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INVESTIGATION OF MECHANISM OF BREAKDOWN IN XLPE CABLES

Final Report

A. L. McKean

MASTER

July 1976

Work performed under Contract No. E(49-18)-1422

Phelps Dodge Cable and Wire Company
Yonkers, New York

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BREAKDOWN IN XLPE CABLES

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ERDA Contract E(49-18)-1422

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ABSTRACT

This research program explores the basic hypothesis that microporosity plays a significant role in the mechanism of breakdown of XLPE cable.

In Part I, the potential improvement achieved by impregnating the microporous regions of the cable core with a neutral liquid is evaluated, with relation to AC voltage life and impulse strength. The effect at higher frequency is also demonstrated.

In Part II, a similar test program is pursued on model cables, designed to explore the effects of gas pressure and gas type on breakdown and life, since it is reasonable to expect that only the microporous regions of the insulation should be sensitive to the gas-pressure environment.

Comparison of gas-pressurized model breakdown stress (and related microvoid size) with basic Paschen curves demonstrates reasonably good agreement, indicating that partial discharge is the basic mechanism of fatigue and breakdown.

The form of the voltage life curve above and below the discharge inception level is proposed, and evidence is presented indicating breakdown originates in the bulk insulation as well as at the shield interface.

It is also shown that model cable discharge energies are below 0.1 pC, even at very high stress, and cannot be measured with modern detectors. Results with liquid or gas impregnation suggest a possible approach to dielectric improvement.

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INVESTIGATION OF MECHANISM OF BREAKDOWN IN XLPE CABLES

PART I

1. INTRODUCTION

The following report summarizes the work, test results and conclusions derived from a project concerning the "Investigation of Mechanism of Breakdown in Crosslinked Polyethylene" which has been carried on from 1972 through 1975, supported and funded by EPRI (Contract RP-7809-1) and ERDA (Contract E(49-18)-1422), together sharing 50% of the total project's costs.

The project was originally proposed by Phelps Dodge Cable and Wire Company as an important and necessary area of research which was justified on the basis of the rapidly expanding usage, nationwide, of crosslinked polyethylene cables by utilities for both distribution and transmission applications.

The study was proposed on the basis of our hypothesis that cross-linked polyethylene is, in a molecular sense, a microporous type of insulation, where microporosity is in the order of several percent. On the basis that microporosity is a main factor affecting the life and breakdown voltage of good quality cable, Phelps Dodge proposed a specific program of investigation to determine the influence of microporosity on the mechanism of breakdown and on cable life.

The work of the proposal is presented in two parts. Part I describes the results of the original test program employing full-scale 15 kV cable, where evaluations were based on comparative performance of cable impregnated with various liquids. Part II describes a subsequent additional study on model cable samples, where evaluations were based on relative performance of cables impregnated with several different gases.

The extended test program described in Part II, was approved and supported by the Steering Committee, because they felt it was desirable to confirm results and conclusions determined in Part I of the project on the basis of a different approach which would be both practical and meaningful in relation to the investigation of breakdown mechanisms.

2. APPROACH TO INVESTIGATION

The main approach to this investigation was based on the premise that microporosity is normally present in crosslinked polyethylene insulation. Since this characteristic may be different in molded and extruded specimens, our primary test program was designed around extruded insulation. Furthermore, initial studies in Phase I were planned around full-scale cable rather than specimens in order to minimize unknown factors in translating and interpreting results.

The test program was designed to determine the influence of microporosity in relation to voltage aging (cable life) and breakdown strength of good quality cable. Many other related factors must necessarily come under consideration, since it is clear that breakdown is a complex phenomenon which may ultimately involve several different processes and reactions.

Many other workers have reported relevant investigations which have treated various aspects of breakdown such as corona deterioration, voltage-life trends, treeing phenomena and high-frequency aging. The literature provides a very broad reference base for continued research on the problem of electrical breakdown of solid dielectric cables.

The test plan in Phase I required that cable insulation be modified by impregnation with an appropriate neutral liquid, thereby minimizing or eliminating deteriorative effects of microvoids under electrical stress. Comparison of standard and impregnated cable performance, through a range of test conditions, was expected to reveal significant differences, if microporosity proved to be a significant factor in cable breakdown.

In addition to electrical tests, chemical, physical, and thermal analyses of breakdown specimens were performed, seeking possible evidence of a fundamental breakdown process.

Microscopic studies of microvoids in XLPE insulation were also conducted, as an important adjunct to the main test program.

3. PRIMARY TEST PROGRAM

The main thrust of the test program was designed to compare the performance of standard cable, and cable impregnated with a neutral liquid. Important considerations relevant to selection of an appropriate impregnating liquid are discussed in the following section of this report.

It was reasonable to expect that comparison of cable response (standard vs. impregnated samples), on the basis of several re-

liable and established high-voltage test procedures, should provide significant evidence regarding the influence of microporosity.

Electrical testing on standard and impregnated cables included:

1. Impulse Breakdown
2. AC Voltage Breakdown
3. Volt-Time Life Tests at 60 Hz
4. Volt-Time Life Tests at 1000 Hz

Corona discharge and power factor were monitored on the series of voltage-life tests, in order to detect any characteristic change, signaling the onset of deterioration or breakdown.

Power factor behavior of cable samples under continuous voltage overstress, and measurement of power factor vs. voltage characteristics (ionization) comprised an important additional area of study performed during the program.

4. IMPREGNATION CONSIDERATIONS

The decision to modify the XLPE insulation by impregnation with a liquid, rather than gas, was based upon several important considerations.

While it was known that gas impregnation of polyethylene could produce moderate improvement in dielectric strength (1), it was anticipated that more dramatic improvement could be obtained with liquid impregnation, hopefully achieving virtually complete elimination of all free void space. This was based upon the assumption that a liquid-filled microspace might exhibit much higher breakdown level than gas-filled cavities.

In addition, we considered it significant that recent research by another Laboratory (2) had demonstrated that the presence of a liquid coating (such as silicone oil) on polyethylene achieves a marked improvement in resistance to corona and breakdown strength.

Consideration of preliminary cable conditioning prior to impregnation was influenced by the knowledge that not only moisture, but also volatile organic residues, principally acetophenone, cumyl alcohol and α -methyl styrene, are present in polyethylene cable as a result of chemical crosslinking through the action of dicumyl peroxide at high temperature.

The pattern of by-product concentration throughout the insulation wall depends largely upon cable age and thermal history. After appropriate aging and/or heat treatment, residues tend to become negligible due to loss by diffusion. Hence a preliminary treat-

ment under moderate vacuum and temperature of 100C for a continuous period of 2 weeks, was established as required pre-conditioning procedure prior to impregnation.

In the process of impregnation of XLPE insulation, transport of the liquid would be expected to occur by diffusion of either vapor or liquid phase. The rate of diffusion, or the amount of constituent permeating per unit time, is known to be a function of the diffusion constant and the concentration gradient (3).

It is well established that the liquid eventually penetrates virtually all microspace regions by diffusion (4). This would include amorphous regions, crystalline-amorphous interface areas, microvoids, and microdefects. However, since diffusion progresses under the influence of vapor pressure gradients, there remains some question as to whether all voids become "completely filled" with a liquid even when the liquid is under positive external pressure.

5. IMPREGNATING LIQUID STUDIES

For the purposes of our comparative breakdown studies, an appropriate neutral liquid was required to "impregnate" the XLPE cable insulation. Desirable properties of such liquids would include chemical inertness, zero dipole moment, high resistivity, high boiling point, and low viscosity. A number of possible candidates were considered in a preliminary review such as liquid paraffin, stearic acid, octyl alcohol, ethylene glycols, and other less promising materials like plasticizers and polyethers.

After due consideration of comparative properties, two promising low-viscosity liquids were more extensively examined, silicone oil(DC 200 2cs-25C) with low dielectric constant(2.2) and diethylene glycol(DEG 42cs 25C), having high dielectric constant(40.0), (See Table I). Preliminary breakdown studies on impregnated XLPE flat sheets indicated greater improvement(2 to 1) obtained with diethylene glycol compared to silicone oil, despite the greater weight gain(10 to 1) exhibited by the silicone-impregnated samples. This provided the basis for selecting diethylene glycol for the first series of voltage tests on impregnated cable.

Similar breakdown studies were subsequently performed on uniform six mil extruded polyethylene film to minimize effects of thickness variations. This study focused on two ethylene glycols, and a penetrating(swelling) agent, paraxylene, was introduced for the purpose of increasing absorption, hopefully serving to further improve breakdown. Two liquid systems were examined in this second test series:

- (a) diethylene glycol/p-xylene/ethanol, (b) triethylene-glycol/p-xylene/ethanol, (c) non-impregnated control.

TABLE IDIELECTRIC STRENGTH OF IMPREGNATED XLPE SHEETS

<u>Sample</u>	<u>Impreg. Temp. °C</u>	<u>Breakdown¹ Volts/mil</u>	<u>Improvement %</u>	<u>Weight Gain-%</u>
Control Sample	-	980	-	-
Silicone Oil(DC 200)	100	1112	12.0	11.7
Diethylene Glycol	100	1400	41.0	0.25
DEG ² System	30	1963	100.0	6.6

Notes: 1. Sample Thickness - .020"
 2. Diethylene glycol/paraxylene/ethanol:
 90/10/15

TABLE IIDIELECTRIC STRENGTH OF IMPREGNATED POLYETHYLENE FILM

<u>Sample</u>	<u>Impreg. Temp. °C.</u>	<u>Breakdown³ Volts/mil</u>	<u>Breakdown Improvement</u>
Control (6-mil film)	30	3440	0%
DEG ¹ System	30	3830	11.3%
TEG ² System	30	4550	32.3%

1. Diethylene glycol/paraxylene/ethanol: 90/10/15
 2. Triethylene glycol/paraxylene/ethanol: 90/10/15
 3. Average of 50 AC breakdown tests

The resulting breakdown voltages (average of 12 specimens) (Table II) were:

(a) 3830, (b) 4550, (c) 3440 volts/mil respectively.
Hence, system (b) above was chosen as the cable impregnant for this cable test series.

In future references in the report, L₁ identifies diethylene glycol system (a) and L₂ identifies the triethylene glycol system (b), for simplicity.

6. MICROPOROSITY

The presence of small cavities in polyethylenes has long been recognized by research workers in this field (5). In the case of XLPE cables under study, their size ranges from the molecular level (angstroms) to micron-size (6), the latter type having been observed with the aid of high optical microscopes.

Recent microscopic studies on XLPE specimens in our Laboratories have confirmed the presence of cavities, referred to hereafter as microvoids, predominantly in the 1-10 micron (um) range. Microvoids constitute sensitive regions of the polyethylene bulk, which can be expected to be more vulnerable to the hazard of microdischarges than the crystalline or amorphous regions which surround them. Such microspaces apparently may contain vapor and/or liquid by-products such as acetophenone, and may change condition and appearance after thermal treatment.

Microvoids in XLPE appear to exist in higher concentrations (up to 10^5 per mm) in the central zone of the insulation wall, diminishing rapidly near the surface regions.

We have confirmed during our microscopic investigations that thermal conditioning (heating) of the insulation tends to drive off liquid in microvoids through simple diffusion. We have also observed that thermally conditioned specimens can be successfully impregnated, and microvoids filled, at least partially, with a neutral liquid. These studies serve to corroborate our earlier work on impregnation, involving slab specimens and film samples.

7. CABLE SAMPLE PREPARATIONS

7.1 Impregnation Procedure

Impregnation of a group of (six) cable samples, each 50 feet in length, was carried out in a specially designed impregnating tank. The chamber comprised a 50 foot long horizontal 8" diameter steel pipe, supported on a 2 percent grade, provided with electric surface heaters thermally insulated, and equipped with appropriate vacuum-tight sealing flanges and valves. Additional accessory

equipment included a hydraulic compensator for pressure control and necessary thermocouple-type vacuum gauge systems. A typical impregnation cycle involved a number of important sequential steps as follows:

1. Initial preheat to 100°C under vacuum (1 mm Hg.)	2 weeks
2. Liquid filling of chamber while under vacuum	8 hours
3. Impregnation period under moderate hydraulic pressure, 50 psig-max, 100°C	1 week
4. Impregnation cooling period under pressure, 50 psig-max, room temperature.	1 week
5. Sample cable storage in separate liquid-filled pipe containers.	as required

7.2 Preparation for AC Voltage Tests

A standard URD type 15 kV XLPE cable was selected for comprehensive evaluation in this cable dielectric breakdown study. The cable construction comprised #4/0 copper conductor, crosslinked extruded conductor shield layer, 0.175" XLPE insulation, extruded insulation shield layer, with tinned copper neutral wires overall. Test samples were designed to be 50 feet in overall length, with both cable ends terminated in a common, watergraded terminal, rated 250 kV.

Shield interruptions designed to serve as guard rings were installed on each cable end, located in the region of the terminal entrance bushing.

For standard non-impregnated cable samples under test, the main cable section remained in free air, unenclosed. In the case of impregnated samples, steel pipe conduit was designed as part of the test assembly to accommodate the main cable section in the impregnating liquid environment while under test voltage.

7.3 Test Procedure - Voltage Life Characteristics

The voltage-life characteristics for standard and modified cable were evaluated in a test program employing a simple step-voltage format. The obvious advantage of such an approach on a volt-time evaluation, in contrast to a constant-voltage format, is the reduction of test time.

The mathematical treatment of step-voltage breakdown data in determining cable lifetime curves is presented in Appendix I & II. In all of the discussions and graphs in this report, AC voltages are rms values unless designated as peak levels.

The program adopted involved the application of a test voltage, with 10% steps, beginning at 50 kV. Step duration periods were designated as 2 minutes, 1 hour and 24 hour groups, providing three separate data points which were considered adequate for defining a life curve, (See Fig. 1).

Tests were performed on groups of samples at room temperature and at elevated (70°C , 90°C) conductor temperatures in order to characterize the standard XLPE cable life curve. Tests on impregnated cables were subsequently performed only at room temperature to provide comparative data, (See Fig. 2).

Both dissipation factor and partial discharge characteristics were monitored by bridge measurements on many of these samples, in order to detect evidence of electrical degradation during the progress of the test. A transformer-ratio type Schering bridge (7) was employed for monitoring dissipation factor, and a modified Kreuger bridge for measuring corona discharge in the cable samples. The main 60 Hz testing transformer facility was rated 250 kV/250 kVA.

In order to perform a similar series of volt-time tests at 1000 Hz, a special 1000 Hz power transformer, rated 150 kV and 500 kVA, was designed and built for this program.

8. DISCUSSION OF TEST DATA

8.1 Volt-Time Studies (Cable Life)

8.1.1 Standard Cable. Results of Volt-Time tests on 50 foot samples of standard cable are shown in Figure 1 for three temperature conditions. In the established expression for cable life, $V^n t = K$, it may be seen on the graphic display of the life curve that n (slope) is found to be somewhat lower at room temperature than at elevated temperature, n having been determined as 12.2 (RT), 18.0 (70°C) and 16.0 (90°C).

The characteristic at RT agrees reasonably well with other Laboratories findings (8) (9) and demonstrates, in view of the moderately low magnitude of n , that voltage fatigue of the cable insulation under high stress develops at a fairly accelerated pace. The RT life curve shows, for example, that a decrease in voltage stress of 50 percent is required to achieve a one-hundred fold improvement in cable life, (from 1 hour to 100 hours). It will be significant to compare corresponding data on impregnated cable, as discussed in a subsequent section.

FIG. 1. Voltage Life of XLPE Cable

FIG. 2. Voltage Life of Impregnated XLPE Cable

The range of these volt-time curves is finite since they are not considered applicable either in the very short time spectrum (microseconds) or at very long times (greater than 10^4 hours).

8.1.2 Impregnated Cable. Similar volt-time characteristics for treated cable samples, impregnated with a liquid, are shown on Figure 2. These comparative tests were conducted only at room temperature.

Curve L_1 reflects the time-to-breakdown characteristic for cable impregnated with diethylene glycol, ($n = 100$) which shows definite improvement both in cable life and breakdown, compared to standard cable performance ($n = 12$), represented by Curve S. In this case, it is observed that a reduction of only 5% in test voltage was effective in improving cable life one-hundred fold, from 1 hour to 100 hours.

For cable impregnated with triethylene glycol-paraxylene, Curve L_2 represents the measured volt-time trend, which is clearly superior in terms of performance to Curve L_1 . Although based on a limited amount of test data, the dramatic and consistent increase in breakdown level obtained with (L_2) (for example 190 kV at 1 hour) is considered quite significant in relation to the overall study.

Thus, it is apparent that impregnation with certain liquids has significantly enhanced both voltage withstand levels and cable life (greater value of n). However, the actual mechanism and reason for such improvement is not entirely apparent partly because the exact role of microporosity (microvoids) in the breakdown has not yet been clearly established. A significant item determined during these tests was the absence of measurable corona discharge in cable samples right up to breakdown. This question will be pursued in subsequent discussion.

The Weibull graph shown in Fig. 3 provides a comparison of standard and impregnated cable performance on 1-hour step-voltage test series. The group of impregnated samples, L_1 , clearly exhibited higher and more consistent breakdown characteristics than the normal cable.

8.2 Impulse Voltage Breakdown

It was considered important to establish the relative performance of standard and impregnated cable on impulse voltage breakdown, in view of the marked improvement demonstrated by impregnated samples on AC voltage.

The excellent quality of the standard cable was demonstrated in part by the relatively high impulse breakdown data obtained,

PROBABILITY OF CABLE BREAKDOWN AFTER 1 HOUR
SINGLE STEP VOLTAGE AT ROOM TEMPERATURE

FIG. 3. PROBABILITY OF 1-HOUR BREAKDOWN

FIG. 4. CABLE IMPULSE BREAKDOWN
IMPREGNATED VS. STANDARD

FIG. 5. STEP VOLTAGE-TIME-BREAKDOWN
PARTIAL DISCHARGE RECORD
15 kV XLPE CABLE

FIG. 6. INCEPTION STRESS & DISCHARGE MAGNITUDE
AS A FUNCTION OF VOID SIZE

averaging 2000 volts/mil. However, the treated samples, impregnated with diethylene glycol (L_1) exhibited approximately 50% improvement in impulse strength, compared with standard cable. This impulse test series on treated cables produced very consistent results, averaging 540 kV(peak) - reflecting a mean breakdown stress of 3100 volts/mil, (Fig. 4).

Such marked improvement was considered significant, since there was some question whether microvoids could become ionized under fast transient conditions. Apparently the presence of microvoids does have some limiting influence on breakdown under surge conditions, since impregnation produced such positive effects on breakdown level.

These test results clearly indicate that even under transient voltage, impregnation of the insulation with a liquid produces a significant and positive effect on breakdown level.

8.3 Corona Discharge Studies

Corona was monitored continuously on many of the 50 foot cable samples employed in the Volt-Time Studies, both standard and impregnated cables. A balanced Kreuger type bridge detector was employed to provide maximum sensitivity, approximately 1pC. It is significant to report that we observed no discernible corona discharge on these test samples, even at extremely high AC stress levels in the order of 800-1000 volts/mil (average), right up to breakdown, (See Fig. 5).

The standard cable clearly was of excellent quality, and had well-bonded extruded shield layers, reflected by the relatively high dielectric breakdown obtained on AC and Impulse voltage tests.

A number of additional special tests were performed at higher sensitivity to confirm the absence of cable corona. Extremely short measured sections, having 1.0 inch active electrode length, provided a cable test arrangement affording an improved sensitivity better than 0.1pC. Again, no corona discharge was observed up to 120 kV, which was the upper limit of the sample terminals employed in this case.

Subsequently, no corona was found on impregnated samples, but this was considered predictable based on results with the non-impregnated samples.

These measurements indicate that corona discharges in microvoids, if they occur, exhibit very low energies, at levels below the sensitivity of modern detector circuitry.

FIG. 7. Inception Stress vs. Discharge Magnitude

FIG. 8. Discharge Magnitude vs. Cable Test Voltage

8.3.1 Breakdown Characteristics of Small Voids. Consideration of corona discharge in a standard 15 kV, #4/0, crosslinked polyethylene cable with 175 mil insulation wall led to the development of the curve in Fig. 6. This graph gives a plot of discharge magnitude C versus void size. This curve represents an extrapolation of measurements made with voids ranging in size from 5.5 to 74 mils (10).

The curve of discharge inception stress, E, versus void size is merely Paschen's curve at atmospheric pressure. Combining these two curves gives us the relationship between discharge inception stress and the discharge magnitude in Fig. 7. This can also be replotted in terms of cable test voltage (above ionization level) versus discharge magnitude, as shown in Fig. 8. This graph indicates for example, that if the test voltage required for corona inception in one void were 100 kV, then the magnitude of the discharge in the void would be in the order of .001pC. Figures 6 and 8 can be combined to give the relationship between cable test voltage and minimum void size permitting ionization discharge. This curve, Fig. 9, indicates that should ionization commence in a void at a test voltage of 100 kV, then the void size would have to be on the order of (.007 mm) (.28 mils).

Voids are predominantly spherical in shape based on our own observations as well as those of other investigators. However, both spherical and oval-shaped voids were considered in calculating the curves of Fig. 8 and Fig. 9.

The indications are that ionization may occur in very small voids; that the magnitude of these discharges is very small; and that with the limited integration time (several microseconds) of the corona detector, the low-level corona pulses rapidly saturate the detector at a level below the amplifier noise level; hence preventing detection. A power factor bridge, however, integrates the corona over a full cycle of 60 Hz voltage and hence could give an indication of increased power factor.

8.4 Power Factor Studies

Power factor studies were conducted on the cable samples employed in the Volt-Time series designed to evaluate cable life characteristics.

It was considered possible that some evidence of corona discharge might be detected by means of the "ionization" characteristic, afforded by the typical "power factor vs. voltage" curve. Since the evaluation of losses by power factor tends to be cumulative, reflecting the sum of many unit losses along the cable length, greater sensitivity in the detection of microdischarge energies was anticipated.

FIG. 9. Cable Test Voltage vs. Ionizing Void Size

FIG. 10. Cable Power Factor vs. Temperature

Initially, both "power factor-temperature" studies and "power factor-voltage" studies were performed on the "standard" cable. The power factor response to temperature followed predictable lines, (Figure 10), showing a definite peaking in the relaxation region around 80°C. This peaking effect, presumably influenced by the crystalline nature of the polymer is well documented (11) (12), and is believed to reflect concentrations of carbonyl groups, primarily.

Cable power factor on standard new samples, through the applicable test voltage range up to 100 kV, appeared essentially flat initially, and this characteristic trend was corroborated on many samples. This suggests again that if microdischarges were occurring in the cable under high stress, they involved only extremely low energies.

The effect of "voltage-aging" was explored on selected samples during the volt-time program. Test voltage was interrupted at appropriate intervals for the short period required to perform power factor measurements. The flat power factor curve was found to persist, even after more than 100 hours at severe over-stress.

However, similar power factor studies on impregnated cables (Fig. 11) showed a very mild "rising" characteristic with increasing voltage. Actually, the change measured less than .01%, but was detectable. Surprisingly, after some hours of voltage aging, the rising trend was found to moderate considerably. Inspection of this power factor chart reveals a noticeable reduction in slope with time (Curve 4 is flatter than Curve 1), indicating a partial suppression of "ionization" losses. This mitigating trend might simply be explained in conventional manner as a result of the gradual development of gas pressure in partially-filled microvoids under discharge at severe overstress.

However, we have demonstrated in this program that gaseous microdischarges, if they occur in microvoids, exhibit very low energies at levels below the sensitivity of modern detector circuitry.

A more realistic mechanism in this case is proposed to be incremental polar losses contributed by distributed liquid globules, constituting high loss microsites. Since the dissipation factor of the impregnating liquid is considerably higher than the host insulation, the "ionization" effect observed by our measurements, on this basis, would appear logical.

By the same token, under continuous voltage, localized heating at high-loss-microsites could be expected to cause some liquid depletion by vaporization and diffusion, effecting a reduction in the measured dissipation factor and "ionization" trend.

FIG. 11. Effect of Voltage Aging on Cable Power Factor

STANDARD CABLE BREAKDOWN VS TIME
COMPARISON OF LIFE AT 60 HZ & 1000 HZ

FIG. 12. Cable Life at 60 Hz vs. 1000 Hz

8.5 Higher Frequency - Effect on Cable Life

In order to study the effect of power frequency on voltage breakdown and cable life, a series of volt-time tests were performed on standard cable samples at 1000 Hz. Tests were carried out in similar manner to those performed at 60 Hz, with all tests starting at 50 kV and increasing in 10% steps. A special 1000 Hz power transformer, rated 150 kV and 500 kVA, was designed and built for this application.

The results of the volt-time test series at 1000 Hz are summarized by the life curve shown in Fig. 12, which also exhibits the equivalent life curve obtained at 60 Hz. Both life characteristics were obtained on cable at room temperature, with the 1000 Hz curve based on a limited number (six) of samples. It may be seen from the graph that for a breakdown level of 100 kV, the cable life at 1000 Hz is 0.25 hours and at 60 Hz is approximately 4 hours, yielding a ratio very close to that of the 2 frequencies involved. Hence, there appears to be a close to linear relationship between cable life and frequency, which confirms other studies (13) previously reported.

This linear relationship is considered a significant finding in relation to breakdown, because it supports the hypothesis that ionization discharge in the microvoids causes gradual fatigue of the insulation leading to breakdown. Since each voltage cycle contributes to fatigue, it is reasonable to expect that cable life at high stress would be reduced in approximate proportion as the power frequency is raised.

8.6 Chemical and Physical Structure Tests

Chemical and physical test procedures were employed in exploring possible structural changes that may occur in polyethylene insulation which has endured high stress aging and ultimate electric breakdown.

Comparison of specimens from the breakdown region with new insulation was expected to reveal possible significant structural or chemical changes.

Tests employed included procedures involving the measurement of density, infra-red absorption, ultra-violet fluorescence, differential thermal analysis, differential scanning calorimeter and heat-aging stability.

Most of these tests have thus far not revealed any significant change in physical or chemical structure of the insulation due to voltage aging and/or breakdown.

However, infra-red absorption studies, on an expanded scale basis, have revealed the presence of a small carbonyl band ($1700-1725\text{ cm}^{-1}$) and vinylidene band (885 cm^{-1}) on voltage-aged insulation specimens taken from the cable breakdown region of impregnated samples. Such evidence, of course, implies the occurrence of localized oxidation during voltage aging.

There is substantial evidence as a result of previous research that both chemical and physical degradation accompany electrical fatigue at high stress levels (See Final Discussion, page 69). Evidence of chemical degradation on short-time breakdown tests is likely to be highly localized, and largely destroyed by failure. Our studies suggest that, at least under short-time voltage test conditions, oxidation and other chemical degradation is a second order effect compared to the more dominant ionization or electronic processes.

9. DISCUSSION OF BREAKDOWN MECHANISMS

On the basis of the hypothesis that microporosity plays a role in voltage aging (fatigue) and in the mechanism of breakdown, the question of corona discharge is considered to be of major significance.

Estimates of apparent discharge in microvoids (1.0 to 20.0 microns) projected, with the aid of Paschen's curve, from characteristic data measured on mil-size voids, indicates that corona in the order of .01 pC or less can occur at cable stresses above 500 volts per mil, rms. Such microdischarges obviously fall below the sensitivity of our corona detector, so their reality cannot be firmly established.

In regard to voltage aging, it may be interesting to speculate on reasons for the improved life curves (Fig. 1), corresponding to higher values of n , obtained at elevated cable temperatures. It is possible, for example, that thermal expansion of the bulk insulation causes a corresponding shrinkage or reduction in the size of microvoids, (and the magnitude of microdischarges), thereby minimizing their influence on voltage-aging and cable life. Under such expansion, microvoids may also tend to change shape and elongate, presenting an effectively smaller gap profile to the electric field.

At elevated temperatures, possibly a reduction of microporosity resulting from a more homogeneous (highly amorphous) state of the bulk insulation, serves to moderate the effect of stress-induced fatigue. In yet another vein, increased conductivity may tend to redistribute charge more readily.

While the microdischarge concept is naturally dominant, the mechanism of voltage fatigue might conceivably involve an electronic

process (not involving gaseous ionization), with microporosity playing a less significant role in breakdown. There is good reason to consider the possibility of an electronic mechanism, especially in the region of the high stress shield-insulation interface, where field emission (14) at surface imperfections and associated electronic degrading processes might dominate, affecting conduction and causing eventual failure.

Previous work on field emission, for example, involving basic liquid dielectric studies under high electric fields (15), has revealed that both free-radical and ionic mechanisms can contribute to degrading reactions.

The evidence for electric field emission in liquids and gases at stresses over a few hundred kV/cm is quite well established (16), and it is reasonable to expect that a similar mechanism could occur in solid dielectric (originating at imperfections, microprotrusions, for example) at local high stress regions.

The resulting dissociation (aging) effects of the molecular structure of the resin would tend to be cumulative with time, and time-to-failure would, of course, be related inversely to the number of voltage cycles imposed.

It is reasonably well established, based on our own Laboratory studies, that electrical treeing will subsequently develop locally as a consequence of dissociative aging of the molecular structure, when deterioration reaches some critical level. Final electrical failure would thus become inevitable.

10. OBSERVATIONS

1. Treated XLPE cables, impregnated with a neutral liquid, exhibit improvement in breakdown strength and cable life.
 - a) Impulse and AC breakdown were improved by 50% or better.
 - b) In volt-time relationship, $V^n t = K$, slope (n) increased from 12 to 100.
2. Corona studies on cable samples revealed no evidence of discharge as a prelude to breakdown.
3. Power factor versus voltage trends on sample cables were essentially flat.
4. Comparison of volt-time characteristics at 1000 Hz and 60 Hz indicate an approximately linear relationship between cable life and frequency.

5. Microscopic studies confirm existence of microvoids in XLPE insulation, predominantly 1-10 microns in size. Concentrations up to 10^5 microvoids per mm^3 were observed in the central wall.
6. No evidence of electrochemical treeing was found during this test program on XLPE cable samples.

11. TENTATIVE CONCLUSIONS - PART I

1. The relative influence of microvoids in relation to the breakdown mechanism of XLPE has not been clearly established.
2. No evidence of measurable corona or glow discharge was detected on standard cable, even under very high electrical stresses (500-1000 volts/mil, rms). Thus, microdischarges, if they occur in microvoids, exhibit very low energy at levels below modern detector sensitivity.
3. The marked improvement in cable breakdown achieved by impregnation is significant. The mechanism of improvement apparently involves the liquid's stabilizing function in one or several critical microspace regions of the insulation:
 - a) microvoids in the bulk insulation
 - b) microvoids at conductor shield interface
 - c) microprotrusions of the conductor shield
4. Cable life (voltage-aging) appears greatly improved by impregnation (greater value of n). Apparently the fatigue mechanism is moderated when liquid replaces gas microspaces, thereby reducing the energy of ionic (ionization) or electronic deteriorating processes.
5. The voltage-aging mechanism appears to be complex, depending not only upon stress magnitude, but also upon frequency and basic insulation structure, involving cumulative dissociation effects of ionic or electronic processes.
6. Results with liquid impregnation appear to suggest a possible approach to dielectric improvement.

INVESTIGATION OF MECHANISM OF BREAKDOWN IN XLPE CABLE

Part II.

12. INTRODUCTION

The results and conclusions developed in Part I of this investigation indicated that both improved breakdown strength and cable life were obtained when cables were impregnated with a liquid. These results, although significant, were not considered entirely conclusive, since neither the mechanism of breakdown nor the "degree of impregnation" of the microvoid regions was clearly established.

Therefore, a new approach to investigate the mechanism of breakdown was conceived and proposed as Part II of this study.

The fundamental hypothesis regarding the significance of microporosity was reaffirmed as the primary consideration of the second phase of investigation. The microporosity under consideration ranged from mil-size, through micron-size to angstrom-size, the latter exemplified by crystal-amorphous interfaces and sub-microvoid defects.

The new basic approach proposed to explore the characteristics of crosslinked polyethylene insulation through a range of gas pressures when the cables were thoroughly gas-impregnated. It was reasonable to expect that only the microporous regions of the insulation structure would be sensitive to the gas-pressure environment, and hence, it was considered very pertinent and relevant to explore the effects of gas pressure on cable breakdown and cable life.

Changes in the breakdown pattern of the cable under different pressures would thus be reasonably linked to the influence of the microporous regions of the insulation. It would also be of significant interest to investigate the variations in electrical response with several different gases, for example, air, nitrogen, SF₆ and helium.

It was proposed in Part II, that major emphasis be concentrated on studies with model cables. This was expected to provide several important benefits: reducing the test sample size, accelerating the speed of testing, and reducing the magnitude of test voltages.

Fig. 13. Predicted Model Breakdown Pattern

Samples made from:
 15 kV, #4/0 AWG XLPE URD
 Cable Length - approx. 5 ft.

Fig. 14. Model Cable

As in the case of the test program in Part I, the primary goal was to obtain volt-time curves (life curves), with supportive measurements such as corona (partial discharge) also scheduled for evaluation on representative samples.

It is reasonable to anticipate in general, that gas-impregnated model cables will show an increasing breakdown level with increasing gas pressure. For example, significant improvement in the dielectric strength of crosslinked polyethylene cables has been demonstrated by other workers (1) under several atmospheres of SF_6 .

The pattern or shape of the breakdown voltage curve vs. gas pressure should provide evidence regarding the influence of the mechanism of partial discharge (corona) as a function of pressure. The Paschen curve for a particular gas readily indicates the expected change in discharge-inception level with changing pressure. A breakdown characteristic such as that shown in Figure 13 is proposed to be representative, in the pressure range up to several atmospheres.

13. DESIGN OF THE EXPERIMENTAL APPARATUS AND MODELS

13.1 Model Cable Design, Conditioning and Sampling

Model-Cable construction (Fig. 14) was simply achieved from "standard" cable by introducing a short turned down, reduced-wall, dual section at the central area of a 5 ft. sample length. Standard cable comprised #4/0 AWG copper conductor, 0.175" XLPE insulation, with extruded semi-con shield layers at conductor and over insulation.

Conditioning of model cable samples was carried out by oven treating at 80°C for a period of two weeks. This treatment served primarily to vaporize off most by-products, and minimize subsequent shelf-aging during storage prior to testing. Preliminary breakdown evaluations on a series of samples treated at 80°C for one week, and on a series treated for two weeks, were compared with a series of non-treated samples. Based on these test results, shown in Table III, two week heat treating period at 80°C was selected for the program. Cable sampling was facilitated by making provisions for 12 successive 500 ft. cable lengths on separate reels (A, B, C, D, etc), representing successive elements of the cable extrusion run. This made it simple and practical to select a series of test samples from distributed areas of the cable run.

13.2 Model Cable-Preparation

Considerable experience was gained during preliminary development work in preparing the short reduced-wall section of our model cable design. The machining operations must be precisely controlled in order to provide a uniform and concentric insulation wall on each model.

TABLE III
Study of Effect of Heat-Conditioning
Oven-Treated Models at 80°C

Condition	Sample No.	Wall at Bkdn-mils.	Breakdown* kV-min.	1 Hour Bkdn** kV-rms	Breakdown Stress-volts/mil	Avg Breakdown Stress-volts/mil
Non-Treated	1	18	40/12	35.5	1972	1894
	2	25	55/49	56.0	2240	
	3	25	60/10	38.0	2320	
	4	28	40/10	37.1	1325	
	5	30	40/53	40.4	1347	
	6	23	50/50	49.6	2157	
1 Week at 80°C	7	18	50/41	50.2	2749	22 2
	8	35	55/2	51.6	1474	
	9	12	30/22	28.3	2358	
	10	28	65/2	62.4	2229	
2 Weeks at 80°C	11	12	55/10	52.7	4392	2563
	12	32	45/4	41.4	1294	
	13	16	45/32	44.3	2769	
	14	32	60/6	57.5	1797	

*Note: Breakdown voltage and time (minutes).
at the breakdown step voltage level.

**Note: Estimated breakdown level, 1-hr. equivalent,
assuming $n=12$, ($V^n t = K$).

Fig. 15. Model Cable Preparation on a Lathe

1. Model cable 2. Ultrasonic eccentricity sensor

Fig. 16. Termination Assembly for Model Cable Testing

1. Insulating Phenolic terminal 2. Pressurized model housing

In order to improve control, and to minimize eccentricity, special adjustable collets (chucks) were designed, which were installed temporarily on the cable model to support the critical area to be machined on the lathe. The collets (Fig. 15) were readily adjusted so that the turned-down insulation circumference would be reasonably concentric with the conductor shield. An ultrasonic eccentricity sensor was also employed to improve uniformity. These refinements were clearly essential in order to obtain consistent breakdown test results on samples.

13.3 Test Assembly Design

For the model cable Volt/Time tests, cable test assemblies including terminals were designed to accomodate single samples, approximately 5 ft. in length (Figure 16). The design of these terminals permits their application in a stacked array assembly, facilitating simultaneous multiple sample testing (Figure 17), in groups of 10 samples, for example.

Terminal fittings were equipped with O-ring seals and designed to handle the complete range of planned pressure conditions. The main terminal bushings employed phenolic insulating tubes, although it subsequently developed that the natural cable ends (surface creepage) could be effectively utilized as terminals (Fig. 18) for the test program. Special insulating plugs (Fig. 19) provide access to the main cable housing for electrical connections, facilitating power factor and corona monitoring, while energized.

Anticipating a terminal problem that might develop should some samples survive voltage levels above the normal capability of the primary test assembly, special flexible terminal adapters (Fig. 20) employing an oil/water terminal filling medium, were utilized to extend the practical test voltage range.

The clock timer associated with each model sample was controlled through a relay energized by the sample charging current. Because of the small current magnitude (< 1.0 ma) a solid state amplifier was required to activate the relay. This arrangement avoided possible spurious effects from flashover transients and other disturbances. A circuit diagram of an individual sample is shown in Figure 19.

14. TEST PROCEDURE

14.1 General

The test procedure for volt-time studies on the model cables involved the setting-up of many series of 10-sample groups in stacked array assembly, Figure 17, which were then tested at various step-durations. Samples were connected thru fast-acting fuses to the high voltage bus, so that failed models would become rapidly disconnected during the long-time test programs.

Fig. 17. Model Volt/Time Test Arrangement
 1. Glass conduit & fuse wire 2. Model Cable

Fig. 18. Model Test With Vacuum Pump
 At High Potential
 1. Cable end terminal 2. Vac.Pump - High Potential
 3. Vac pump grounded

FIG. 19. CIRCUIT DIAGRAM FOR MODEL TEST ARRANGEMENT

For all positive pressure test conditions, gas pressure was applied to the main external cable surface within the metal housing. The conductor was not pressurized, and therefore a pressure gradient existed across the insulation wall. The pressure at the conductor shield-insulation interface would therefore attain only about 50% of the maximum applied pressure in the housing surrounding the cable surface. However, it was felt that the influence of gas impregnation and gas pressure with this arrangement could be satisfactorily demonstrated through comparison of performance at several different pressures.

14.2 Vacuum

For the tests with cable models under vacuum, preliminary studies indicated this simplistic procedure would not be satisfactory.

Test models with exposed cable ends, and with only the housing under high vacuum, showed no measurable difference in volt/time pattern compared to models in air at 1 atmosphere. Additional tests were subsequently performed employing phenolic terminal sleeves, which placed all outer cable surfaces under vacuum, with again no satisfactory results due to terminal glow discharge.

In view of these findings, it was decided to employ a modified approach, affording vacuum at both conductor and insulation shield. In order to accomplish this, one vacuum pump was placed at high potential, Fig. 18, and powered by an insulated belt-drive from a remote motor-driven pulley.

This modified approach proved relatively successful, providing more realistic test data in the low pressure range. Hence this test approach was adopted for the model tests under vacuum.

14.3 Gas Impregnation of Model Cables

A simple procedure for impregnating the model cables was established with Air, N_2 and He. The permeability, diffusion and solubility coefficients of these gases (17) are shown in Table IV. Calculations show that for N_2 complete impregnation of a model with 40 mil (0.1 cm) wall could be achieved in 1 day at the selected pressure. Treating was carried out at the designated test pressure (see Table VI) on model samples installed for test, but for 3 days to provide assurance of complete saturation.

In the case of SF_6 , Table IV reveals that permeability thru polyethylene at room temperature is 18 times lower than N_2 , and solubility runs more than 4 times greater, together resulting in an impregnation rate approximately 80 times slower for SF_6 compared to N_2 . Hence impregnation at $80^\circ C$ was considered, where the coefficients for SF_6 are found more reasonable. Reference to

TABLE IV

Gas Flow Through Polyethylene*

Gas	Permeability $P \times 10^{-11}$ $\frac{\text{cc (STP) cm}}{\text{cm}^2 \text{ sec cmHg}}$	P^{***} Ratio	Diffusion $D \times 10^{-7}$ $\text{cm}^2 \text{ sec}^{-1}$	D^{***} Ratio	Solubility $S \times 10^{-4}$ $\frac{P}{D}$ $\text{cm/cm}^3\text{-cmHg}$	S^{***} Ratio
N ₂	1.84	18	1.2	80	1.53	3.8
Air	2.5	25	1.4	93	1.79	4.5
He	14.2	142	35.5	2370	0.40	1.0
SF ₆ **	.99	10	.15	10	6.6	16.5
SF ₆	.099	1	.015	1	6.6	16.5

Notes: *Characteristics at 30°C
 **Characteristics at 80°C
 ***Ratio columns simply show relative magnitudes
 compared to smallest value, arbitrarily assigned
 as 1.0

Fig. 20. Flexible Terminal Adapters
 1. Lucite terminal 2. Flexible elbow

Fig. 21. Fast-Film Discharge Detector Set-up
 1. Model cable set-up 2. Fast-film loading

Table IV shows that at 80°C, permeability is only 1.8 times slower, and solubility 4.3 times larger, resulting in an impregnation rate approximately 8.0 times slower for SF₆. Thus model impregnation should be achieved in a reasonable period of time. Calculation illustrates that saturation can be achieved in 7.7 days at 80°C ambient.

Model cable samples were actually treated for 8 days with SF₆ at 80°C, under 10 atmospheres to assure full impregnation.

Sample calculations for impregnation with N₂ and SF₆ are shown below, assuming a 40 mil (.1 cm) insulation wall, and impregnation at 30°C for N₂ and 80°C for SF₆.

Calculation of Impregnation Time in XLPE

$$\text{Time for Impregnation} = \frac{t^2 \text{ cm}^2}{D \text{ cm}^2 \cdot \text{sec}^{-1}} \quad (18)$$

D = Diffusion Constant, t = insulation wall, cm

$$T = \frac{(0.1)^2}{1.2 \times 10^{-7}} = .965 \text{ day (N}_2\text{)} : T = \frac{(0.1)^2}{.15 \times 10^{-7}} = 7.7 \text{ day (SF}_6\text{)}$$

15. CORONA STUDIES

15.1 General

As in the first phase of the investigation on full scale cable samples, a study of the corona discharge characteristic of the model cable was carried out on a number of typical model samples. Our original studies showed that partial discharge energies on full-scale cables were very low, < 0.1 pC, below the sensitivity of modern detector circuitry.

15.2 Optical Studies

During the initial stages of Part II, we performed some simple experiments with model cables, planning to employ high-sensitivity photodiodes, to determine whether any form of light energy, (corona or glow discharge) develops within the cable dielectric under high stress. Such basic experiments on energized samples were expected to provide additional evidence regarding the presence or absence of light-spectrum energy within the electrically stressed dielectric.

The actual tests were performed employing fast-film techniques based on a test arrangement shown in Fig. 21 where water provided the outer insulation shield in the electrode area of interest. The

model cable was energized at 500 volts/mil, with the exposed film setup appropriately enclosed in a test chamber, facilitating measurement of emitted light as an integrating or accumulative function of time.

Tests were performed for several extended periods including 2 minutes, 30 minutes and finally 90 hours. There was no observable indication of emitted light energy upon inspection of each developed film. The model cables were tested at 20 kV, with nominal 40 mils insulation wall, affording a tested volume of about 0.50 cm^3 .

The sensitivity of the fast film employed for recording light emission, in terms of visible threshold of exposure (light fogging), was estimated at 20×10^{12} electron volts, equivalent to a dissipation factor of about $\tan \alpha = 10^{-5}$.

However, in this experiment there was some absorption effect resulting from the surrounding environmental elements, water and glass tubing, so that the ultimate sensitivity for the stated condition was slightly reduced from the above estimate. Hence, we concluded that for the exposure times considered, power factor bridge measurements should provide an equivalent sensitivity.

15.3 Corona on Model Cables

Corona studies were performed on several typical model samples to determine whether measurable discharge occurred anywhere within the thin-wall cable samples, and to attempt to correlate these measurements with the predictable discharge levels calculated from Paschen's curves, based on the range of microvoid sizes determined by careful microscopic examination and analysis.

In this connection we made comparative micrograph records of the microvoid population in the central wall (Fig. 22) of the standard 15 kV cable, and within the 30 mil insulation wall of the model cable. These initial studies indicated that a significant microvoid population running in the order of $10^3/\text{mm}^3$ exists in the model cable, which is not as great as the population in the central main portion of the standard cable wall, $10^5/\text{mm}^3$.

The measurement and detection of "true" corona within the small model cable represents a difficult measurement problem because of the great sensitivity required, and the difficulties involved in eliminating noise and shielding problems from the test setup.

The corona measurements on our typical sample No. 1, shown in Table V demonstrates several aspects of the test performance. During the initial voltage-conditioning run at very high stress, (1500 volts/mil) only a small discharge (2 pC) was recorded over a period of 5 hours of continuous testing. This discharge appeared to be external to the main sample, probably terminal discharge,

Fig. 22(a) Microvoid Population in Model Cable

Fig. 22(b) Microvoid Population in Standard Cable

FIG. 22.

TABLE V

CORONA MEASUREMENTS ON MODEL CABLE

I. Voltage Conditioning at 45 kV (Sample No. 1)

Steady Voltage applied - 5 hours - 1500 volts/mil.

1. Continuous corona-monitoring of model
2. Measurement: 2pC - (Apparently terminal discharge).
3. Status: Model stable after 5 hours test.

II. Step Voltage Test Program

1. Increasing voltage - starting at 10 kV.
2. Voltage Steps - 5 kV for 1 hour.
3. Test History shown below:

<u>Test Voltage</u>	<u>Step Duration</u>	<u>Corona pC</u>	
10 kV	1 hr.	10	Inception voltage level
15	1	15	
20	1	15	
25	1	15	
30	1	15	
35	1	15	
40	1	15	
45	1	15	
50	.1	15	
50	1	10	After 6 minutes, held 10 pC for 1 hour.
55	.1	10	
55	.6	15	After 6 minutes, held 15 pC for 35 minutes.
55	-	600	Few seconds, prior to failure
Breakdown	-	-	Terminal Failure.

based on simple bridge analysis with momentarily grounded sample shield. (19).

When the sample was re-energized on the following day, this spurious discharge had increased significantly as shown in Table V, but again this discharge did not appear to originate in the sample, but in the terminal area. This analysis was corroborated, since the model eventually experienced terminal breakdown on the second test day after 10 hours of step testing up to 55 kV, (1800 volts/mil).

Several other samples were tested with no measurable corona detected. Based on calculations of the expected discharge energy from the measured void size in the model cables (See Table XIII), only 2.24×10^{-3} pC would be developed in a typical 10 μ m void. This level is far below the estimated sensitivity (0.1 pC) of our bridge detector. Note: (μ m = micrometer)

16. VOLT/TIME STUDIES

16.1 Model Cable Approach

The use of model cable samples was approved because of the lower test voltages required, and the resulting ease of testing hundreds of samples in a reasonable length of time. It was considered essential and significant to evaluate the volt/time characteristic (and slope n) of the model cable so that it could be compared with the performance of the full-scale 15 kV rated cable employed in Part I of this investigation.

Results of a preliminary volt/time test series at room temperature on model cables are shown in Fig. 23, where the developed life curve is presented as a function of maximum stress. The typical life curve for the full-wall standard cable developed in Part I is shown for comparison in the same context.

The fact that the slope " n " was found essentially equivalent (12.2 vs. 12.4) in both cases, provided significant evidence in support of the use of model cables. The similarity of slope for each life curve (model vs. full-size) strongly suggests that the voltage fatigue mechanisms are similar.

The relatively higher breakdown stress characterized by the model cable probably reflects some slight "thin-film" effect, but more predominantly reflects the better dielectric quality (smaller and fewer microvoids) in the conductor region.

VOLT-TIME CHARACTERISTIC COMPARISON OF MODEL & STANDARD CABLE

Fig. 23

FIG. 24

Average Stress - - kV/mil - rms.

16.2 Volt/Time Test Program

The test program of Volt/Time studies on Model Cables which was finally developed and approved in Phase II is shown in Table VI.

TABLE VI

Volt/Time Breakdown Test Program on Model Cable

<u>Phase</u>	<u>Gas</u>	<u>Pressure</u>	<u>No. Model Samples</u>	<u>Planned¹ Voltage Steps</u>
I	Air	1 atm	30	2 min., 1 hr., 24 hr.
		3 atm	30	2 min., 1 hr., 24 hr.
II	Vacuum	33 atm	30	2 min., 1 hr., 24 hr.
		10 ⁻⁴ atm	30	2 min., 1 hr., 24 hr.
III	N ₂	1 atm	30	2 min., 1 hr., 24 hr.
		3 atm	30	2 min., 1 hr., 24 hr.
IV	SF ₆	1 atm	30	2 min., 1 hr., 24 hr.
		3 atm	30	2 min., 1 hr., 24 hr.
V	He	1 atm	30	2 min., 1 hr., 24 hr.
		3 atm	30	2 min., 1 hr., 24 hr.

Notes:

1. Due to terminal flashover problems which consistently developed at relatively higher required test voltages, the 2-minute step test was eliminated from the actual program of evaluations.
2. Tests planned at 3 atmospheres were actually performed at 3 atmospheres gauge (45 psig or 4 atmospheres absolute) pressure.

16.3 Results and Analysis of Volt/Time Breakdown Tests

The complete test results of our step-voltage breakdown test program on model cables are presented as life curves on Figure 24, and they are also detailed on Weibull probability graphs. Figs. 25-32 cover studies on four gases, Air, N₂, SF₆, and He at several different pressures. The same Weibull data is also summarized on the bar graph, Fig. 33, which indicates very clearly that gas pressure, as expected, does influence the breakdown level. The breakdown characteristic for Air was most comprehensively explored as shown in Fig. 34, where the characteristic trend closely resembles our previously predicted breakdown pattern, Fig. 13.

It is also quite apparent from Table VII which summarizes pertinent data of this study, that significant improvement in breakdown is achieved at higher pressure (4 atmospheres), for each gas con-

TABLE VII

AC Breakdown According to Volt-Time Studies on Model Cables
Impregnated with Various Gases

Gas	Pressure	Breakdown — Volts/mil — 50% Prob. —rms—		
		1 Hour	6 Hour	24 Hour
Air	10^{-4} Atm	2030	1550 ¹	1280
Air	1/3 Atm	1720	1150	840 ¹
Air	1 Atm	1780	1500 ¹	1350
Air	4 Atm	2980	2800 ¹	2620
N ₂	4 Atm	2700	2300	1950
SF ₆	4 Atm	3000 ¹	2900	2800
He	4 Atm	2800	1900 ¹	1400

Note: 1. Values interpreted from Volt-Time Curves.

Fig. 25. Weibull Breakdown Probability
Air at 10^{-4} atm.

Fig. 26. Weibull Breakdown Probability
Air at $1/3$ atm.

Fig. 27. Weibull Breakdown Probability
Air at 1 atm.

Fig. 28. Weibull Breakdown Probability
Air at 4 atm.

Fig. 29. Weibull Breakdown Probability
 N_2 at 4 atm.

Fig. 30. Weibull Breakdown Probability
 N_2 at 4 atm.

Fig. 31 Weibull Breakdown Probability
He at 4 atm.

Fig. 32. Weibull Breakdown Probability
SF₆ at 4 atm.

Fig. 33. Model Breakdown on Volt/Time Series

Fig. 34. Model Breakdown Pattern vs. Air Pressure

Note: Breakdown values on models at several pressures (air) were obtained from 24-hour step test results, (see Table VII).

FIG. 34.

sidered, when compared to standard conditions (Air-1 atm). On the other hand, moderate vacuum causes significant reduction below standard, especially under longer duration testing.

We have presented in graph form on Fig. 35, a series of modified Paschen Curves for 4 gases under selected pressures. These graphs show the corona discharge inception voltage versus void diameter in the micron range. The complete series of Paschen curves on Fig. 35 are further shown in two additional graphs for clarity. Fig. 36 gives Paschen curves for Air only under various pressures. Fig. 37 gives Paschen curves for four gases at 4-atmospheres only.

The graphs were derived from the basic Paschen curves, Fig. 38, employing the simple equation shown below to calculate the relationship between corona inception stress and void size (20):

$$V_g = \frac{3 \epsilon_1}{2 \epsilon_1 + \epsilon_2} d E_i;$$

V_g = corona inception voltage from Paschen curve
(kilovolts)

ϵ_1 = 2.3 (polyethylene); ϵ_2 = 1.0 (gas)

d = void diameter (mm)

E_i = Average stress in the cable, kV/mm

Thus, the corona inception voltage (V_g) determined from the Paschen curve for any void size is translated to average stress in the cable.

In Table VIII we have presented a summary of discharge-inception stress levels through a range of microvoid sizes for each gas. These values were taken directly from the modified Paschen Curves discussed above.

This data reflects the trend of the discharge-inception characteristic for the various gases considered. For example, the discharge-inception level for each gas at 4 atmospheres, is improved compared to standard (1-atmosphere-Air) conditions, for small microvoids in the range below 10 μ m, although He is lower for larger microvoids.

The Table also indicates improvement in discharge-inception at 1/3 atmosphere (vacuum) in the same microvoid range, yet predicts reduced inception levels with larger microvoids. This is made perfectly clear in Fig. 36, where it is seen that the vacuum curve crosses below the 1-atmosphere curve in the void region just above 10 μ m. We shall consider this anomolous behavior again, in our Discussion.

FIG. 35. Modified Paschen Curves
For Various Gases

FIG. 36. Modified Paschen Curves
Air Only

Fig. 37. Modified Paschen Curves
 Gases at 4 Atm.

FIG. 38. Original Paschen Curves

Fig. 38a. Paschen Curve - N_2

Fig. 38c. Paschen Curve - SF_6

Fig. 38b. Paschen Curve - Air

Fig. 38d. Paschen Curve - He

TABLE VIII

Calculated Corona Discharge Inception Stress
As a Function of Void Size
Based Upon Paschen Curve for Various Gases

Corona Inception Stress¹ (kV/mm)
 (And Per Unit Ratio³ Relative to Air-1 Atm)

<u>Void Size (um)</u>	<u>Air 1 Atm</u>	<u>Vacuum 1/3 Atm</u>	<u>Air 4 Atm</u>	<u>N₂ 4 Atm</u>	<u>SF₆ 4 Atm</u>	<u>He 4 Atm</u>
2	-	-	136.0	108.0	230.0	-
3	119.1 (1.00)	- -	98.0 (0.82)	69.0 (0.58)	170.0 (1.43)	670.0 (5.63)
4	77.1 (1.00)	200.0 ² (2.59)	80.2 (1.04)	56.0 (0.73)	140.0 (1.82)	83.0 (1.08)
5	56.8 (1.00)	120.0 ² (2.11)	70.0 (1.23)	49.0 (0.86)	120.0 (2.11)	49.0 (0.86)
6	46.0 (1.00)	82.0 ² (1.78)	63.0 (1.37)	43.0 (0.93)	110.0 (2.39)	31.0 (0.67)
8	33.5 (1.00)	48.0 (1.43)	52.5 (1.57)	38.5 (1.15)	92.0 (2.75)	20.0 (0.60)
10	28.4 (1.00)	33.7 (1.19)	47.0 (1.65)	35.5 (1.25)	81.0 (2.85)	14.8 (0.52)
15	20.5 (1.00)	18.9 (0.92)	38.0 (1.85)	31.5 (1.54)	65.0 (3.17)	9.5 (0.46)
20	17.4 (1.00)	13.7 (0.79)	33.5 (1.93)	29.0 (1.67)	57.0 (3.28)	7.3 (0.42)
25	15.3 (1.00)	11.0 (0.72)	31.5 (2.06)	28.0 (1.83)	52.0 (3.40)	6.0 (0.39)
30	13.6 (1.00)	9.5 (0.70)	29.0 (2.13)	27.0 (1.99)	47.5 (3.49)	5.1 (0.38)
40	11.6 (1.00)	7.5 (0.65)	26.5 (2.28)	25.5 (2.20)	47.5 (3.66)	4.1 (0.35)
50	10.6 (1.00)	6.5 (0.61)	24.5 (2.31)	24.5 (2.31)	39.0 (3.68)	3.4 (0.32)

- Notes:
1. Based on Paschen Curve, peak stress
 2. Extrapolated Values
 3. Air-1 atm used as per unit (1.00) reference base

16.4 Relationship of Breakdown Voltage and Void Size

We now want to consider the relation of void size and model breakdown. Table IX, gives a summary of "predicted" void size determined from the cable model breakdown values of Table VII. Based on these voltages, the corresponding stress is calculated and used to enter the graph of Fig. 35 on the vertical axis. The "predicted" void size is then read from the horizontal axis for any given gas and pressure. The data for all samples indicates the microvoid population of these models ranged below 10 μm , generally from about 2 to 8 μm size.

16.5 Summary Review of Volt/Time Studies

- All curves tend to converge in the short life region. This tends to confirm that differences in cable quality are more sensitive to long-time voltage life tests.
- Based on the n factor, cables under 1/3 atm (vacuum) deteriorate and fatigue very rapidly. This also appears true for Helium. Paschen curves predict low discharge inception for these gas conditions.
- N_2 at 4 atm shows improved breakdown over air at 1 atm, but only fair life ($n=9.8$). This indicates more severe voltage fatigue than for Air, (See Discussion).
- SF_6 at 4 atm shows superior life curve, but Air at 4 atm is suprisingly good, too.
 - a) Electronegative charge trapping yields improved SF_6 life curve, ($n=40$). Paschen curve indicates 2250 v/m discharge-inception for 8 μm void.
 - b) The Air-4 atm life curve shows good stability ($n=25$). Paschen curve indicates 1300 v/m discharge-inception for 8 μm void.
- Higher gas pressure yields improved life curve and larger n for air. This may be true for N_2 and SF_6 , although no data was obtained.

17. MICROSCOPIC EXAMINATION

17.1 Examination of Model Cables

A comprehensive microscopic study of failed model samples was carried out in order to determine the actual microvoid size range as well as the microvoid population. This evaluation work followed a prescribed procedure as follows:

TABLE IX

Predicted Void Size¹ Determined From Model² Breakdown Levels
Based on Interpretation of Paschen Curves

<u>Step Duration →</u>		<u>Void Size-um</u> <u>1 Hour</u>			<u>Void Size-um</u> <u>6 Hour</u>			<u>Void Size-um</u> <u>24 Hour</u>		
<u>Gas</u>	<u>Pressure</u>	<u>50%</u>	<u>Max.</u>	<u>Min.</u>	<u>50%</u>	<u>Max.</u>	<u>Min.</u>	<u>50%</u>	<u>Max.</u>	<u>Min.</u>
Air	1 Atmosphere	3.4	2.7	4.7	-	-	-	4.0	3.7	4.7
Air	4 Atmospheres	1.6	1.2	4.8	-	-	-	1.8	1.5	2.6
Air	1/3 Atmospheres	5.8	4.8	7.8	7.0	6.3	8.3	-	-	-
N ₂	4 Atmospheres	1.6	1.2	2.0	1.7	1.4	3.2	1.9	1.6	2.2
SF ₆	4 Atmospheres	-	-	-	3.1	2.2	5.2	3.3	2.6	4.0
He	4 Atmospheres	3.6	3.4	4.0	-	-	-	4.1	3.7	5.0

Notes: 1. Void Diameter (um)
 2. Model Cable

TABLE X

Actual Void Size in Model Cables
Summary of Microscopic Examinations
Magnification: 1500

Model Cable	Specimen No.	Sampling Area	Maximum Size of Void (um)						Specimen	Entire Model
			A ₁	A ₂	A ₃	B ₁	B ₂	B ₃		
1	1.1		4.0	4.0	3.2	4.0	3.2	3.2	4.0	4.0
	1.2		4.0	4.0	4.0	3.2	4.0	4.0	4.0	
	1.3		3.2	4.0	3.2	4.0	3.2	3.2	4.0	
	1.4		3.2	4.0	4.0	4.0	3.2	4.0	4.0	
	1.5		3.2	2.4	2.4	3.2	2.4	2.4	3.2	
2	2.1		3.2	3.2	3.2	3.2	3.2	3.2	3.2	8.0
	2.2		3.2	3.2	3.2	3.2	3.2	3.2	3.2	
	2.3		8.0	3.2	3.2	3.2	3.2	3.2	8.0	
	2.4		3.2	4.0	3.2	3.2	3.2	4.0	4.0	
	2.5		3.2	8.0	3.2	3.2	8.0	3.2	8.0	

On each model examined, 5 circular core-slice specimens (15-20 mils thick) were obtained adjacent to the failure. These specimens were dyed with methylene blue solution, and treated for 36 hours at 70°C prior to examination.

Each specimen was examined through a powerful microscope at two diametrically opposite regions of its circular section as shown in Table X; specimen 1 at top (oriented by failure puncture) and bottom, specimen 2 at opposite sides, specimen 3 at top and bottom, etc. Three observations focusing on 3 separate representative large microvoids were recorded at both stations A & B. This amounted to 30 observations per model.

A magnification of 300 was generally employed, and a careful search for evidence of treeing or other degradation was also made during these studies. Greater magnifications were occasionally employed up to 400, as conditions required. Photographic enlargement resulted in a final magnification of 1500.

A summary of typical data is presented in Table X representing complete examination of two models which were tested to breakdown at standard conditions under the 24 hour step voltage format.

In addition to the details of specimen measurements, Table X also indicates the maximum size of microvoid for each of the two models; in this case showing values of 4.0 μm and 8.0 μm , respectively.

The complete results of the microscopic study showing the maximum void size on all models are summarized in Table XI. Some of the more interesting microvoid specimens encountered during our microscopic studies of the failed models are exhibited in Fig. 39-A and Fig. 39-B. These microphotographs illustrate very clearly that electrical treeing does occur in very small voids ($<10 \mu\text{m}$) at high stresses near the breakdown level. Brief comments follow on each photo:

- (a) This microvoid illustrates mild electric treeing.
- (b) Small microvoid shows more intense bow tie treeing.
- (c) Mild treeing here, with evidence of transverse mechanical/micro-crack.
- (d) Microvoid illustrates fan-like streamers
- (e) This microvoid exhibits profuse electric treeing
- (f) Microvoid region with possible agglomerate of undispersed antioxidant.
- (g) Significant Illustration: electrical trees emanate from microvoids near the shield interface, and grow towards the conductor.

TABLE XI

Actual Void Size in Model Cable

<u>Step</u> <u>Gas</u>	<u>Duration</u> <u>Pressure</u>	<u>1 Hour</u> <u>Diam: um</u>	<u>6 Hour</u> <u>Diam: um</u>	<u>24 Hour</u> <u>Diam: um</u>
Air	1 Atm	3.2-8.0	-	3.2-8.0
Air	1/3 Atm	4.0-4.8	4.8-8.0	-
Air	4 Atm	3.2-4.0	-	3.2-4.8
N ₂	4 Atm	3.2-4.0	3.2-4.0	3.2-4.0
SF ₆	4 Atm	-	4.0-8.0	3.2-4.0
He	4 Atm	4.0-6.0	-	3.2-4.0

Note: Each entry represents measurements on 60 specimens, as shown in Table X

- (h) Microvoids of larger size found in center region of full size cable (.175" wall).

Several important observations are noted from this study.

1. Microvoids in these models range from 2-8 μm
2. Microvoids in full size cable are somewhat larger.
3. Electrical treeing definitely occurs in small microvoids at high stress, and in the direction of the electric field.
4. Treeing occurs in microvoids located away from shield interface. This proves that breakdown inception can occur in the bulk insulation as well as at the shield interface.

17.2 Examination of Full Size Cable

A comprehensive microscopic study was also made of the insulation cross-section taken from samples of our standard full-scale cable. This work confirmed our earlier studies and showed a definite pattern of change across the wall (See Fig. 40) going from smaller voids ($< 10 \mu\text{m}$) at the conductor to larger voids ($< 20 \mu\text{m}$) in the middle and outer regions. However, near the insulation shield interface, there is again a notable sparsity of microvoids and they are very small.

The microvoid population has been estimated at about 10^3 per mm^3 in the model cable insulation, and as high as 10^5 per mm^3 ($\leq 20 \mu\text{m}$) in the full-size cable.

17.3 Actual vs. Predicted Void Size in Models

As previously discussed, Table XII presents a summary comparison of actual vs. predicted void size on the model cables. There appears to be relatively good agreement under virtually all tests conditions and gases considered. The microvoids were observed to be below the $10 \mu\text{m}$ level, principally from 2 to 8 micron size. In general, these results agree with the microvoid size predicted from the basic Paschen curves.

Most importantly, the good correlation between actual and predicted void size serves to confirm our original hypothesis. The presence of microporosity in XLPE, and subsequent ionization discharge in microvoids at high stress, seems to initiate breakdown. These discharges are below the sensitivity of modern corona detectors, (19) as illustrated by the sample calculation of discharge energy, Table XIII, and by the graphic relationship of discharge energy, inception stress and void size, Figure 41.

(a). Microvoid (6.0um) in model, with mild electric treeing.

(b). Microvoid (2um) in model, showing electric bow-tie.

(c). Microvoid (6.0um) in model. Mild treeing with evidence of transverse mechanical microcrack.

(d). Microvoid (5.5um) in model with fan-like streamers.

Fig. 39-A. Typical Microvoid Specimens From Failed Models

(e). Microvoid (4um) in model, with profuse electric treeing.

(f). Microvoid region with possible agglomerate of undispersed antioxidant.

(g). Electrical trees emanate from microvoids near the shield interface, and grow toward the conductor.

(h). Microvoid (11um) at outer region of full-scale cable (.175") wall.

Fig. 39-B. Typical Microvoid Specimens From Failed Models

MICROVOIDS IN FULL WALL CABLE

Population at Conductor Shield

.045" Away from Conductor

.090" Away from Conductor

.135" Away from Conductor

.175" Away from Conductor
(At Insulation Shield)

Fig. 40. Void Population In Cross-Section
Of Standard Cable (1500 X)

MAGNITUDE OF CORONA (pC)

(XLPE Model Cable - .020" Wall)

CORONA IN MICROVOIDS IN XLPE CABLE

FIG. 41

TABLE XII

Actual vs. Predicted Void Size* in Model Cable

<u>Step Duration</u>		<u>1 Hour</u>		<u>6 Hour</u>		<u>24 Hour</u>	
<u>Gas</u>	<u>Pressure</u>	<u>A</u>	<u>B</u>	<u>A</u>	<u>B</u>	<u>A</u>	<u>B</u>
Air	1 Atm	3.2-8.0	2.7-4.7	-	-	3.2-8.0	3.7-4.7
Air	1/3 Atm	4.0-4.8	4.8-7.8	4.8-8.0	6.3-8.3	-	-
Air	4 Atm	3.2-4.0	1.2-4.8	-	-	3.2-4.8	1.5-2.6
N ₂	4 Atm	3.2-4.0	1.2-2.0	3.2-4.0	1.4-3.2	3.2-4.0	1.6-2.2
SF	4 Atm	-	-	4.0-8.0	2.2-5.2	3.2-4.0	2.6-4.0
He	4 Atm	4.0-6.0	3.4-4.0	-	-	3.2-4.0	3.7-5.0

Notes: A - Actual void size by microscopic study

B - Void size predicted from voltage breakdown utilizing Paschen curves

* - Void Diameter (um)

TABLE XIII

Sample Calculation of Discharge Energy in Microvoids

The formula for calculating the discharge energy (19) in a void may be written as follows:

$$Q_a = \frac{4 \pi a^3}{d} E \frac{3 \epsilon_1^2}{2\epsilon_1 + \epsilon_2} \quad \text{Coulombs}$$

ϵ_1 = dielectric constant of polyethylene
($2.3 \times \epsilon_0$); $\epsilon_0 = 8.855 \times 10^{-12}$ F/m

ϵ_2 = dielectric constant of void = ϵ_0

a = radius of spherical void (m)

d = thickness of insulation wall (m)

E = electrical stress V/d (v/m)

For the case where $d = 20$ mil wall thickness, and

$a = 5.0 \text{ } \mu\text{m} = 5 \times 10^{-6} \text{ m} \sim (10 \text{ } \mu\text{m void})$

E = corona inception stress from Paschen curve,
air-1 atm, (Fig. 34).

$E = 28.4 \text{ kV/mm} = 28.4 \times 10^6 \text{ v/m}$

$d = .020" = 0.5 \times 10^{-3} \text{ m}$

$$Q_a = \frac{4 \pi \times (5 \times 10^{-6})^3}{.5 \times 10^{-3}} \times 28.4 \times 10^6 \times \frac{3 \times (2.3 \times \epsilon_0)^2}{(2 \times 2.3 \times 10^{-12} + 10^{-12}) \epsilon_0}$$

$$Q_a = 22.4 \times 10^{-16} \text{ C} = 2.24 \times 10^{-3} \text{ pC}$$

18. DISCUSSION

In general, the good correlation of actual vs. predicted void size based on the Paschen curves confirms that ionization discharge is the basic mechanism of breakdown. It is interesting to note, however, that in several cases, (Air-1/3 atm, Air-1 atm, Helium-4 atm), it was necessary to obtain Paschen data beyond the Paschen minimum (See Table XIV) relating to microvoids in the 1.0-10 μm range.

Table XIV Paschen* Minimum

	AIR			N ₂	SF ₆	He
	1/3 Atm	1 Atm	4 Atm	4 Atm	4 Atm	4 Atm
Breakdown Volts	330	330	230	255	515	175
Size of Void (μm)	21	8	1	3	1	15

*Note: (Peak Voltage)

Since there is serious question regarding the validity of the Paschen curves beyond the "minimum", we prepared "adjusted" Paschen curves (Fig. 42) in accordance with Gerner's findings (21) which propose a flat characteristic (Fig. 43) at small gap spacings below the knee. These adjusted curves would appear to be more realistic, because, for example, the "inverse" behavior of air at 1/3 atm vs. 1 atm, predicted by crossover in the void range below 10 μm , has been eliminated. Moreover, the adjusted curves exhibit a more reasonable slope in this critical region.

Fig. 42. Adjusted Paschen Curves-Gerner

Fig. 43. Gerner's Adjusted Paschen Curve

FIG. 44.
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It is interesting to observe from the bar graph of model breakdown data (Fig. 33), that (a) better consistency or smaller spread is obtained at longer times (24 hr. vs. 1 hr.) and (b) greater spread of data is found at higher pressures (4 atm). The first observation confirms well known test behavior patterns, and partly explains industry's reliance on long-time life tests. The second observation regarding broader scatter at higher pressures (and high stress) is perhaps not so widely appreciated, but has been experimentally confirmed on gas-insulated cable systems (22) and by other workers in the field of gas dielectric breakdown.

In reference to the family of Volt-Time curves (Fig. 24) it was noted that all curves tend to converge in the short life region, which again suggests that breakdown levels corresponding to longer life times are more definitive and representative. In this regard it is interesting to study the curves for Air and SF_6 at 4 atmospheres, projected to extended life durations (Fig. 44). These life curves can be expected to show a sharp change in slope below the corona-inception level. It is proposed that when the stress falls below inception, the slope will change markedly (approaching horizontal), because the modified fatigue mechanisms then reflect only second-order, mild aging compared to the effect of partial discharge. Hence, it is reasonable to expect that cables operating below the ionization level should exhibit comparatively long life and very high n factor, ($V^n t = K$).

For cables operating right at the corona-inception stress, assuming 8 μm maximum void diameter, it is seen that cable life for SF_6 is about 6×10^4 years at the limiting peak stress of 2300 v/m;* for Air cable life is estimated to be in the order of 10^8 years at 1300 v/m. In similar vein, on the same graph, Air-1 atm curve projects to about 70 years life at 840 v/m, and Air-1/3 atm curve predicts a cable life of only 120 hours at 840 v/m (the corona-inception stress). Note the steep slope, $n=4.4$, for this 1/3 atm characteristic. *(v/m = volts/mil)

This analysis indicates that modern installed cables should provide stable long life performance, at rated voltage, under reasonable service conditions. In addition, the extraordinary stability shown at higher gas pressure suggests a possible approach to greatly improved cable performance.

In regard to the noted improvement in performance at higher pressures, it is interesting to consider why the life curve for Air so closely matches SF_6 at 4 atmospheres, in view of the significant difference in their corona-inception stress. We believe discharge-induced semi-con surface films (23), formed due to the presence of oxygen, may coat the inside of the voids and inhibit further ionization and subsequent polymer bond-breaking, at least temporarily. In addition, for the same voltage stress, corona intensity has been observed as different in various gases, for example Air,

TABLE XV

Relation of Actual vs. Predicted Breakdown and Void Size

Gas	Pressure (atm)	A	Max. Size Void μm	B	Predicted Size Void - μm	$\frac{B}{A}$
		Predicted Breakdown Peak - kV/mm		Actual Breakdown Peak - kV/mm		
Air	1/3	49.0	8	65.0 ¹	7.0	1.33
Air	1	33.5	8	76.4	4.0	2.28
Air	4	52.8	8	148.2	1.8	2.81
N ₂	4	38.1	8	110.3	1.9	2.90
SF ₆	4	91.5	8	158.4	3.3	1.73
He	4	20.3	8	79.2	4.1	3.90
Air ²	1/3	33.5	8	65.0	4.1	1.94
Air ²	1	33.5	8	76.4	3.5	2.28
He ²	4	17.8	8	79.2	1.8	3.45

A: Predicted breakdown determined from Paschen Curve based on 8 μm max. void size

B: Breakdown stress (50% Probability), 24 hr. step

1. 6 hour step breakdown

2. Based on adjusted Paschen Curves (Fig. 42)

N₂, CO₂ exhibit relative intensities in descending order (24).

As previously discussed, our microscopic studies indicated the maximum void size in the models to be 8.0 μ m. On this basis, a comparison of predicted breakdown from the Paschen curves, contrasted with actual breakdown (24 hr. step), is summarized for the several gases and pressures in Table XV. Similar results relating to the "adjusted" Paschen curves are also shown.

It is apparent that actual breakdown is consistently higher than predicted breakdown (ratio greater than 1.0), and it is also evident that predicted void size corresponding to actual breakdown is consistently smaller than 8.0 μ m. These observations are considered reasonable, since it is virtually certain that model breakdown occurs at a level considerably higher than the corona-inception stress, as demonstrated in the preceding Fig. 44.

It is reasonable to consider why the experimental breakdown ratios obtained in our research are not the same for all the gases shown in Table XV. There are a number of considerations which help to explain experimental variations.

It is possible, of course, that the model cable series with SF₆, for example, contained larger microvoids, but this is unlikely based on our planned cable sampling procedure, and also in view of multiple testing.

We know, however, that a very small change in void size yields a relatively large change in breakdown level, so this could be related as a contributing factor. In addition, it is well established that breakdown voltage of gases depart from the Paschen curve at higher stresses, (25) primarily attributed to electron emission at surface imperfections. This could be occurring in the microvoids since the test stresses exceed 2000 Volts/mil.

It is well known that cable ionization can often become self-healing when local pressure rise tends to diminish or snuff-out partial discharge. The degree of pressure build-up due to corona in voids containing various gases would be expected to be characteristically different, depending on the actual chemical reaction involved. This effect could definitely be expected to modify the rate of insulation fatigue and the resulting life curves obtained.

Finally, we must recognize the significance of chemical degradation of the polymer in this complex electrical fatigue/breakdown process under high electrical stress. The presence of corona subjects insulation to ozone, acids, ultra violet and to bombardment by electrons and ions (26), which alter the polymer both chemically and physically. There is no reason to expect these effects to be the same for all gases.

Development and migration of gaseous and polymer decomposition products will occur at a different rate in various gas atmospheres, depending upon gas molecule size, mobility of gas ions and the energy level of partial discharge or electronic emission. Hence the dominant mode of degradation could be chemical(24) for some gases and physical (erosion) for other gases.

Even under conditions of low energy emission within the microvoids, below the ionization level, it is known that sub-critical electron avalanches occur at high stress, which can result in significant local chemical degradation of the polymer.

19. FINAL CONCLUSIONS

1. Impregnation of microspaces in XLPE with appropriate liquids or gases improve cable life and breakdown.
2. Microvoids in XLPE cable play a significant role, at high stress, in mechanism of fatigue and breakdown.
3. Breakdown in XLPE models with gas-pressurized microvoids appears to follow Paschen's Law of discharge inception.
4. On the basis of close agreement of experimental data and Paschen curves, as exemplified by summary Tables comparing predicted vs. actual (a) void size and (b) breakdown voltages, all gases correlate properly. In other words, the predicted and actual breakdown sequences in descending order (using adjusted Paschen curves) can be listed as follows:

Predicted: SF₆-4, Air-4, N₂-4, Air-1, Air-1/3, He-4

Actual: SF₆-4, Air-4, N₂-4, He-4, Air-1, Air-1/3

With the exception of the anomalous behavior of Helium, these sequences are identical.

5. The mechanism of breakdown at high AC stress primarily involves partial discharge (ionization) in gas filled microspaces of the insulation. Discharge energies are normally well below 0.1 pC, even at very high stress, and cannot be measured with modern bridge detectors.
- *6. Results with liquid or gas impregnation appear to suggest a possible approach to dielectric improvement.
7. The volt-time life curve for XLPE cable at high stress appears to follow a prescribed slope (n) down to the voltage of discharge-inception, and based on our hypothesis, extrapolates close-to-horizontally beyond.
8. Cable breakdown initiates predominantly in the bulk insulation, rather than at the extruded shield interface. This is substantiated by examination of hundreds of specimens, many containing incipient breakdowns, that seem to originate only in the bulk dielectric.

9. Extensive microscopic examinations of XLPE cable involved in this program revealed a maximum void size up to 20 μm . If we hypothesize that manufacturing control can assure such quality on a continuing basis, and assuming 50 μm (2 mil) maximum voids as a safety factor for estimating purposes, then cable operation could be justified at 185 volts/mil (7.4 kV/mm) maximum stress-rms, based on Paschen corona inception.

*Footnote: Results suggest that if the cable insulation were to be impregnated with an appropriate fluid which subsequently could be immobilized, then significant dielectric improvement should result, with no need for accessories. A pressurized system of this type, employing either a liquid or gas filled cable approach, would clearly be considered less attractive, economically.

20. REFERENCES

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APPENDIX I

DERIVATION OF LIFETIME CHARACTERISTICS FROM EXPERIMENTAL DATA

It has been confirmed experimentally by many researchers that the lifetime versus voltage characteristic of extruded insulation can be described by the empirical equation:

$$A = \sum_{a=1}^k V_a^n t_a \quad (1)$$

Where:

V = Applied Voltage
 t = Time; k = No. of voltage steps
 A, n = Constants for the insulation

Equation 1 indicates that a sample subjected to various voltage levels during its lifetime exhibits the characteristic that the summation of the products of each voltage level to the n^{th} power and the duration of the voltage level is a constant, A.

Testing was conducted by energizing the samples at an initial voltage level and then increasing voltage by a constant fraction of the previous voltage level at constant time intervals until failure occurred. Under these conditions, equation 1 can be rewritten as follows: (See Appendix II).

$$A = V^n t \frac{(1 + \alpha)^{kn} - 1}{(1 + \alpha)^n - 1} + (1 + \alpha)^{kn} \frac{\Delta t}{t} \quad (2)$$

Where:

V = Voltage level of first step
 t = Step Time
 α = Fractional voltage increase
 k = Number of whole steps survived by sample
 $\Delta t/t$ = Fraction of final step survived by sample

The multiple step test of equation 2 is exactly equal to a single step test of duration t and voltage level V_0 as illustrated in Fig. 1. The single step test is given by:

$$A = V_0^n t \quad (3)$$

In equation 2 and 3, the insulation constants A and n and the step duration t are equal. Combining these two equations permits

us to convert values of breakdown voltages of the multiple - step test results to the equivalent single - step breakdown voltage, V_0 . The equation for V_0 in this conversion is given approximately by: (See Appendix II).

$$V_0 \simeq V (1 + \alpha)^k \left[0.31 + \frac{\Delta t}{t} \right]^{1/15} \quad (4)$$

Using equation 4 to calculate the single - step breakdown voltage from the values of breakdown voltage of the multiple-step tests performed to date, we get the results shown in Fig. 2. The initial voltage and voltage increment used in these tests were $V = 50$ kV and $\alpha = 0.10$. These graphs are Weibull plots of the probability of breakdown versus breakdown voltage for each of the test conditions used. The intersection of the straight lines fitted through the plotted points with the 50% line gives us the most probable value of single - step breakdown voltage for each of the test conditions.

The 50% breakdown voltage for the three different step durations at room temperature shown on Fig. 2 are plotted in Fig. 3. Fig. 3 represents the "voltage versus lifetime" characteristic of the cable at room temperature. The 50% line of Fig. 3 does not fall precisely on the three plotted points. This line was positioned on the basis of equal deviation from all three points; this deviation being somewhat less than 3 kV. On the basis of the 50% line, the constants for the insulation at room temperature are found to be: $A = 7.0 \times 10^{24}$ and $n = 12.2$. Hence the lifetime characteristic of the insulation at room temperature is given by:

$$7.0 \times 10^{24} = V_0^{12.2} t \quad (5)$$

Where:

V_0 = Breakdown voltage in kV

t = Time to breakdown in hours

Also plotted in Fig. 3 are the 1% and 99% breakdown probability curves. These curves can be obtained from the Weibull plots of Fig. 2; however, their accuracy can be improved by making use of all the data points available. Since n is known, and considering that:

$$V_1^n t_1 = V_2^n t_2 = V_3^n t_3 \quad (6)$$

Then the breakdown voltages of the 2 minute and 24 hour tests can be converted to their equivalent 1 hour step value. These results are shown in the Weibull plot of Fig. 4. Extrapolation of the curve to the 1% and 99% probability levels gives us the two points:

at 1 hour in Fig. 3. The 1% and 99% curves are then drawn with a slope of $n = 12.2$. These curves indicate the spread of results that can be expected in breakdown tests; for example, at 85 kV, 98% of the samples tested will fail within a time greater than .015 hours and less than 750 hours.

EQUIVALENCE OF SINGLE-STEP TO MULTIPLE-STEP TEST

FIG. 1 - APPENDIX I

PROBABILITY OF BREAKDOWN VS. SINGLE-STEP VOLTAGE

FIG. 2. (Appendix I)

BREAKDOWN VOLTAGE VS. TIME TO BREAKDOWN

FIG. 3 - APPENDIX I

PROBABILITY OF BREAKDOWN VS. SINGLE-STEP VOLTAGE
ALL STEP-TEST DATA-ROOM TEMPERATURE

FIG. 4 (Appendix I)

APPENDIX II

CONVERSION OF MULTIPLE STEP TEST TO SINGLE STEP TEST

The Power Law relating lifetime to voltage is given by:

$$A = \sum_{a=1}^k V_a^n t_a$$

V = Applied Voltage

t = Time; k = No. of voltage steps

A, n = Constants for the insulation

For step tests carried out at equal step durations and with the voltage increasing at a constant fraction of the previous level, then the following conditions apply:

$$V_a = (1 + \alpha) V_{a-1} = (1 + \alpha)^2 V_{a-2} = \dots$$

$$t_a = t_{a-1} = t_{a-2} = \dots$$

Fractional voltage increase

From which equation 1 can be rewritten as:

$$A = V^n t \left[1 + (1 + \alpha)^n + (1 + \alpha)^{2n} + \dots + (1 + \alpha)^{(k-1)n} + (1 + \alpha)^{kn} \frac{\Delta t}{t} \right]$$

$$A = V^n t \frac{(1 + \alpha)^{kn} - 1}{(1 + \alpha)^n - 1} + (1 + \alpha)^{kn} \frac{\Delta t}{t} \quad (8)$$

Where:

V Voltage level of first step

t Step Time

k Number of whole steps survived by sample

$\Delta t/t$ = Fraction of final step survived by sample

Converting the multiple step breakdown test of equation 8 to a single step breakdown test of voltage level V_0 and step duration t , we have:

$$A = V_0^n t = V^n t (1 + \alpha)^{kn} \frac{(1 + \alpha)^{kn} - 1}{(1 + \alpha)^{kn} (1 + \alpha)^n - 1} + \frac{\Delta t}{t}$$

APPENDIX II

Therefore:

$$V_0 = V(1 + \alpha)^k \left[\frac{(1 + \alpha)^{kn} - 1}{(1 + \alpha)^{kn} (1 + \alpha)^n - 1} + \frac{\Delta t}{t} \right]^{1/n} \quad (9)$$

In equation 3, the term $(1 + \alpha)^{kn}$ is generally much larger than unity and hence equation 3 can be simplified to:

$$V_0 \simeq V(1 + \alpha)^k \left[\left\{ \frac{1}{(1 + \alpha)^n - 1} - \frac{\Delta t}{t} \right\} \right]^{1/n} \quad (10)$$

The term in the brackets in equation 4 varies only within a few percent of unity and is only weakly dependent on n ; hence selecting a typical value of $n=15$:

$$V_0 \simeq V \cdot (1 + \alpha)^k \left[0.31 + \frac{\Delta t}{t} \right]^{1/15} \quad (11)$$