is a function of the voltage at the point of fault and the conductance from the surface of the cable to remote ground. This conductance consists of the conductance of the earth backfill area and the conductance of the surrounding undisturbed soil. Within the voltage test limit of $\sim$8kV to conductor to ground, the conductance of the earth backfill and conductance of the surrounding undisturbed soil are linear with voltage.

7. The type and size of the neutral conductor (full or half) did not have a significant influence on the touch and step voltages in this test program. The differences in measurements were within experimental error. The size of the neutral conductor did not influence the touch and step voltages because impedance did not significantly influence the overall low side impedance of the circuit due to the short lengths of cable tested.

8. The direction of the return fault current flow in the concentric neutral conductor did not significantly affect the magnitudes of the touch and step voltages.

APPENDIX A

All cable samples employed stranded aluminum conductors with extruded crosslinked polyethylene conductor shield. Cable insulation was 175 mils or 345 mils wall thickness crosslinked polyethylene for 15kV and 35kV ratings, respectively. An extruded thermoplastic polyethylene semiconducting insulation shield covered the insulation. The concentric neutral was approximately equal to or 1/2 conductance of the line conductor and covered by approximately 50 mils wall thickness thermoplastic semiconducting or insulating polyethylene jacket. The neutral construction consisted of longitudinally folded metal tape and concentric neutral conductor extruded so as to fill all spaces between the wires and ribbons as applicable. The outer jacket was free stripping from the insulation shield. All cable dimensions are in compliance with AEIC No. 5-74.

Letter Designation	Cable Description
(A)	#2AWG - 15kV cable with 10 #14AWG annealed bare copper concentric neutral. #1/0AWG - 35kV cable with 16 #14AWG annealed bare copper concentric neutral.
(B)	#2AWG - 15kV cable with 5 #14AWG annealed bare copper concentric neutral. #1/0AWG - 35kV cable with 8 #14AWG annealed bare copper concentric neutral.
(C)	#2AWG - 15kV cable with 10 #14AWG annealed copper concentric neutral and semiconducting jacket. #1/0AWG - 35kV cable with 16 #14AWG annealed copper concentric neutral and semiconducting jacket.
(D)	#2AWG - 15kV cable with 5 #14AWG annealed copper concentric neutral and semiconducting jacket. #1/0AWG - 35kV cable with 8 #14AWG annealed copper concentric neutral and semiconducting jacket.
(E)	#2AWG - 15kV cable with 10 #14 AWG annealed copper concentric neutral and insulating type jacket. #1/0AWG - 35kV cable with 16 #14AWG annealed copper concentric neutral and insulating type jacket.

Letter Designation	Cable Description
(F)	#2AWG - 15kV cable with 5 #14AWG annealed copper concentric neutral and insulating type jacket. #1/0AWG - 35kV cable with 8 #14AWG annealed copper concentric neutral and insulating type jacket.
(G)	#2AWG - 15kV cable with 12 mils longitudinally fold copper tape concentric neutral and insulating type jacket. #1/0AWG - 35kV cable with 12 mils longitudinally fold copper tape concentric neutral and insulating type jacket.
(H)	#2AWG - 15kV cable with 6 mils longitudinally fold copper tape concentric neutral and insulating type jacket. #1/0AWG - 35kV cable with 6 mils longitudinally fold copper tape concentric neutral and insulating type jacket.
(I)	#2AWG - 15kV cable with 12 mils longitudinally fold copper tape concentric neutral and semiconducting jacket. #1/0AWG - 35kV cable with 12 mils longitudinally fold copper tape concentric neutral and semiconducting jacket.
(J)	#2AWG - 15kV cable with 6 mils longitudinally fold copper tape concentric neutral and semiconducting jacket. #1/0AWG - 35kV cable with 6 mils longitudinally fold copper tape concentric neutral and semiconducting jacket.
(K)	#2AWG - 15kV cable with 12 x 175 mils x 25 mils aluminum flat strap neutral and insulating type jacket. #1/0AWG - 35kV cable with 19 x 175 mils x 25 mils aluminum flat strap neutral and insulating type jacket.
(L)	#2AWG - 15kV cable with 8 x 170 mils x 20 mils aluminum flat strap neutral and insulating type jacket. #1/0AWG - 35kV cable with 12 x 170 mils x 20 mils aluminum flat strap neutral and insulating type jacket.
(M)	#2AWG - 15kV cable with 12 x 175 mils x 25 mils aluminum flat strap neutral and semiconducting jacket. #1/0 AWG - 35kV cable with 19 x 175 mils x 25 mils aluminum flat strap neutral and semiconducting jacket.

Letter Designation	Cable Description
(N)	#2AWG - 15kV cable with 8 x 170 mils x 20 mils aluminum flat strap neutral semiconducting jacket. #1/0AWG - 35kV cable with 12 x 170 mils x 20 mils aluminum flat strap neutral and semiconducting jacket.
(O)	#2AWG - 15kV cable with 20 mils longitudinally fold aluminum tape concentric neutral and insulating type jacket. #1/0AWG - 35kV cable with 20 mils longitudinally fold aluminum tape concentric neutral and insulating type jacket.
(P)	#2AWG - 15kV cable with 10 mils longitudinally fold aluminum tape concentric neutral and insulating type jacket. #1/0AWG - 35kV cable with 10 mils longitudinally fold aluminum tape concentric neutral and insulating type jacket.
(Q)	#2AWG - 15kV cable with 20 mils longitudinally fold aluminum tape concentric neutral and semiconducting jacket. #1/0AWG - 35kV cable with 20 mils longitudinally fold aluminum tape concentric neutral and semiconducting jacket.
(R)	#2AWG - 15kV cable with 10 mils longitudinally fold aluminum tape concentric neutral and semiconducting jacket. #1/0AWG - 35kV cable with 10 mils longitudinally fold aluminum tape concentric neutral and semiconducting jacket.

APPENDIX B

Procedure for Calculation of Approximate Touch and Step Voltages for Bare and Semiconducting Jacketed Concentric Neutral Cables

1. Measure the resistance of the concentric neutral conductor of the URD cable to a remote ground (not station ground) employing a resistance bridge or equivalent test equipment. Disconnect the concentric conductor from the system neutral at both riser poles prior to connecting the bridge and making the measurement.

2. Using Figure B-1, read the corresponding resistance of concentric conductor to station ground under fault conditions.

3. Calculate conductance of cable to ground (the reciprocal of resistance.)

4. Calculate the voltage at fault (V_{RG}) for the circuit employing conventional symmetrical component methods. See procedure on Page B-3.

5. Estimated touch and step voltages are then calculated with the use of Figure B-2. The touch voltage is calculated by reading the percent voltage to remote ground corresponding to the value of conductance calculated using the V_o line. This value is subtracted from 100% and multiplied by V_{RG} to calculate the estimated touch voltage.

   To calculate step voltages, the difference between the percent voltage to remote ground for desired spacing is multiplied by V_{RG}.

   For example: If it has been calculated (Step 3 above) that the conductance of the cable to ground is .4 MHOS and V_{RG} is 10kV, the touch voltage would be equal to (100% - 61%) x 10kV = 3900 volts. The step voltage between zero and three feet is equal to (61% - 52%) x 10kV = 900 volts.

To calculate the range of voltages which could occur, use of Figures B-3 through B-6 is recommended since they depict the actual data and its range.

NOTE: Figures B-7 through B-11 (Insulating Type Jackets) are included for illustrative purposes. Insulating type jacketed cables do not readily lend themselves to calculation of touch and step voltages under fault conditions. The conductance of the concentric neutral conductor to ground is extremely high at low voltage and is a function of the arc impedance under fault conditions.

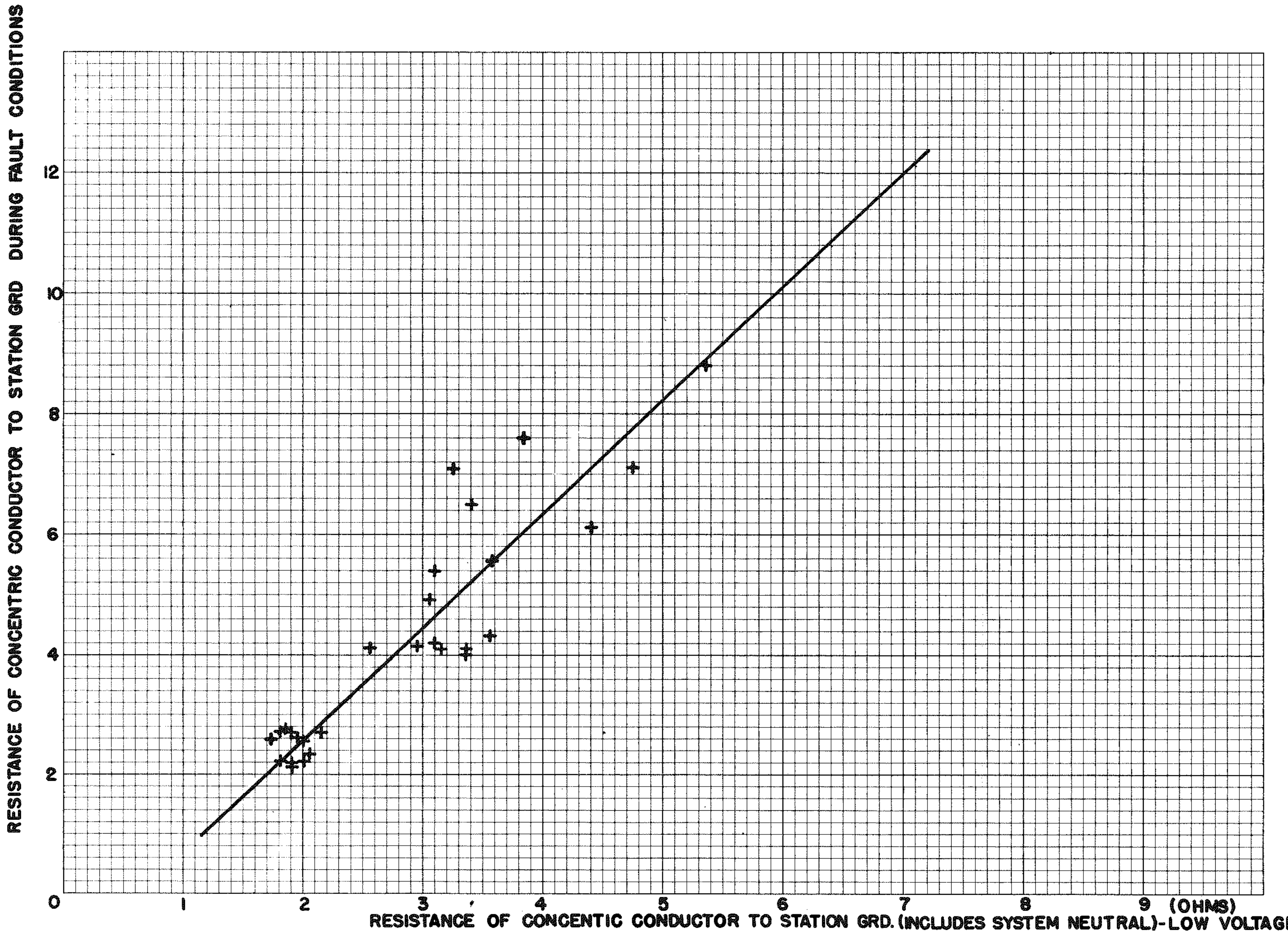

RESISTANCE OF CONCENTRIC CONDUCTOR TO STATION GRD DURING FAULT CONDITIONS
0
2
4
6
8
10
12
1
2
3
4
5
6
7
8
9 (OHMS)
RESISTANCE OF CONCENTIC CONDUCTOR TO STATION GRD. (INCLUDES SYSTEM NEUTRAL)-LOW VOLTAGE

FIGURE B-1.

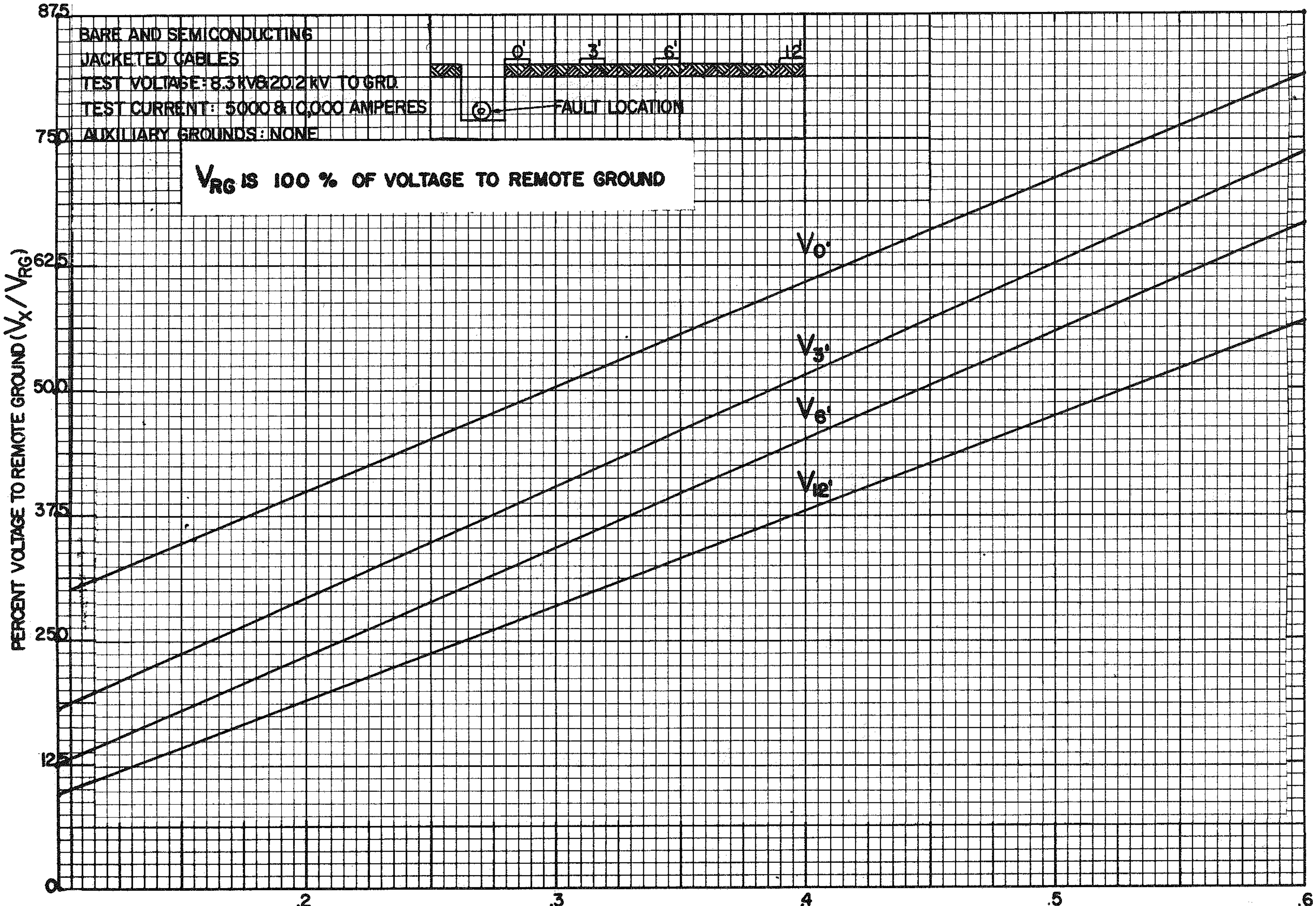

BARE AND SEMICONDUCTING
JACKETED CABLES
TEST VOLTAGE: 8.3 KV & 20.2 KV TO GRD.
TEST CURRENT: 5000 & 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_RG IS 100 % OF VOLTAGE TO REMOTE GROUND
V0'
V3'
V6'
V12'
PERCENT VOLTAGE TO REMOTE GROUND (Vx/VRG)
87.5
75.0
62.5
50.0
37.5
25.0
12.5
0
.2
.3
.4
.5
.6
CONDUCTANCE OF CABLE TO GROUND (IFR3/VRG) MHOS

FIGURE B-2.

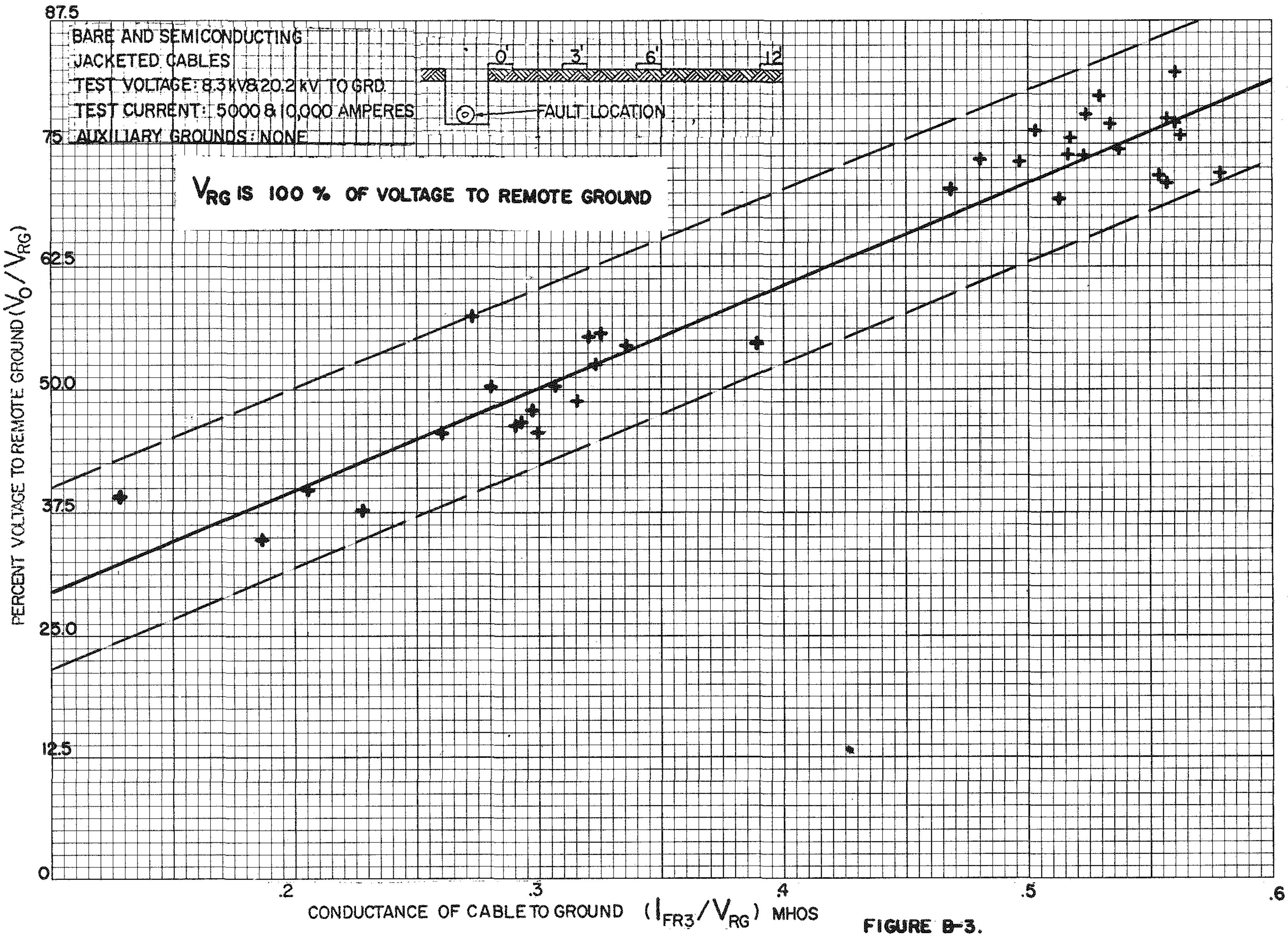

BARE AND SEMICONDUCTING
JACKETED CABLES
TEST VOLTAGE: 8.3 kV & 20.2 kV TO GRD.
TEST CURRENT: 5000 & 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_{RG} IS 100 % OF VOLTAGE TO REMOTE GROUND
87.5
75
62.5
50.0
37.5
25.0
12.5
0
PERCENT VOLTAGE TO REMOTE GROUND (V_O/V_{RG})
.2
.3
.4
.5
.6
CONDUCTANCE OF CABLE TO GROUND (I_{FR3}/V_{RG}) MHOS

FIGURE B-3.

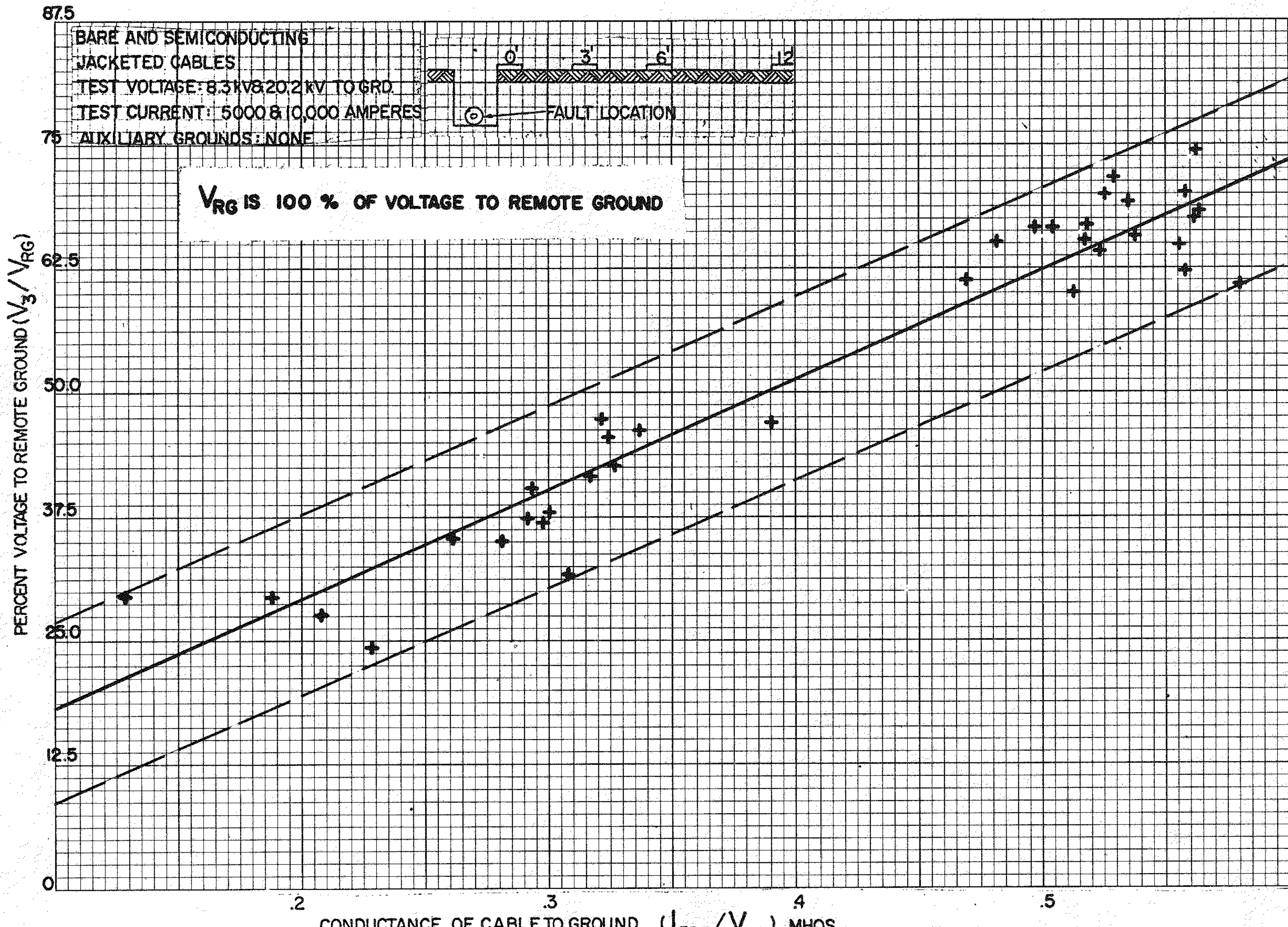

BARE AND SEMICONDUCTING
JACKETED CABLES
TEST VOLTAGE: 8.3 kV & 20.2 kV TO GRD.
TEST CURRENT: 5000 & 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_{RG} IS 100 % OF VOLTAGE TO REMOTE GROUND
PERCENT VOLTAGE TO REMOTE GROUND (V_3/V_{RG})
87.5
75
62.5
50.0
37.5
25.0
12.5
0
.2
.3
.4
.5
.6
CONDUCTANCE OF CABLE TO GROUND (I_{FR3}/V_{RG}) MHOS

FIGURE B-4.

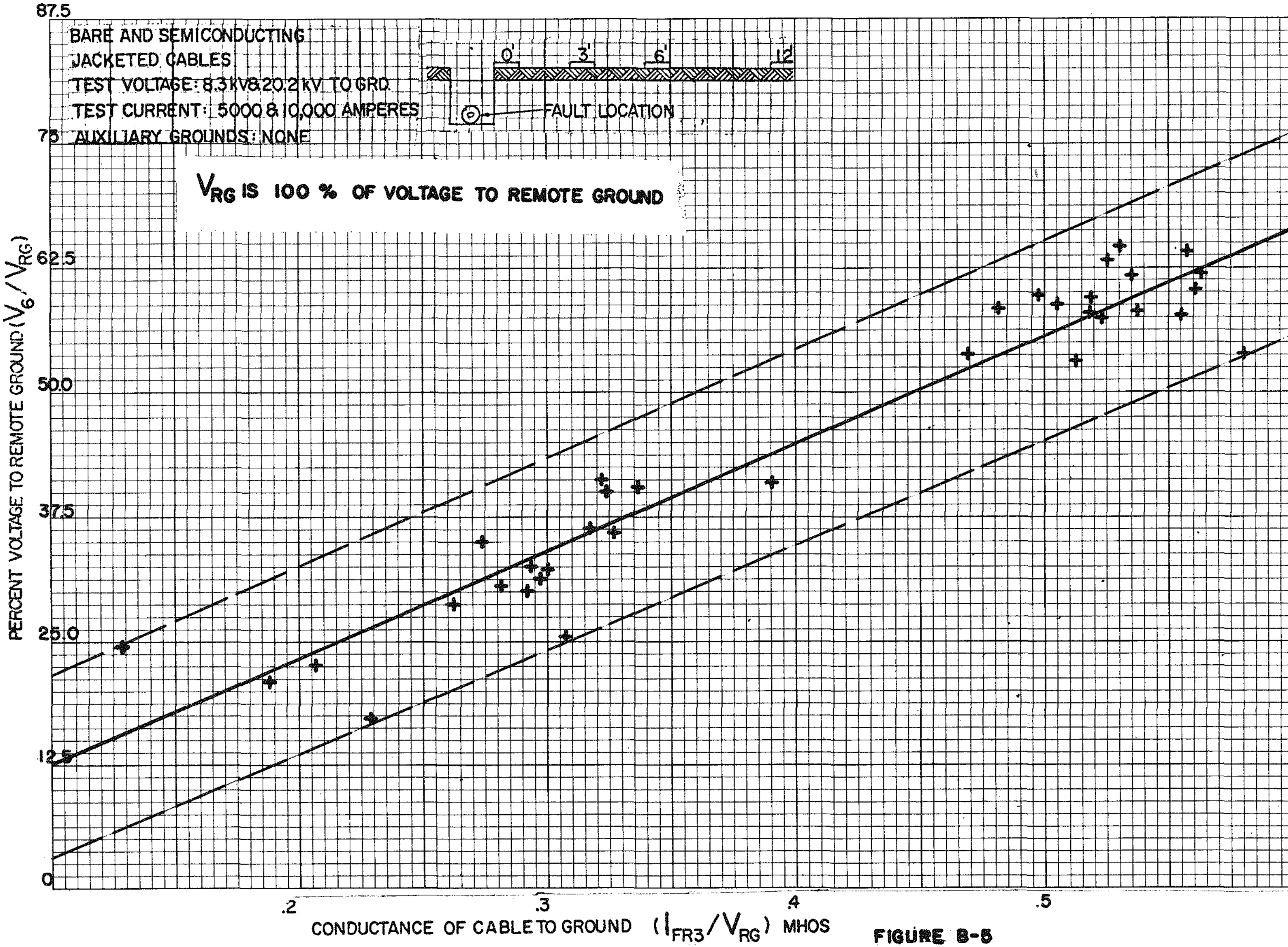

BARE AND SEMICONDUCTING
JACKETED CABLES
TEST VOLTAGE: 8.3 KV & 20.2 KV TO GRD.
TEST CURRENT: 5000 & 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_{RG} IS 100 % OF VOLTAGE TO REMOTE GROUND
87.5
75
62.5
50.0
37.5
25.0
12.5
0
PERCENT VOLTAGE TO REMOTE GROUND (V_6/V_{RG})
.2
.3
.4
.5
.6
CONDUCTANCE OF CABLE TO GROUND (I_{FR3}/V_{RG}) MHOS

FIGURE B-5

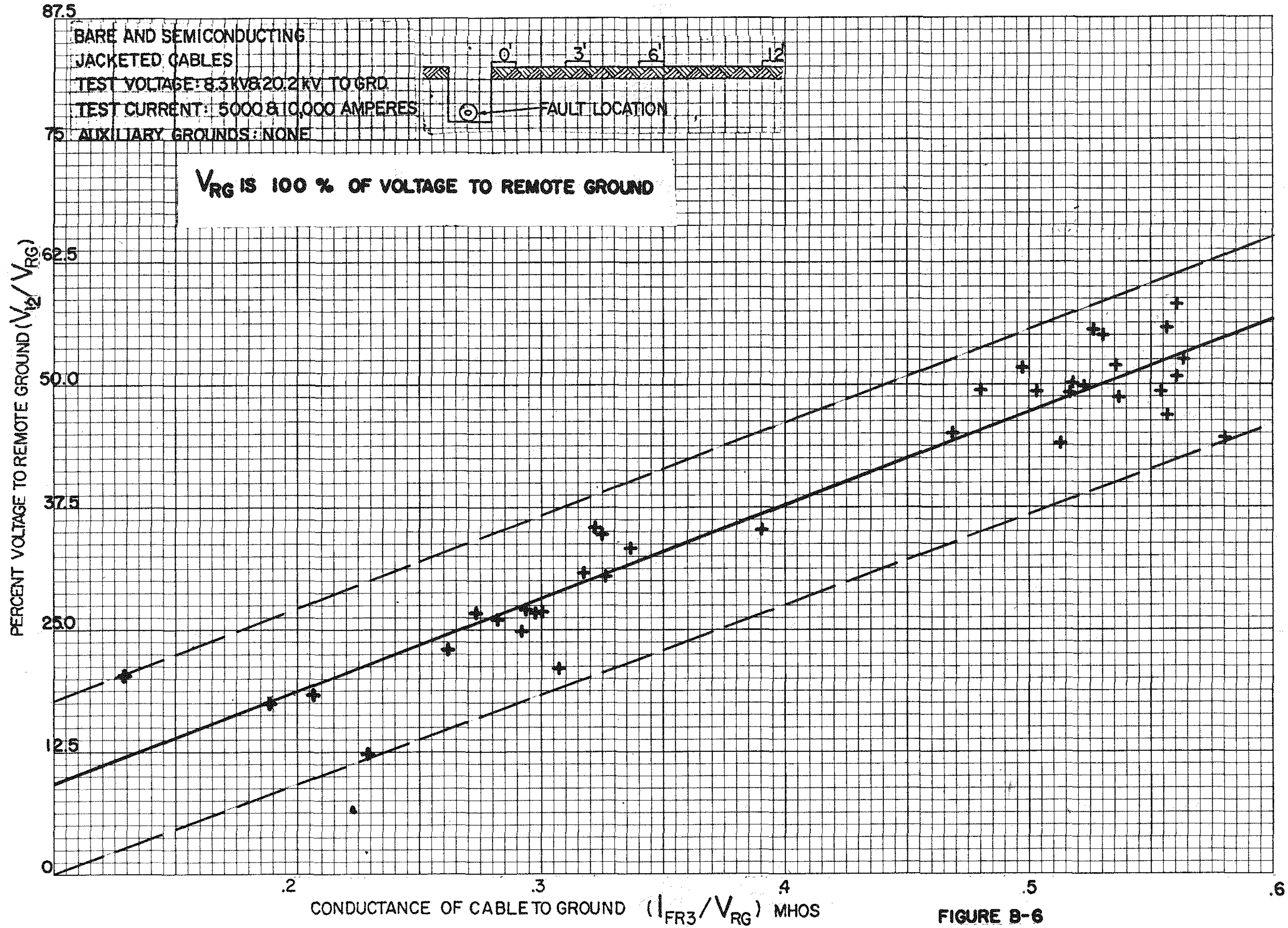
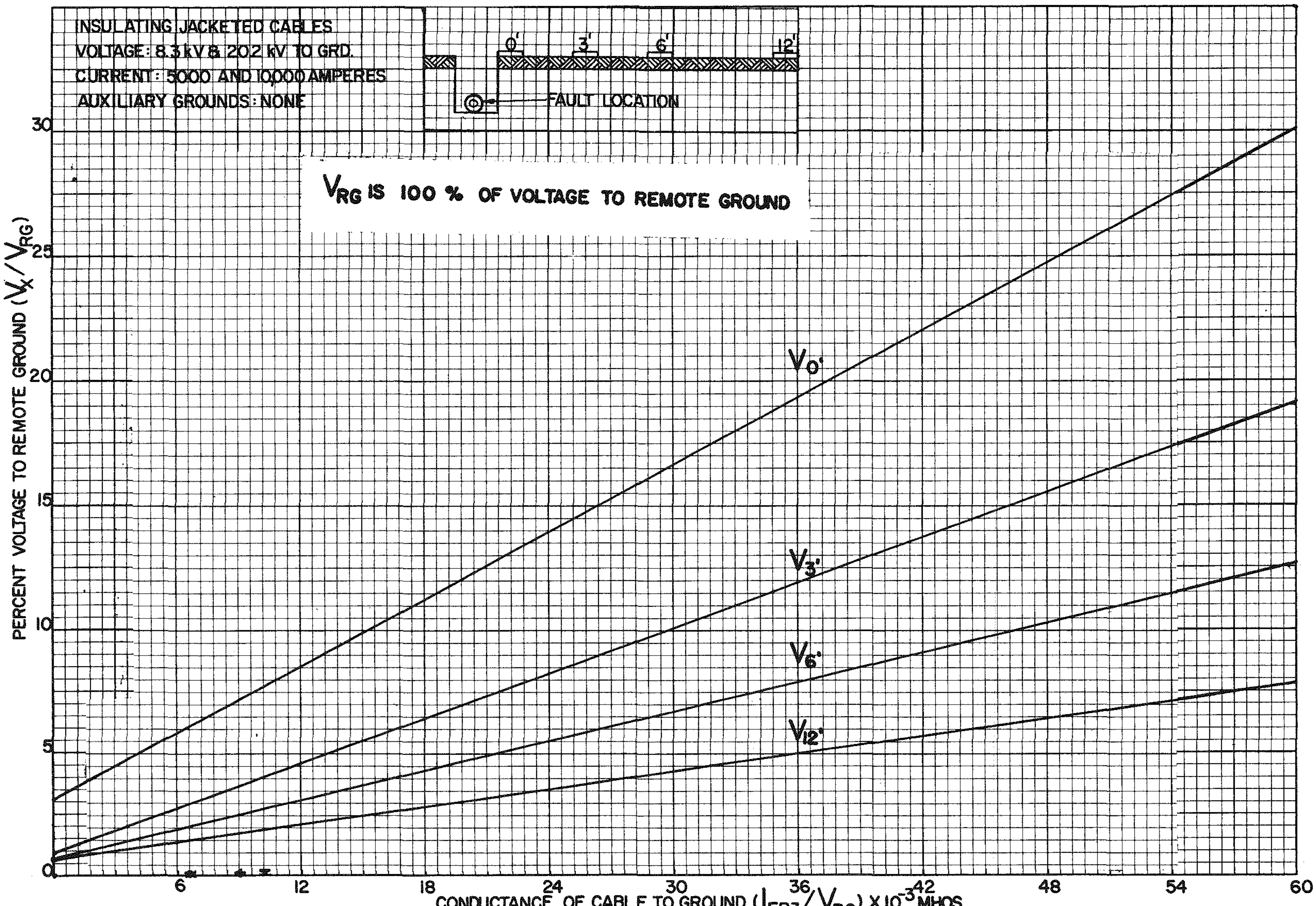

BARE AND SEMICONDUCTING
JACKETED CABLES
TEST VOLTAGE: 8.3 KV & 20.2 KV TO GRD.
TEST CURRENT: 5000 & 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_{RG} IS 100 % OF VOLTAGE TO REMOTE GROUND
PERCENT VOLTAGE TO REMOTE GROUND (V_{12}/V_{RG})
87.5
75
62.5
50.0
37.5
25.0
12.5
0
.2
.3
.4
.5
.6
CONDUCTANCE OF CABLE TO GROUND (I_{FR3}/V_{RG}) MHOS

FIGURE B-6



INSULATING JACKETED CABLES
VOLTAGE: 8.3 kV & 20.2 kV TO GRD.
CURRENT: 5000 AND 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_{RG} IS 100 % OF VOLTAGE TO REMOTE GROUND
PERCENT VOLTAGE TO REMOTE GROUND (V_X/V_{RG})
$V_{0'}$
$V_{3'}$
$V_{6'}$
$V_{12'}$
0
5
10
15
20
25
30
6
12
18
24
30
36
42
48
54
60
CONDUCTANCE OF CABLE TO GROUND (I_{FR3}/V_{RG}) X 10^{-3} MHOS

FIGURE B-7.

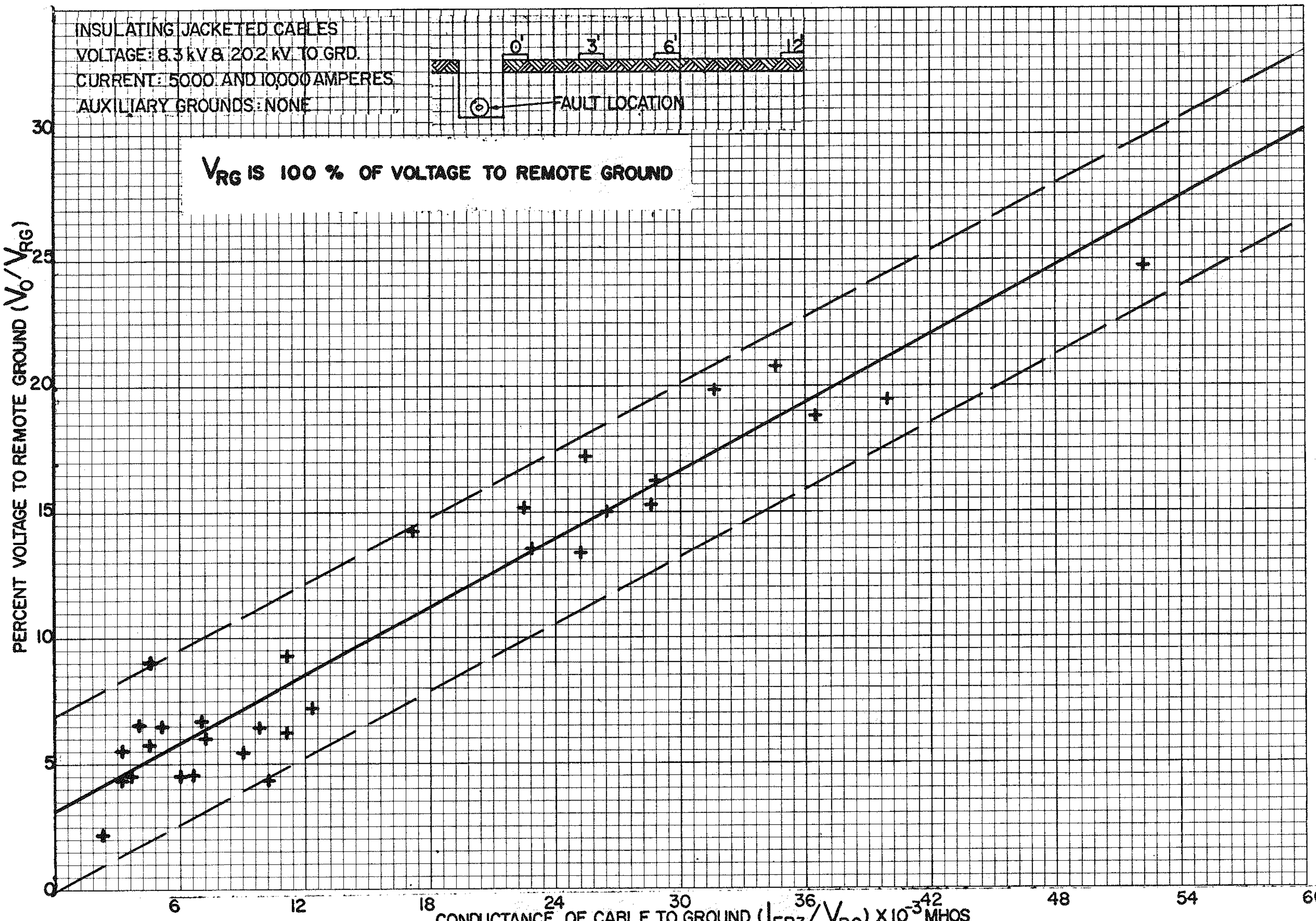
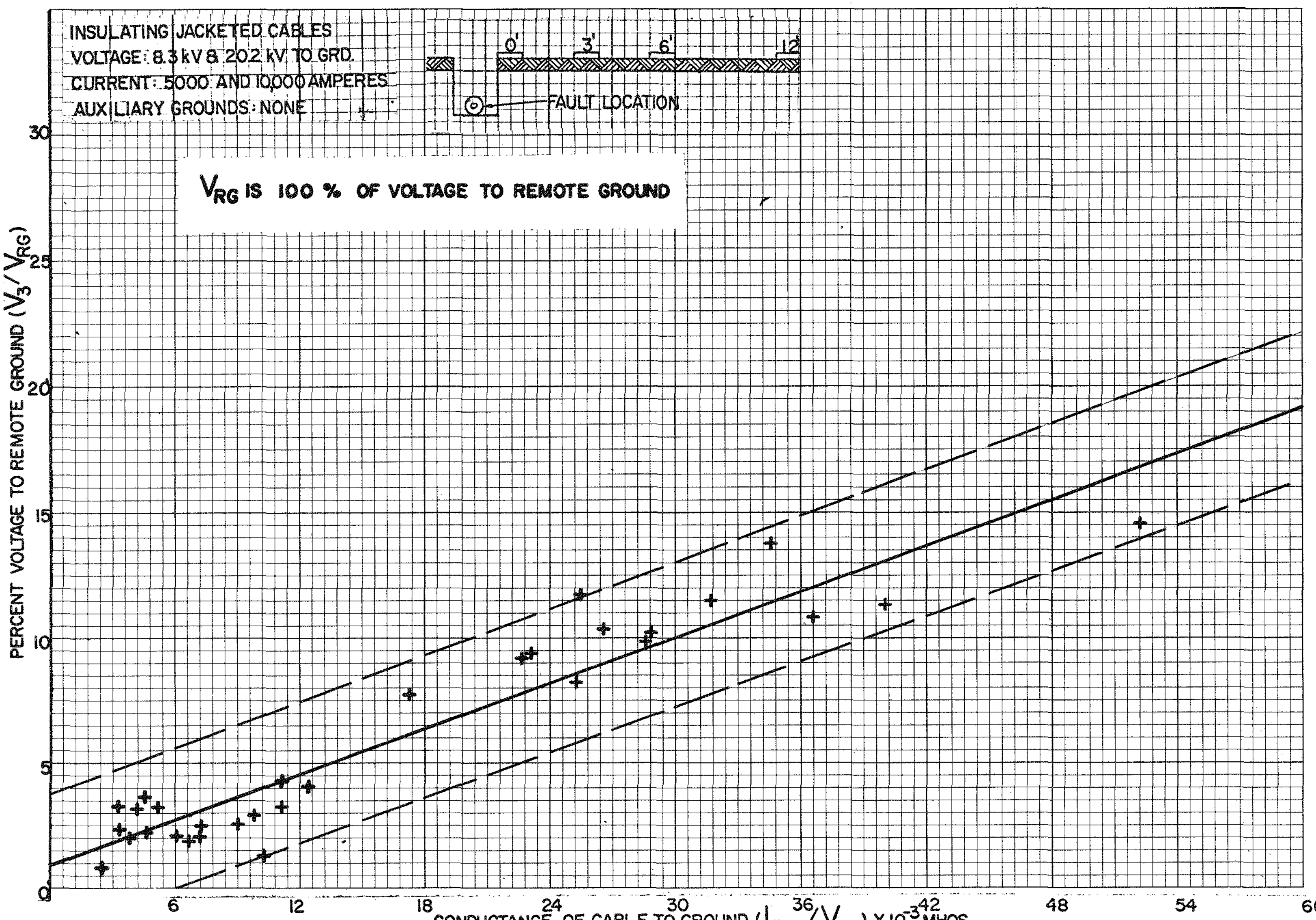

INSULATING JACKETED CABLES
VOLTAGE: 8.3 kV & 20.2 kV TO GRD.
CURRENT: 5000 AND 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_{RG} IS 100 % OF VOLTAGE TO REMOTE GROUND
PERCENT VOLTAGE TO REMOTE GROUND (V_O/V_{RG})
0
5
10
15
20
25
30
6
12
18
24
30
36
42
48
54
60
CONDUCTANCE OF CABLE TO GROUND (I_{FR3}/V_{RG}) X 10^{-3} MHOS

FIGURE B-8.



INSULATING JACKETED CABLES
VOLTAGE: 8.3 kV & 20.2 kV TO GRD.
CURRENT: 5000 AND 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_{RG} IS 100 % OF VOLTAGE TO REMOTE GROUND
PERCENT VOLTAGE TO REMOTE GROUND (V_3/V_{RG})
0
5
10
15
20
25
30
6
12
18
24
30
36
42
48
54
60
CONDUCTANCE OF CABLE TO GROUND (I_{FR3}/V_{RG}) X 10^{-3} MHOS

FIGURE B-9.

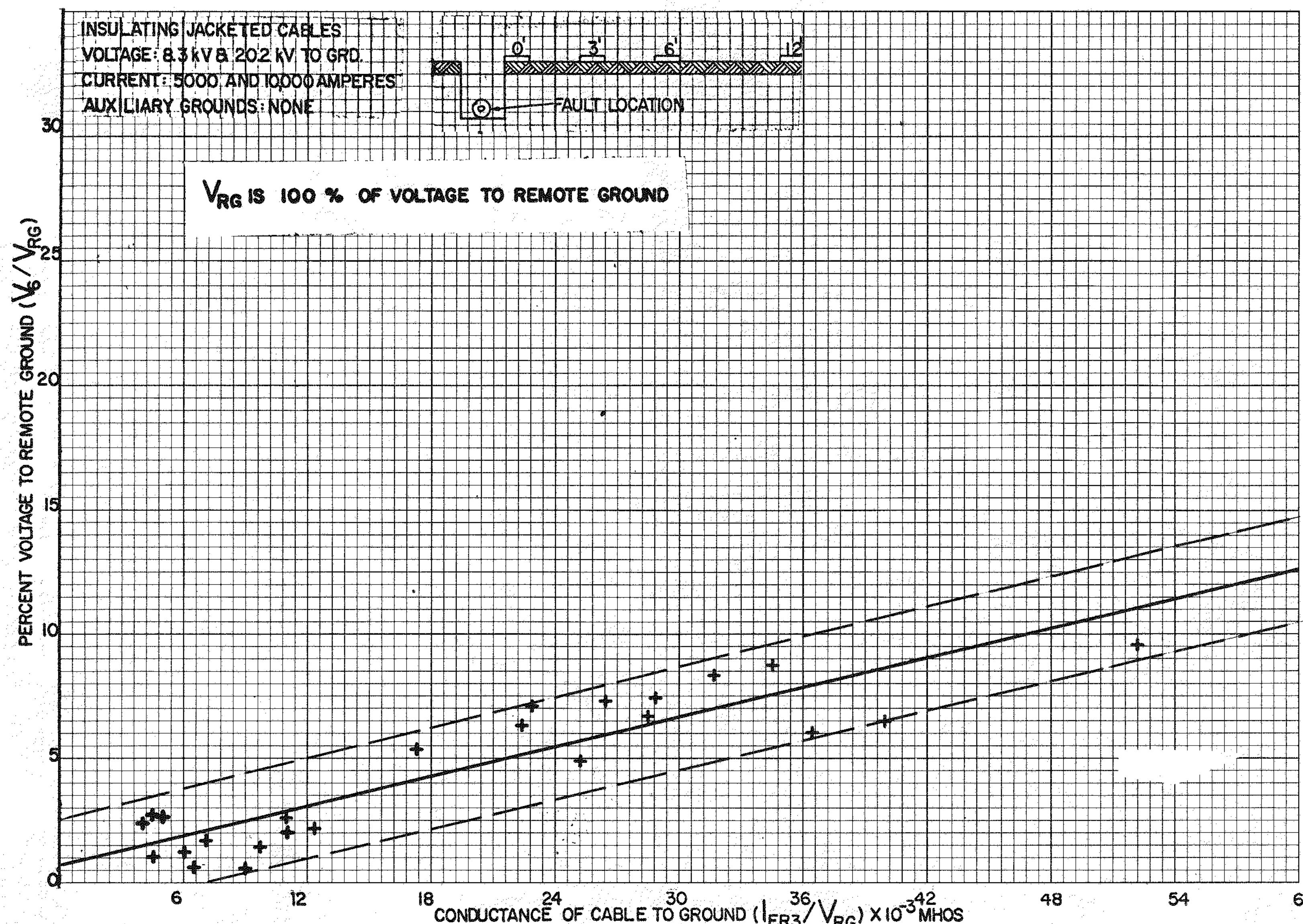

INSULATING JACKETED CABLES
VOLTAGE: 8.3 kV & 20.2 kV TO GRD.
CURRENT: 5000 AND 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
VRG IS 100 % OF VOLTAGE TO REMOTE GROUND
PERCENT VOLTAGE TO REMOTE GROUND (V6/VRG)
0
5
10
15
20
25
30
6
12
18
24
30
36
42
48
54
60
CONDUCTANCE OF CABLE TO GROUND (IFR3/VRG) X 10-3 MHOS

FIGURE B-10.

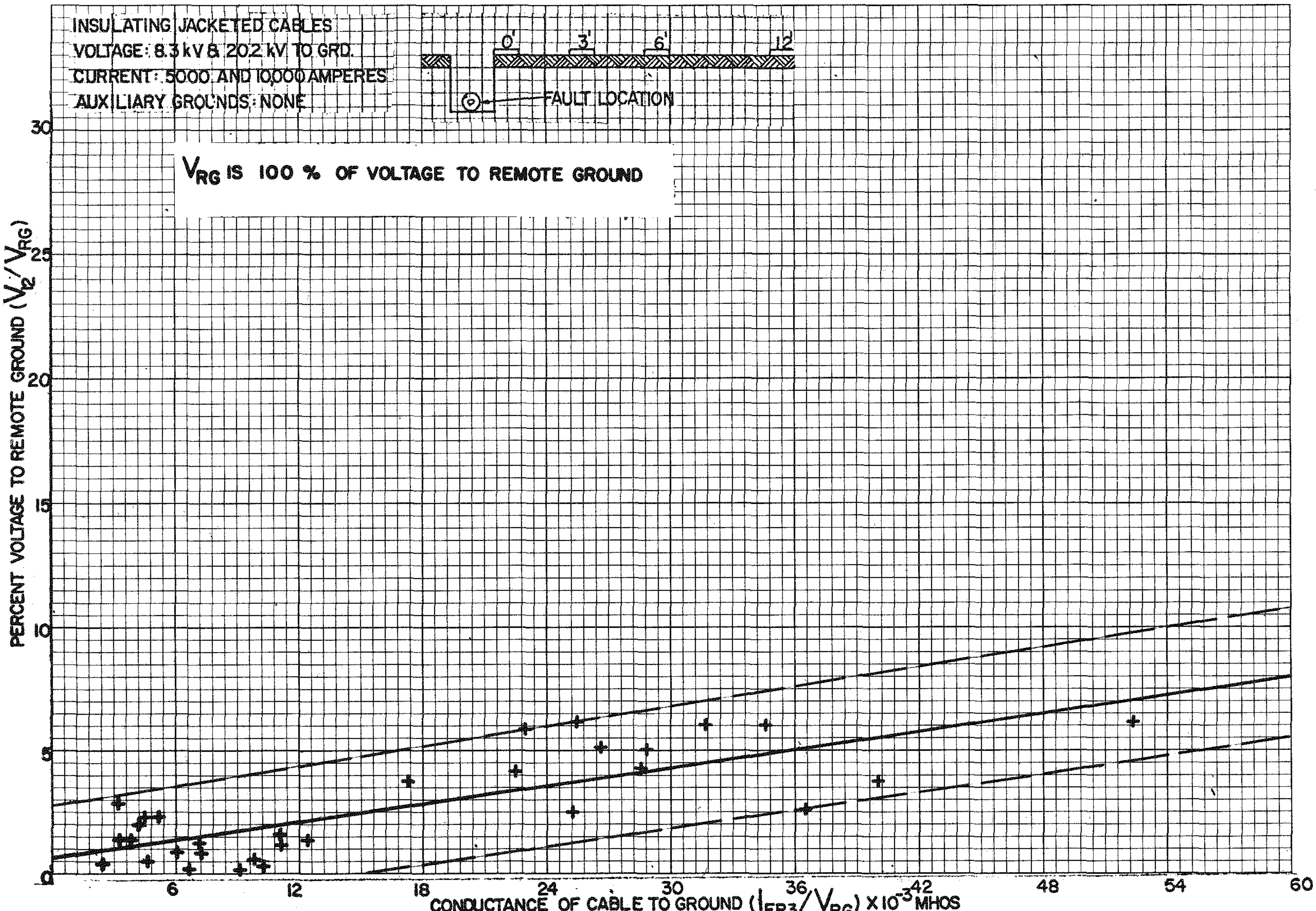

INSULATING JACKETED CABLES
VOLTAGE: 8.3 kV & 20.2 kV TO GRD.
CURRENT: 5000 AND 10,000 AMPERES
AUXILIARY GROUNDS: NONE
0'
3'
6'
12'
FAULT LOCATION
V_{RG} IS 100 % OF VOLTAGE TO REMOTE GROUND
PERCENT VOLTAGE TO REMOTE GROUND (V_{12}/V_{RG})
30
25
20
15
10
5
0
6
12
18
24
30
36
42
48
54
60
CONDUCTANCE OF CABLE TO GROUND (I_{FR3}/V_{RG}) X 10^{-3} MHOS

FIGURE B-11.

Procedure for Calculation of the Voltage at Fault (V_{RG}) for Buried Cables

The voltage "V_{RG}" is defined in this report as the voltage to remote ground. This voltage is also the driving voltage at the point of fault and is equal to the supply voltage less the voltage drop between the supply and the point of fault. In numerical form $V_{RG} = (Z_{LS}/Z_{LS}+Z_{HS}) \times V_S$,

where: Z_{LS} = circuit low side impedance
Z_{HS} = circuit high side impedance
V_S = supply voltage

The calculation of "V_{RG}" may employ a complete analytical approach with conventional symmetrical component impedances or may employ field measurements to best determine the low side impedance with respect to the earth circuit. If symmetrical component impedances are selected for the calculation, then the following analytical approach may be used:

$$Z_{HS} = Z_1$$

$$Z_{LS} = \frac{Z_0 - Z_1}{3}$$

substituting for Z_{HS} and Z_{LS}

$$V_{RG} = \frac{(Z_0 - Z_1/3)}{(Z_0 - Z_1/3) + Z_1} \times V_S$$

$$V_{RG} = \frac{Z_0 - Z_1}{2Z_1 + Z_0} \times V_S$$

where: Z_1 = positive sequence impedance
Z_0 = zero sequence impedance

If the earth's portion of the zero sequence impedance is significant with respect to the impedance of the metallic return circuit, then it may be desirable to utilize field measurements to determine the impedance of the earth return circuit and the voltage at the fault. Such measurements would include fall of potential tests to determine the impedance to ground of the substation (Z_{SG}*) and of the buried cable (Z_C*). Additional tests should be performed to determine the impedance of Z_C, Z_{SG}, the system neutral and the earth's portion of the electrical circuit in series. Since the impedance of the system neutral can be readily calculated, the impedance of the earth's portion of the electrical circuit can be determined. The true low side impedance (A_{LS}) would then be determined by calculating the parallel equivalent impedance of the earth circuit and the system neutral. "V_{RG}" would then be calculated as follows:

$$V_{RG} = \frac{Z_{LS}}{Z_{LS} + Z_1} \times V_S$$

*When measuring Z_{SG} and Z_C by the faull of potential method, reader is cautioned to select an adequately distant remote ground and to use a spectrum analyzer to measure the faull of potential at the power frequencies that are selected for the test.