EPRI
Electric Power
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Topics:
Cable insulation
Aging (materials)
Transmission cables
Distribution cables
Extruded cables
Dielectric materials

EPRI EL-7090
Project 7898-98
Proceedings
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Proceedings: JICABLE / EPRI / CEA Workshop "Cable 89"

The Aging of Extruded Dielectric Cables

Prepared by
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Section 1

INTRODUCTION

by L. Deschamps

Today, the technical, economic, and operational qualities of polymer-insulated cables are leading to their ever increasing use in electric power transmission and distribution networks. The use of new materials, the implementation of new manufacturing techniques, improved knowledge of the electric, thermal and thermomechanical behavior of polymer insulations, and new operational requirements for cables are factors producing a rapid evolution of this technology. Good management of a power system requires a good knowledge of degradation and aging mechanisms of this system to optimize its design, choice, and operating conditions.

JICABLE is thus happy to contribute to the organization of this workshop, "Cable 89", on the aging of polymer insulated cables. JICABLE has set itself the task of providing a "platform" for exchanges between research workers, physicists, chemists and other scientists, and manufacturers and users of cables for all voltage levels. Besides successful JICABLE conferences in 1984 and 1987 (each with 600 participants from 40 countries), three workshops have covered three topical problems: HT 84, "Behavior in Overload Conditions"; HT 87, "Behavior in High Electric Fields"; and F 87 "Fire Behavior". This present workshop, "Cable 89", organized jointly by the Electric Power Research Institute, the Canadian Electric Association and JICABLE will cover the important problems of cable aging.

Connections between JICABLE, CIGRE, CIRED, and IEEE permit a concerted organization and avoids wasteful competition and duplication of effort. Formed in France by the Societe des Electriciens et des Electroniciens, JICABLE is presently broadening its scope, and, with its new status, will have its next conference between 2-8 March, 1991 in Europe.

I warmly thank EPRI and CEA for their essential parts in the organization of "Cable 89". I wish to thank more particularly Ralph Samm of EPRI, general chairman of the workshop, who had the delicate mission of organizing "Cable 89". Finally, I would like to thank all the participants at this meeting for their contributions and active participation. I wish great success to our efforts. Thank you very much.

REPORT SUMMARY

SUBJECTS	Underground transmission construction / Underground distribution / Underground cables
TOPICS	Cable insulation; Aging (materials); Transmission cables; Distribution cables; Extruded cables; Dielectric materials
AUDIENCE	R&D managers / Engineering/design technical staff

Proceedings: JICABLE / EPRI / CEA Workshop "Cable 89"

The Aging of Extruded Dielectric Cables

Service experience data on solid-dielectric power distribution cables show that significant numbers of cables exhibit a shorter-than-desired lifetime. Although less data exist on transmission class cables, the aging parameters, with the exception of moisture, should be similar. A recent workshop addressed means of improving both distribution- and transmission-class cable lifetime and performance reliability at a reasonable cost.

OBJECTIVE To improve understanding of aging phenomena associated with extruded dielectric cables.

APPROACH The Cable 89 workshop—cosponsored by EPRI, the Canadian Electric Association, and JICABLE of France—was held November 2–3, 1989, in Saint Petersburg Beach, Florida. More than 60 representatives of universities, research organizations, and electric utilities as well as manufacturers of insulating polymers and power cables attended the workshop. Expert presentations focused on life predictions of aging, materials, cables and accessories, accelerated aging, diagnostics, and service experience. Three working groups discussed materials aging and diagnostics, cable/accessory aging and diagnostics, and service experience with accelerated aging.

KEY POINTS The workshop initiated an important dialogue between cable users, cable designers, and dielectrics experts. Workshop attendees agreed on the following:

• The potential benefits and limitations of diagnostics for materials aging require greater clarification because of the wide variety of disciplines represented in the cable insulation community. More interdisciplinary communication is needed.

• Accelerated testing on cable specimens should be limited to a reasonable time limit of two years maximum.

• No satisfactory accelerated aging procedure for cables has been developed.

• Imperfections are a major source of failures in cables.

EPRI PERSPECTIVE

This workshop aided in outlining resolutions of problems associated with the aging of extruded dielectric cables. The overall workshop consensus was that improved diagnostic and accelerated aging tests that duplicate real-world situations will more accurately aid in estimating cable life and evaluating enhanced manufacturing techniques. Future international collaborations to discuss ongoing efforts in these areas are planned. Related EPRI reports address dielectric diagnostic techniques (reports EL-6207 and EL-7076).

PROJECT

RP7898-98
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ABSTRACT

This report presents the proceedings of the workshop "Cable 89" on The Aging of Extruded Dielectric Cables. The workshop was held in St. Petersburg Beach, Florida, on November 2-3, 1989. The sponsoring organizations are the Electric Power Research Institute (US), the Canadian Electric Association and JICABLE (France).

Attendance at the workshop was by invitation only, and attendees included 60 representatives of universities, research organizations, electric utilities, and manufacturers of insulating polymers and power cables, from ten countries. The workshop was created as a forum for world experts to relate and compare their service experiences, theoretical, fundamental and experimental studies, and test results on the topic of aging of solid dielectric cables. The overall topic included materials aging, cable and accessories aging, diagnostic tests, accelerated aging and service experiences and conditions. The first half day of the workshop featured six overview presentations by international experts. These presentations and the brief discussions that followed each presentation are included in this report. The second half day was devoted to discussions within three separate working groups dealing with the three topic areas: materials, cables, and accelerated tests. Reports from the three working groups were given on the third half day, and are included in this report with the general discussions that followed each one. Detailed questionnaires were mailed to participants in advance, to focus attention on areas of primary concern. The data from these questionnaires made a foundation for the working group discussions and the general discussions on the last day of the workshop. Participants had an opportunity to present brief formal presentations during the working group sessions. The content of these were incorporated into the working group reports. They were also made available, as separate written documents, to the participants at the meeting. These workshop discussions were recorded, transcribed and edited and included in the proceedings. Conclusions (representing an informal consensus of the attendees) are also included in the report.

Key words: Extruded dielectric cables, electrical aging, electrical insulation, electric power cables, accelerated tests, distribution cables.

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Section 2

WORKSHOP DESIGN

This workshop, "CABLE 89", was scheduled just prior to the November, 1989 ICC meeting in St. Petersburg Beach, Florida, for the convenience of those attending both meetings. The central topic of the workshop is "The Aging of Extruded Dielectric Cables". Attendance at the workshop was by invitation only, and attenders included 60 representatives of universities, research organizations, electric utilities, and manufacturers of insulating polymers and power cables, from ten countries. The attendance list is presented in Appendix A, and those having official duties related to the workshop are listed in Appendix B.

The three organizations sponsoring this workshop are JICABLE (France), the Electric Power Research Institute (US), and the Canadian Electric Association. The workshop was created as a forum for world experts to relate and compare their service experiences, theoretical, fundamental and experimental studies, and test results on the topic of aging of solid dielectric cables. The overall topic included materials aging, cable and accessories aging, diagnostic tests, accelerated aging and service experiences and conditions.

The first half day of the workshop featured six overview presentations by internationally renowned experts. Brief discussions followed each presentation. The second half day was devoted to discussions within three separate working groups dealing with the three topic areas: materials, cables, and accelerated tests. Reports from the three working groups were given on the third half day, followed by lively discussions among all participants. The program of the meeting is presented in Appendix C.

Detailed questionnaires were mailed to participants in advance. These served to focus attention on areas of primary concern. The data from these questionnaires made a foundation for the working group discussions and the general discussions on the last day of the workshop. Participants had an opportunity to present brief formal presentations during the working group sessions. The content of these were incorporated into the working group reports. They were also made available, as separate written documents, to the participants at the meeting.

These workshop discussions were recorded, transcribed and edited for inclusion in the proceedings. The edited discussions are not presented in chronological order but rather are grouped under several topics, for ease in reading the discussions and seeing the basis for the conclusions that follow each topic group. These conclusions, along with conclusions from the six overview presentations and the three working-group reports are included in Section 3 of this report.

Section 3

SYNOPSIS OF PROBLEMS AND CONCLUSIONS

Improving cable lifetime and performance reliability at a reasonable cost is a major goal of the organizations sponsoring and participating in this workshop. Service experience data on solid-dielectric power distribution cables ($\leq$ 35 kV) show that significant numbers of cables have less than the desired lifetime of 30 years. Large numbers of premature cable failures (greater than 5 failures/year/100 mi of cable) are costly and inconvenient. And yet, predictive tests to better estimate cable lifetime often fall short of their purpose. Furthermore, various options for incorporating new technology into the manufacture and installation of the next generation of cable systems present to insulation and cable makers and to their customers, the utilities, the problem of which of the new "improvements" to adopt.

Either the polymer insulating materials, cable construction or installation practices are usually blamed for cable performance problems. Steady, ongoing improvements are being made in all of these areas, but there is a long time-lag between the implementation of new cable technology and the accumulation of sufficient service data to evaluate new cables. For example, D. Mintz showed that service experience in North America was much worse than that in Europe. Attendees generally discounted the relevance of those data to the newest generation of cables, which use tree-resistant polymers, cleaner materials and, in some cases, manufacturing precautions to exclude water from the cables. The introduction of transmission cables ($\geq$ 69 kV) also is too recent to allow much service experience. To overcome this time-lag and better evaluate current cables, accelerated aging techniques are used to estimate long-time service performance with short-time tests. While attendees agreed that present accelerated aging methods were necessary, they tended to distrust the results of these tests, and leaned toward minimizing the severity of accelerating conditions and maximizing test times. Even the most important extrapolation techniques like Arrhenius temperature behavior and Weibull failure statistics were sometimes criticized in the discussions. The goal of evaluating eventual cable performance with a short-time test seems yet to be realized.

Workshop organizers took care to distinguish between transmission and distribution cables and between the effects of wet and dry environments during aging. The insulation in transmission cables (as compared to distribution cables) may be a better grade, is usually extruded to greater wall thicknesses and is usually dry cured rather than wet cured. Insulation in the two types of cable are cooled at different rates and hence probably to different morphologies. The insulation is operated at different stresses for the two types of cable. Transmission cables are protected by a metallic moisture barrier, while distribution cables, in general, are not. Thus, in service, insulation in transmission cables ages in a dry environment, while the insulation in distribution cables is usually exposed to ambient ground moisture. While wet aging is not considered relevant to transmission cables, dry aging is sometimes considered relevant to thermal overload conditions in distribution cables where elevated temperatures may drive out moisture from the insulation. Because transmission cable technology is newer than distribution cable technology, the service experience with transmission cables is more limited than that with distribution cables, and workshop discussions were mostly about distribution cables.

Attendees seemed relatively comfortable with present methods of testing full reels of cable following manufacture. These tests eliminate large defects (because they cause the cable to fail) and condition small defects by annealing them and reducing volatiles. Attendees expressed little confidence in present in-ground diagnostic tests to predict the remaining life of distribution cables. The extent to which such a test would affect decisions about cable replacement was questioned.

Attendees generally favored tests to evaluate new materials and material modifications for comparison with older materials. ACBD and oxidation resistance were highly regarded partly because of their close connections to service requirements. Less favored were measurements of properties like morphology and space charge that had less apparent relevance to service requirements. The popularity of newer measurements on materials presumably suffered from a lack of familiarity throughout the cable community.

A summary of conclusions from the overview presentations, working group reports and general discussions is given below. These conclusions should not be viewed as "truth" as they do not represent the result of a critical scientific process of data analysis. They are merely opinions expressed during the workshop discussions, presentations and surveys. At best, they represent the general understanding among the attendees about the current general knowledge and practice in cable technology.

We group these conclusions according to their applicability to distribution cables, or transmission cables or both.

GENERAL - TRANSMISSION AND DISTRIBUTION CABLES

- The potential benefits and limitations of diagnostics for materials aging require greater clarification especially because of the wide variety of disciplines represented in the cable insulation community. Ways to communicate better between disciplines are needed.
- Accelerated testing on cable specimens should be limited to two years as a reasonable practical time limit.
- There is no satisfactory accelerated aging procedure for cables.
- Imperfections are a major source of failures in cables.
- The factory test procedures commonly used to deal with imperfections are effective.
- Breakdown strength increases slightly with insulation density for a given material.
- The effects of morphology on cable performance under normal operating conditions are not widely understood or agreed upon.
- Antioxidant concentrations in the insulation of cables with coextruded screens are changed because of migration of antioxidants between the insulation and screen.
- Oxidation is retarded by screens, jackets and antioxidants.
- Increased power factor of a cable is a strong indication of some problem with the cable.
- Power factor measurements in the field are not sensitive enough to detect many problems in cables.
- Surge damage is best avoided by use of adequate protection devices and correct installation procedures.
- Metal sheaths provide the best protection against water but add a significant fraction to the cost of a cable.
- Weibull statistics are mathematically correct and experimentally valid under carefully controlled conditions.
- In many practical applications data do not fall on a straight-line Weibull plot presumably due to changing external conditions or uncontrolled parameters.
- Past experience has shown that improvement in one property with a new or modified material always goes with a loss in some other property.
- The intrinsic strength of PE and XLPE is probably > 1000 kV/mm.

DISTRIBUTION CABLES

- During accelerated aging with load cycling, the order of property loss for dry aging is oxidation resistance, elongation and ACBD, and for wet conditions the order is ACBD, oxidation resistance and elongation. This observation can be considered a guide to appropriate tests.

- Water treeing is the most significant aging factor in MV cables without water barriers. Any method to reduce water influx is beneficial.

- Residual moisture in cable insulation produces bow-tie trees that do not cause problems at operating stresses during dry aging.

- An improved standard accelerated aging test is needed to evaluate wet aging in both insulations and semiconducting materials.

- Bow-tie trees sometimes grow to the extent of causing breakdown. Many breakdowns occur without any apparent connection with bow-tie trees.

- Present diagnostic tests giving remaining cable life often do not affect replacement decisions because of lack of confidence in the test.

- Ions affect tree growth during wet aging but have little effect during accelerated dry aging.

- 30 years is normally considered an adequate cable lifetime.

- About 5 failures/year/100 mi of cable is considered by many to signify the end of a cables practical life.

- Tree-retardant materials show significantly reduced tree growth in accelerated tests compared to XLPE.

- A continuous supply of liquid water is necessary before tree growth becomes significant.

- Liquid water in cables under voltage stress is a major source of failure in polyethylene-based insulation.

- The use of polyethylene-based jackets and semiconducting layers and care to exclude the ingress of water during manufacture and installation significantly reduce water related damage in cables without metallic barriers.

- Water-tree-retardant materials have significantly better performance in accelerated wet aging tests than does ordinary XLPE.

- Indications are that service performance of TR materials will be better than ordinary XLPE.

- Careful cost and performance analysis is needed to evaluate the relative merits of new materials and structures such as metal sheaths and TR polymers.

- It is sometime difficult to distinguish between changes in a material due to external conditions (like ingress of water from the surroundings) and aging (like the growth of large trees).

- Three stages in the life of a cable are: Early failures (defect elimination - failure rate decreases with time), maturity (failure rate constant), and aging (oxidation or some other deterioration begins - failure rate increases with time).

- No single effective diagnostic test to predict remaining life of wet-aged polymers is presently foreseen.

- Experience with numerous available diagnostics for wet aging is presently too limited for practical use.

TRANSMISSION CABLES

- In dry HV cables, inorganic and metallic impurities are the worst contaminants.

- The ratio of factory test voltage to service voltage commonly decreases with increase in service voltage because of practical problems of applying high voltages.

- Increasing the field in HV cables beyond their design stress is not recommended without a careful analysis of cost and performance.

- The Arrhenius equation has been suggested as useful for extrapolating thermal aging results to long times.

Section 4a

WORKING GROUP REPORT - MATERIALS AGING AND DIAGNOSTICS

B. Bernstein, Chairman

The objectives of this group were 1) to understand materials behavior (life prediction and accelerated aging behavior) in order eventually to understand cable behavior, and 2) to examine the significance of diagnostic techniques. Discussions included dry and wet aging and we occasionally included cable results and problems along with materials. We summarized the questionnaire results (18 respondents for dry conditions and 19 for wet), had prepared presentations, had a general discussion and then returned to the questionnaire to see what suggested changes the attendees felt strongly about.

For dry aging, important factors included field, time, contamination in the semicon and insulation, voids, cavities, and the semicon-insulation interface. For wet aging, external water, field, time, contamination, voids and cavities were also ranked high in importance. For diagnostic techniques, methods for measuring contaminants - conventional optical microscopy and dielectric strength were the highest ranking. For test geometry, respondents preferred coaxial geometry with semiconducting electrodes for wet aging, and parallel geometry with semiconducting electrodes for dry aging. There was no strong consensus in favor of the EFI test. ACBD and time to breakdown were the most favored assessment methods. Analytical techniques ranked high as a group, but different people preferred different techniques. Respondents split on the importance of morphological changes, and diffusion of components was considered an important factor. Everyone thought there were good tests for evaluation of retardant additives, but differed on what those tests are.

NESTE and Siemens presented data on a new tree retardant material. Andras Farkas talked about laboratory testing. Schroth talked about cable testing. Conventional EFI tests show the new material has good resistance to both bow tie and vented water trees. Dr. Dalle talked about new diagnostic techniques for dry and wet aging, particularly space-charge measurements using shock waves. Dr. Favrie discussed migration of additives from the semiconductor layer into the insulation of cables. Dr. Fallou made suggestions on the use of the controversial tanδ test, and measurements of gas evolution under stress. (The problem of differentiating trapped gases from those due to decomposition was noted.) Dr. Mayoux discussed dry aging using partial-discharge methods and chemical changes in the channel walls. He focused on the effects of ions on aging. Dr. Barlow discussed secondary recrystallization in polyethylene and resultant microvoids that can grow to potentially harmful sizes. Dr. Braun discussed x-ray-induced partial discharges as a way to increase the sensitivity to small voids.

One change from the survey results was the suggestion that concurrent stresses should be considered. Ranking of survey results did not change. Unfamiliarity with certain techniques that have provided extensive results seems evident. We concluded that more effort should be made to communicate these results to the general cable community. We differentiated between temperature cycling and temperature gradient which some attendees considered an important parameter.

The highest ranking diagnostic techniques are old ones from the 1970's - contaminants, visual inspection and dielectric strength. A new method like chemiluminescence is so sensitive that interpretation is difficult. Measurements of density are also promising. Optical and electron microscopy are of known value. FTIR was one of the highest ranking techniques in spite of sensitivity limits. Proton-induced x-ray emission and ion chromatography are worth attention, and dielectric strength is an important method. We concluded that not enough information was available to the industry to use many of the new materials measurement methods. Dr. Boone's tree length results relating tree lengths to breakdown strength suggested that similar unsuccessful studies in this country should be reexamined.

For wet accelerated aging ACBD is the first property to disappear and oxidation resistance is the second. Physical properties degrade later. For dry accelerated aging, the first property to degrade is oxidation resistance. Only afterwards are there changes in elongation. ACBD strength is lost last. For wet aging, electrical measurements seem appropriate. For dry aging other properties may change before the electrical properties. It has been suggested that TR additives may affect these observations, but they can be a guide to the selection of the most appropriate aging tests.

Section 4b

WORKING GROUP REPORT - CABLE/ACCESSORY AGING AND DIAGNOSTICS

L. Deschamps, Chairman

This working group included 15 participants from Europe, Japan, the US and Canada. Topics included PE, XLPE and EPR, MV (< 5 kV/mm), HV (5 to 10 kV/mm) and EHV (> 10 kV/mm) cables, and wet and dry conditions. A summary of the answers to the questionnaires about the main factors affecting the lifetime of cables and accessories, and the most important diagnostic tests are given in Table 4b-1.

Water treeing is the most significant aging factor in MV cables without water barriers. Any method used to reduce influx of water into the insulation is beneficial. The degree of moisture protection is a matter of economics. Cables with metal sheaths can cost up to twice as much as equivalent cables without metal sheaths. Tree retardant additives can significantly reduce tree growth in the presence of water. 45% of MV cable in the US is presently made with tree-retardant compounds. Increasing the insulation wall thickness, using expanding tapes under the jacket to block longitudinal flow of water and the use of solid conductors are examples of water reduction methods, the use of which is an economic problem.

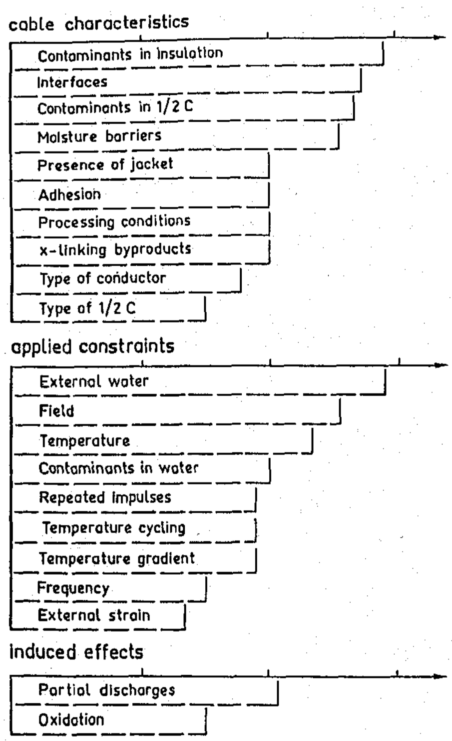
In Japan, MV cables (6 to 33 kV) are not waterproofed, and lead foil is being considered for 22 to 33 kV cables. 69 to 500 kV HV cables will be waterproofed in the future. In Europe MV cables are not waterproofed except in France, and EHV cables are. In France, MV, HV and EHV cables are waterproofed. In the US many utilities are changing philosophy from lowest initial cost to longer service life and ease of replacement, for example TRXLPE insulation and PE jackets. For HV cables no failures attributable to water trees have been reported except when there was accidental flow of water into the cable. This suggests that intrinsic water in the insulation does not reduce the expected life of a cable.

It is difficult to dissociate the water problem from the problem of contaminants, both in the insulation and at the interface between the insulation and semiconducting layer. Paper fiber contaminants with moisture initiate water trees and result in a lower breakdown strength even with low electric fields. In dry HV cable metallic impurities are the worst, especially in the maximum field region and

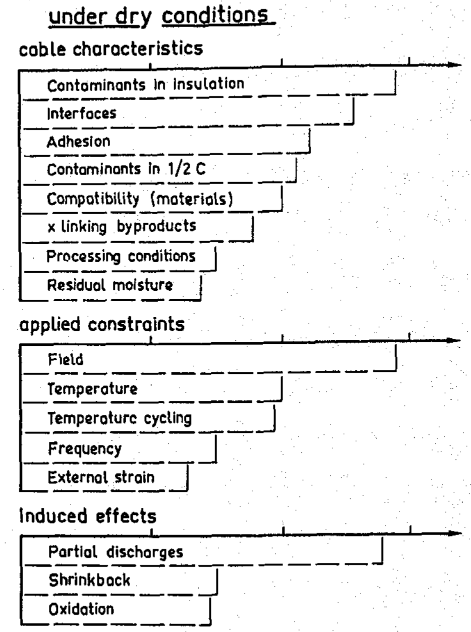
Table 4b-1

FACTORS AFFECTING WET AND DRY AGING OF CABLES AND ACCESSORY AGING AND DIAGNOSTIC TESTS RATED FROM THE QUESTIONNAIRE
Score is indicated by the bar lengths

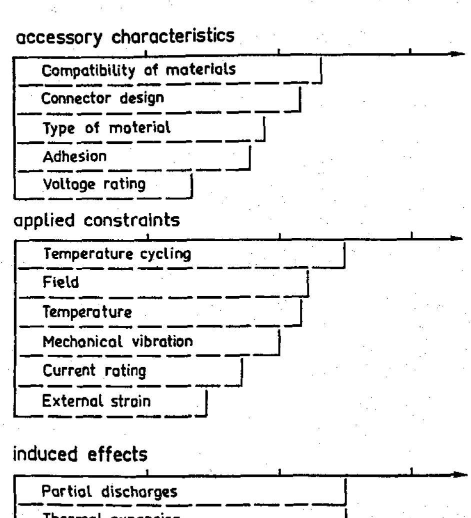
under wet conditions



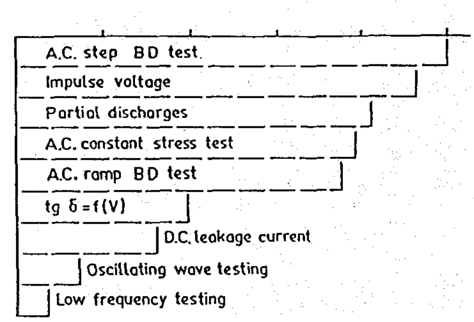
under dry conditions



Aging of accessories



Diagnostic test



especially when the particles are not imbedded and produce partial discharges and breakdown. Particles greater than 30 μm to 40 μm in low density PE and 100 μm in XLPE are to be avoided. Interface contaminants involve roughness (want better than 30 μm or 100 μm smoothness as above) and quality of carbon black. Emission shields do not produce as much improvement with the latest generation of semiconducting materials as with older semiconducting materials, probably because they are cleaner.

Maximum overload temperatures depend on the mechanical properties of the insulation, and appear to be 105°C for XLPE [this value is used in Europe and Japan, while 130°C is used in North America] and slightly higher for EPR cables, and 80°C and 90°C for low and high density PE, respectively. Creep can occur in XLPE and EPR above 90°C. Residual deformation occurs if pressure remains during a cooling transient, and is relatively small in EPR. Choice of screen and bedding materials and careful installation practices can alleviate damage, and increase the maximum overload temperature to 130°C. Accessory aging problems involve material compatibility, for example the filler in the silicone grease used to connect accessories. HV cables do not show aging when external influences such as water are avoided.

Diagnostic tests apply to wet conditions only. CIGRE tests are summarized by W. Boone in Section 5e of this report. The practical use of tanδ and conduction-current tests are not clear. Partial-discharge tests do not detect water tree degradation until just prior to breakdown, but they can detect cavities and electrical trees.

Section 4c

WORKING GROUP REPORT - ACCELERATED AGING AND SERVICE EXPERIENCE

J. Densley, Chairman

The objectives of this working group were to:

- share knowledge on accelerated aging by discussing mechanisms of aging under "dry" and "wet" conditions, evaluating the roles of various stresses, and discussing diagnostic techniques,
- tabulate a range of stresses for accelerated aging tests under dry and wet conditions, and
- discuss normal and abnormal service experience.

Questions to be answered to reach these objectives are:

- How do particular stresses affect aging?
- What are the mechanisms of aging over a wide range of stresses?
- What synergistic effects occur between stresses?
- What are the limitations of present accelerated aging tests to screen materials and to guarantee a minimum cable life of 30 years for both wet and dry conditions?

DRY AGING

The results of the workshop questionnaire showed general agreement on the importance of: E, t, contaminants, cavities, partial discharges, interfaces, connectors and test geometry. There was less agreement about residual moisture (the long term effects of bow-tie trees), temperature (maximum temperature, thermal aging), temperature cycling (thermomechanical effects and morphology changes), frequency (usefulness of accelerated aging), residual and external mechanical strain (void formation, cracking and loss of adhesion), antioxidants (chemical reaction control), residual and dissolved gases (void formation and deterioration) and space charge (high field effects).

The following salient points resulted from the discussion:

- To detect gross imperfections during manufacture, a cable should be sampled over a year and subjected to ACBD testing.

- The Weibull plot of the results gives useful information.

- Residual moisture produces bow tie trees and these should not be a problem at operating stresses.

- The French long term test was described in detail, using standards HN-33-S-52, -51 and -54 for single core cables up to 100 kV, 245 kV and 420 kV respectively. For 100 kV cables, a length of 100 m with indoor and outdoor terminations and 4 joints are aged for 6000 h (250 days). Termination flashover precludes ACBD testing. With an aging voltage of $1.73V_o$, 167 cycles at 100°C and 83 cycles at 105°C were applied as 8 h on and 16 h off per cycle. The 100°C and 105°C tests apply to XLPE. A $2.2V_o$ acceptance test is described for $\leq$ 220 kV cables and for 400 kV cables, $1.91V_o$ for 10 hours and $1.74V_o$ for one hour is described. Weibull statistics were used to estimate the maximum number of breakdowns (5 in 30 km) to give a maximum fault level of 0.2 faults/100 km (3-phase) per year.

- Cables removed from service after 14 years (63 and 225-kV LDPE transmission cables) had small bow-tie trees and impulse and ACBD exceeded new cable specifications. IR, UV and DSC tests gave no unusual results.

- Italian practice is to test each core length of cable at $3V_o$ for 0.5 h and to test finished cable at $2V_o$. However long term tests at too high a stress can produce ionization in microvoids.

- The effect of 10 kV/mm aging on XLPE morphology showed no significant changes. Thermal gradients did change the structure of the lamellae. Mechanical stress is known to affect recrystallization. SAXS and WAXS seemed not to be effective in this study.

WET AGING

The workshop questionnaire showed general agreement on the importance of E, t, water ions, contaminants in the semiconductor layer, cavities, connectors and test geometry (uniform and coaxial with SC electrodes). There was less agreement on temperature (conflicting data), morphology (importance of), residual and external mechanical strain (how much does it effect tree growth?), frequency (extent of usefulness). Discussions of these points included:

- Morphology may influence the way trees propagate independent of detailed mechanism.

- While large tensile strain will promote treeing, normal values of strain are no real problem.

- A new standard test is needed to evaluate new materials (both insulations and semiconducting materials).

- The EFI test uses semiconducting electrodes (1 metal electrode and salt solution as the high voltage electrode), 15 kV/mm, cyclic temperature. At 3, 8, and 16 weeks diagnostic tree counts and ACBD tests are done. The interface as well as the insulation and semiconductor are tested. Comparing this test with a standard defect test (needle/plane) was proposed.

- Water trees in insulated wire with a square conductor (no semiconducting shield) are similar to those in full sized cables. Tests on full-sized cables should be made over a range of conditions to avoid misleading information about materials. These conditions include E and T. Ions are important. Time to breakdown tests were preferred. Tests by CIGRE and AEIC seemed to give similar materials evaluations even though they used significantly different test conditions.

- Accelerated aging test that relates to service experience is still needed.

A range of test conditions suggested for cables is: E = 2 kV/mm - 8 kV/mm, f = 50 Hz - 60 Hz, T_M = 50°C, 80°C, T_C = room temperature to the melting temperature, ion composition should be controlled, t = time to breakdown with a limit of two years.

Suggested diagnostic tests on cables are: time to breakdown, AC step tests (after 2 years), visual observations, water content. Tests needing further study include TSC, space charge measurements, conduction current, low frequency (0.1 Hz), tanδ, and repeated surges.

Good collection and analysis of service failures are needed to pinpoint problems and guide design of valid accelerated tests. The service data is of low probability events (less than 0.1%), which is much lower than the 63% levels for laboratory tests.

Section 4d

SUMMARY OF GENERAL DISCUSSION FOLLOWING WORKING GROUP REPORTS

ACCELERATED AGING

E. Brancato: John Densley, you said tests and field results don't agree. Could we predict lifetime with an equation that combines Arrhenius temperature dependence with E^{-n} field dependence including the temperature dependence of n itself? **J. Densley:** Under dry conditions maybe. I don't think the aging models that you suggest apply to wet conditions. For example, n for water treed insulation is around 4; under dry conditions it is from 9 to 20, and failures are almost independent of temperature on slab materials in the laboratory. However, I don't want to infer that there is no hope for prediction in the lab. **W. Boone:** John Densley, as the required test duration is, in general, much shorter for dry aging than for wet aging, by choosing the same duration for both tests, the conditions for your recommended accelerated aging tests are less severe for wet than for dry aging. Why not compensate by increasing frequency for wet aging? **J. Densley:** Our objection to high frequency aging is the high cost of equipment for testing cables. I like the use of high frequency for wet and dry, but the consensus of our group was to not include high frequency tests. **W. Boone:** Why use the same two year time for both tests, was it just for practical reasons? **J. Densley:** I think so. It can take more than a year for some aging phenomena to become apparent. Two years is a compromise. **W. Boone:** Do you agree that your recommended dry aging test is more "accelerating" than the wet aging test? **J. Densley:** No, the parameters for dry aging are not intended to be more accelerating. **R. Samm:** I propose the wet and dry tests are equally severe. In the dry case you have eliminated the most severe condition, the water. With too severe conditions one risks doing extra, artificial damage. **C. Katz:** J. Densley, why are AC breakdown tests preferred over impulse BD tests - is it due to lack of impulse BD equipment? You said tests to BD were preferred and then said ACBD should be used after a two year limit. Why AC and why two years? **J. Densley:** AC tests were preferred because they are more convenient. We thought one year aging was not long enough for some of the newer materials, but we needed an upper limit. **D. Silver:** It was pretty unanimous. Two years was a reasonable compromise. **J. Tanaka:** How would we best test a new material to see if it would make better insulation than existing materials? **B. Bernstein:** We don't have a good answer to that. But for wet tests: dielectric testing, peripheral tests, 2 years wet aging. For dry tests: oxidation resistance, thermal aging. **J-M. Braun**: I would add non-destructive tests to measure the condition and remaining life of a cable containing Tanaka's new material.

- Accelerated testing on a specimen should be limited to two years as a reasonable practical time limit.
- There is no satisfactory accelerated aging procedure.

BOW-TIE TREES & BREAKDOWN

J-P. Crine: Has anyone seen a cable break down due to bow-tie trees? **S. Verne**: Yes, we've seen breakdown originating from bow-tie trees. The likelihood of this happening increases with increasing size and density of bow-tie trees. A bow-tie tree always grows towards a neighboring defect, which may be in the bulk or at the surface of the insulation. Connecting to a surface defect transforms a bow-tie into a vented tree. **N. Srinivas**: We have seen large bow-tie trees near the failed region in 175-mil XLPE cable. There are not a lot of small trees but big ones grown from very small sized contaminants. This cable had a wet conductor when it went in and when it came out. **D. Mintz**: I found large bow-tie trees in 5-kV cables and their size related to the defect that they grew from. Bow-tie trees do not become larger as the insulation thickness increases, so I don't believe that the bow-tie trees would be significant in larger cables (25 kV or 35 kV). In about 40% of failed cables samples I looked at, I did not see large sizes or numbers of water trees that could be implicated in the failure.

- Bow-tie trees sometimes grow to the extent of causing breakdown. A significant number of breakdowns occur without any apparent connection with bow-tie trees.

CABLE TESTS FOR DEFECT DETECTION AND DEFECT CONDITIONING

D. Silver: ACBD should be at the top of the list for both wet and dry aging. Oxidation is not enough to cause significant changes in the physical characteristics of XLPE in cables even after 30 years in service. Imperfections are the main thing. 1) Production samples should be selected periodically over a period of a year and ACBD tested. 2) The data evaluated with a Weibull plot - essentially a straight line for XLPE insulation. The position of the plot and the slope gives a good assessment of imperfections. In addition, we need a full reel voltage test to eliminate gross imperfections. The US tests at 200 V/mil, (much below the 15 kV/mm or 20 kV/mm used in France). I suggest we increase the full-reel voltage test above 200 V/mil. In the US, we use four times Vo for 15 kV cables and 3.25Vo for over 35 kV cables. It disturbs me that as we go up in operating voltage, we continually drop the ratio of test voltage to operating voltage. What is the justification for this? **B. Bernstein**: 1) this chart assumes no imperfections. We were concerned with material aging, not cable defects. **S. Banati**: We treat polymer cables like paper cables and I see now there is a big difference. What tests should we do to get good polymer cables? **L. Deschamps**: In France we test at $2.2V_0$ and check Weibull parameters to generate a breakdown if there are big defects and condition the small defects to eliminate the early failures. I do not know the best ratio of test stress to operating stress. **W. Boone**: IEC has almost decided to increase the routine test for medium voltage cables to $3V_0$. The Netherlands is considering $5V_0$ for 10 kV and $3V_0$ for 30 kV. This is done mainly to eliminate defects, and will not change the life of the cable. **E. Favrie**: For 400-kV cables, we have a test, 440 kV for 10 h and after 24 h, 400 kV for one hour to check that the 440 kV did not damage the cable. We think there is threshold voltage. If there is no problem during the routine high level test, there will be no problem in service. **J. Moran**: Testing 225 kV and 400 kV cables is increasingly expensive and complex as test voltage goes up. I see a trend around the world to substitute hours for kilovolts as a compromise at extremely high voltages.

- Imperfections are a major source of failures in cables.
- The test procedures commonly used to deal with imperfections seem adequate.
- The ratio of test voltage to service voltage commonly decreases with increase in service voltage because of practical problems of applying high voltages.

CABLE TESTS OF REMAINING LIFE.

S. Grzybowski: We still need ways to use the test results to say how good a cable is. I suggest we need a standard reference material, and low frequency AC tests at 0.1 Hz. **J. Moran**: I certainly concur that ac breakdown strength is the most dominant indicator of residual life. Perhaps we need some practical version of the 30- to 35-yr-old concept of a very-low-frequency ac test to be conducted in the field. **N. Srinivas**: Jim Moran's question: does what we study here mean anything about the life of the cable in the field. We are looking for at least a 30-year life. We ignore failures in the first five years, but the main life of the rest of the cables should be at least 30 years. **J-P. Crine**: I repeat J-M. Braun's question: How can we evaluate the condition and age of a cable without removing it from the ground? **F. Garcia**: An operating cable is undergoing a continuous withstand test merely by being alive. That's a good test of performance. If utilities have a black box to tell when a cable might fail, I don't think they're going to change that cable until it actually fails. I suggest that's a perfectly valid way of doing things. The first failure you ignore - the second failure requires a decision and data from the black box might help with that decision. **D. Mintz**: Northeast Utilities used such a replace-as-it-fails type program (with HMWPE), unsuccessfully - failure rates continued to increase. Only a few utilities would go around and replace cables if they could have a black box that told them which ones to choose. **W. Boone**: A large utility in our country decided to replace cables to avoid unannounced failures. It just depends on how dependent a utility is on certain connections. They sometimes must do more than just wait and see. **N. Srinivas**: Do you have a diagnostic tool to tell the life of the cable? **W. Boone**: The CIGRE characterization tests (BD of pieces of cable from the field and inspection for trees), together with practical experience, are considered a diagnostic tool. **C. Katz**: An alternative to replacement is to dry the cable by passing dry gas or dielectric fluid through it. A number of utilities are prolonging service life of cables this way.

- A diagnostic test giving remaining cable life would often not affect replacement decisions.

INCREASED STRESS IN HV CABLES

L. Deschamps: For high voltage cable it is not possible to see the aging, suggesting possible use of higher stresses. **G. Matey**: We don't see changes in XLPE at higher stresses but we do not know about the effect of higher stress on the semicon or at the interface, or the effect of impulses and high frequency currents. We must be cautious before recommending higher gradients. **L. Deschamps**: Also the non-distributed energy loss should be considered. And if we increase the field in a cable that is in service, we will change the rate of failure, and can't extrapolate the Weibull statistics for that cable. For this reason I am not in favor of increasing the field in high voltage cable without caution and careful evaluation of the economics.

- Increasing the field in high voltage cables is not recommended before a careful analysis of cost and performance.

IONS

B. Bernstein: Ions migrating from the semicons during wet aging also affect tree growth (Katz and coworkers in 1973 or 1974). From EPRI report EL5757, ions did not cause decreased BD strength during dry aging. The importance of ions differs greatly between wet and dry aging. **C. Katz**: The moisture (and not the ions) reduces the dielectric strength.

- Ions affect tree growth during wet aging but have no effect on dry aging.

MORPHOLOGY

J-P. Crine: Concerning a critical field in XLPE, I have shown that microcavities start at a relatively low temperature and at a field on the order of 15 kV/mm to 20 kV/mm, and these microcavities are the first step in aging that leads to breakdown. I doubt that we could operate XLPE cables for long above about 20 kV/mm. I showed that EPR is better than XLPE in the above respect. **J. Densley**: Mr. Favrie discussed a 400-kV cable subjected to 27 kV/mm (above Crine's proposed 20 kV/mm critical field) for 7,700 h without detectable change.

- Breakdown strength increases with density for a given material.
- Morphology and its effect on cable performance is not widely understood.

OXIDATION RESISTANCE

S. Verne: Oxidation resistance measured on insulation for medium voltage cables is misleading. Such insulation is fully stabilized. With coextruded screens, the antioxidant disappears from the insulation into the screen, but screens do protect the insulation from oxidation. Our measurements on cables with coextruded screens show oxidation resistance remains throughout the lifetime of cable. **B. Bernstein**: Excellent point. Data from the thermal overload project show that both screens and jackets slow down oxidation in XLPE. Oxidation resistance is going to be related primarily to how much antioxidant remains after the extrusion process.

- Antioxidant diffuses from the insulation into coextruded screens.
- Oxidation is inhibited by screens, jackets and antioxidants.

POWER FACTOR

D. Silver: If the power factor increases from 0.01 for XLPE or 0.05 for TRXLPE, to greater than 0.1, it indicates extensive water treeing. **[unknown]**: You can't do a power factor in the field because XLPE, EPR, and paper cables are all connected to the same feeder. You could take a piece of cable to the lab, but it will not show the field condition. **J. Moran**: Power factor is sensitive to wide variations in conductor and insulation shield resistivity.

- Increased power factor is a strong indication of impending breakdown in a cable.

- Power factor is not sensitive enough to detect many problems in a cable.

SERVICE LIFE OF CABLES

J. Moran: Like M. Brancato, I want to extend laboratory aging to cable life. Could someone define service life? **D. Mintz**: 3 to 7 failures/100 mi/year seems to be when most people think of replacement. I think a cable should give less than 1 failure/100 mi/yr after 10 to 15 years of service. **M. Mashikian**: I perceive from the discussions many islands of knowledge, but not the bridges that connect these islands, and tell us how much this cable has aged or how much more life it has. Can we bring this information together? **J. Densley**: Exchanging ideas between disciplines in a forum like this workshop is the first step toward bridging these islands.

- 30 years is normally considered an adequate lifetime.
- About 5 failures/year/100 m of cable is normally considered end of life.

SURGES

J-M. Braun: Aren't surges important in the life of water treed cables and in accelerated tests? **J. Densley**: That was discussed briefly at the end of our session and did not get in the summary. We think better protection by utilities will lessen the impact of surges. Surges were discussed as a diagnostic tool. **S. Harper**: In EPRI sponsored work, we showed a definite decrease in life for cables in accelerated AEIC type tests using three times voltage and surges as low as 40 kV.

- Surge damage is best avoided by installing adequate protection devices.

TREES AND TREE RETARDANT POLYMERS

N. Srinivas: Treeing and semiconductor migration seem more important to me than ACBD on the list of important influences for materials. **B. Bernstein**: I'm sure ac breakdown is related to treeing in wet aging. **M. Broadhurst**: Is it correct that ten years ago treeing might have been an important factor on your list and now tree resistant polymers have reduced that problem? Should a materials scientist now focus on oxidation resistance and breakdown strength to make the next improvement in cable materials? **B. Bernstein**: There are data (paper by CTL at the 1989 T&D Conference) showing that one of the newer tree retardant XLPE's doesn't tree, but still undergoes reduction of breakdown strength. For conventional XLPE there should be a relationship between treeing and breakdown strength. For discussion purposes, we now have adopted Silver's suggestion to put breakdown strength on the top for both wet and dry aging. The dry aging items are for thermally induced accelerated aging and we need to study it more. We need materials peoples input, and more information on the relationship that you described. We must distinguish between oxidation resistance and the presence of oxidation. **C. Katz**: We showed that most tree resistant polymers did show at least small trees after aging. **A. Mendelsohn**: ICC updates show data on tree retardant XLPE that is significantly better than ordinary XLPE at a comparable service age (8 years). **L. Deschamps**: What kind of tests did you use to compare the materials? **A. Mendelsohn**: Field service statistics, and various accelerated aging tests. That data can be made available. **D. Mintz**: Eight years age for the first piece of TRXLPE is too soon to know much about its service performance. The average age of TRXLPE cables is only a couple of years, and we should have virtually no failure data yet. **C. Katz**: We conducted accelerated laboratory tests 2.5 years ago, with cables made recently. All tests started at the same time, under the same conditions, using the same water, wall thicknesses and conductor sizes. We saw at least 50% improvement with TRXLPE over XLPE. We conservatively estimate the accelerated age was equivalent to at least 10 service years. **R. Schroth**: If we do accelerated cable tests on both TRXLPE and XLPE, and we know 20-years' service data for XLPE and how to extrapolate the accelerated data for XLPE; we can extrapolate the TRXLPE the same way to tell if the TRXLPE gives better results in service. **B. Bernstein**: Dielectric losses are higher in some TR polymers. Dr. Schroth, how high are the losses in cables made with the new material you talked about yesterday? **R. Schroth**: We use an additive that does not affect $\tan\delta$. Cable losses will be the same as XLPE. **G. Matey**: The losses are well below AEIC's specifications. **J. Chan**: For low-voltage and medium voltage cables, conductor losses are significantly higher than dielectric losses. For extra-high-voltage cables, the dielectric losses become significant. Oil-paper has a 0.25% power factor and polyethylene, < 0.1%, so you should be concerned about paper cables if you are concerned about losses. **J-P. Crine**: The IEEE Electrical Insulation Symposium will have a special session on water treeing in Toronto next summer. I invite you as the Technical Program Chairman.

- Tree retardant materials show significantly reduced tree growth in accelerated tests compared to XLPE.
- Continuous supply of liquid water is necessary before tree growth becomes significant.

WATER IN CABLES

D. Silver: Why didn't the questionnaire returns mention internal water? Water in the conductor is perhaps the most important factor in water treeing. **B. Bernstein**: External water was listed under wet aging and ranked high in importance. It wasn't listed in the dry aging. **[unknown]**: External water means external to the insulation, be it in the conductor or outside the cable; internal water means within the insulation. **R. Eichhorn**: Dr. Deschamps, the jackets you pointed out as becoming more popular in the US, but they are PE and not PVC. **L. Deschamps**: The US is shifting attention from lowest cost to longest service life and ease of replacement. For medium voltage polymeric cable, it's clear water has bad effects. We have to optimize the cable technology regarding particles, interfaces, new materials (e.g. tree resistent), solid conductors, and sealed conductor systems to avoid propagation of water between the semiconducting layer and the jacket. The US is evolving the technology. **C. Katz**: Permeation of moisture reduces the breakdown strength. We can remove the moisture from the insulation and restore the electric strength to 80% - 90%. **J. Chan**: What is the critical moisture for treeing and breakdown, 100 ppm, 50 ppm, 0 ppm? **D. Silver**: A steam cured cable has about 2000 ppm of water. If you don't add water to the conductor or on the outside, you don't get any significant development or propagation of water trees. Bow-tie trees can develop from the residual moisture during the factory full reel voltage test. **B. Bernstein**: If you accept dielectrophoresis as the mechanism for moisture migration to the high stress site, then the question doesn't have a practical answer because in service you have years for the moisture to migrate, and local concentrations are much different than overall concentrations of moisture. **B. Eichhorn**: I remember that Sletbak and Botne in a 1977 paper reported that 70% relative humidity was necessary to grow bow-tie trees (not vented trees) in cable insulation. **G. Matey**: Breakdown comes from a continuous supply of water, rather than any fixed moisture level in the insulation. **J-P. Crine**: The water could be local or bulk. There could be 100% water in a small void. Is the state of the water important? We only know that we need water in an electric field to get water trees. **B. Bernstein**: Are you suggesting that the water's role is to move the ions? **J-P. Crine**: No. **J. Chan**: We have done experiments with dry-cured and steam-cured cables. Steam-cured cables have 6,000 ppm moisture because of the microvoids. Dry-cured cable has 200 ppm - 300 ppm. Yet, trees grow as much in dry-cured cables as in steam-cured cables. I think that hygroscopic contaminates concentrate the moisture to high concentration while we measure only the average moisture. **S. Verne**: We tested particularly pure thermoplastic PE with a solubility of 150 ppm of water. It behaved no better than various kinds of less pure XLPE. We immersed it in water and applied a voltage. We detected treeing and the water increased to 1000 ppm. **M. Broadhurst**: Since water is so important, I think a fundamental study of the factors affecting the degree that polymers take up water would be useful. Fluoropolymers take up very little water. Could we make an economical polymer that was its own water barrier? How much extra in insulation costs would it be worth to have a waterproof polymer? **L. Deschamps**: For 40-year cable life we have to avoid water. That's why we use metallic sheaths in France, on high and medium voltage cables. The question of insulation cost involves a complete analysis including investments, replacement etc. to optimize the system. I have made estimates of cost for increased life using tree retardant polymers. (For utilities, trees are not the problem, cable life is the problem.) **W. Boone**: The statement that if you require a 40-year life, you should avoid water, goes too far. As with cars, the risk of failure generally decreases with the price of the car. But nobody will recommend a Rolls Royce as the only way to avoid problems. A metal enclosure adds substantially to the costs of the cable. I am not sure this increase in costs is really necessary. Some cables lie in water for 15 to 20 years without trees or failures. **L. Deschamps**: From the data shown yesterday, the rate of failure of medium voltage cable installed without protection against water increases rapidly with time. **W. Boone**: I am saying that new tree retardant materials are being developed and tested and not all the data are available yet, but this solution could become a very interesting alternative to the metal enclosure, particularly from an economic point of view. **D. Silver**: The statistics on XLPE are for 20-year-old cables without effective water exclusion. A Japanese paper showed that a 15°C - 20°C temperature gradient impedes the ingress of water. With a PE jacket, no water in the conductor, and tree retardants, we should be able to get 40-year life without doubling the cost of the cable by adding a metallic moisture barrier. We already have conventional XLPE cables in service now for 27 years. **J. Moran**: The cost of a lead sheath or laminar barrier does not double the cost of the cable. It is more like 5% - 10%. **D. Silver**: At the ICC Meeting, lead foil laminate was reported to add 100% to the cost of a 1/0 AWG aluminum 35 kV cable and 50% to the cost of a 1000 kV/mil aluminum 35 kV cable. For more expensive transmission cables the lead sheath will add a lower percentage.

- Liquid water in cables is a major source of failure in XLPE.
- PE jackets, semiconducting layers and care to exclude the ingress of water during manufacture and installation significantly reduce water related damage.
- Water tree retardant materials have significantly better performance in accelerated wet aging tests than does ordinary polyethylene-based insulation.
- Indications are that service performance of TR materials will be better than ordinary polyethylene-based insulation.

- Metal sheaths add a significant fraction to the cost of a cable.
- Careful cost and performance analysis is needed to evaluate the relative merits of new materials and structures such as metal sheaths and TR polymers.

WEIBULL STATISTICS

B. Eichhorn: We should reevaluate the use of Weibull statistics because the very early failures of concern in the field rarely lie on the Weibull line determined from most of the data. **J-P. Crine**: I support Eichhorn's view that one never sees data in a straight line on a Weibull plot. Shouldn't we abandon Weibull statistics in favor of something else to predict cable lifetime? **J. Densley**: Some data lie on very good straight lines on Weibull plots. These data are being used successfully by the Japanese and French to successfully design cables. Maybe slope changes indicate a need to control parameters better. **L. Deschamps**: Use of the Weibull law requires a very well defined material without changes by external influence. A metal sheath around the cable avoids modification of the material. In France we use this law for pure PE material with good correlation between tests on materials, tests on cables and failure rates. If you change the population it won't work. **S. Verne**: In many cases early failures do not lie on the Weibull line. We have the resistance of the material 1) under general conditions and 2) with concentrated stresses (as are found near defects). Concentrated stress effects tend not to show up in Weibull statistics because of their infrequent occurrence in test samples. **J. Chan**: We did a 10-yr or 15-yr analysis of breakdown failures using Weibull statistics to determine the 63% lifetime of the cable. A 15-kV cable had a lifetime of around 12 years. Doubling that lifetime still doesn't give 30 years.

- Weibull statistics are mathematically correct and experimentally valid under controlled conditions.
- In many practical applications data do not fall on a straight line Weibull plot.
- It is sometime difficult to distinguish between changes in a material due to changing conditions (like ingress of water) and aging (like the presence of large trees).

SUMMARY BY WORKING GROUP CHAIRMEN

R. Samm: Has anybody come here and changed their mind? Have we just reinforced our attitudes and opinions? Should we do this again in a year or two? I call on the working group chairman for final comments.

B. Bernstein

1) EPRI has a number of projects that we haven't mentioned. Two major projects are designed to compare service aging and lab aging. I hope as a result of this workshop we will have a project on dry aging. 2) Ongoing projects at Georgia Power and Detroit Edison are showing that we can't definitively relate ac breakdown strength to aging especially with applied transients. I now think we need a better summary of potential benefits and limitations of newer diagnostics. We need better communications between technical disciplines in this area, both for materials and cable evaluation. We may be able to use different diagnostic approaches for different wet and dry agings. We need to distinguish between 1) manufacturing imperfections appropriately diagnosed by applying high withstand stresses and 2) aging-induced imperfections in the insulation that were the focus of my working group. We need better clarification of the whole subject of morphology. We need to clarify apparent differences between the European results as described by L. Deschamps and US results that I know about. I think there is a problem with thermal overload and morphology. There is some merit to both 90°C and 130°C maximum thermal overload temperature, but some valid questions need answers if one talks about 105°C. We should examine Dr. Boone's longest tree determination, and seek to relate it to dielectric strength and power factor. The AEIC accelerated test procedure makes dry-cured cable look like steam-cured cable. We must carefully define how XLPE has been laboratory aged before interpreting dry-cured cable data. We must also be careful that accelerated aging tests do not make a material look better than it will prove to be in the real world. I'm aware that for conventional URD construction, 15-kV, 175-mil-wall, standard shield wall thicknesses, that the film foil barrier increases the cost by 50% to 100% in the US, but my understanding is that there is room for improvement here. I thank my secretary, John Tanaka, for his excellent job as secretary of my working group.

John Densley

I think this has been worthwhile, and I hope JICABLE, EPRI and CEA will fund another workshop. It's good for experts from different continents with different philosophies on aging and on testing to exchange and communicate ideas. It is essential in order for us to advance the state of the art. For conclusions, I think that we definitely need an accelerated aging test to evaluate the large numbers of new insulations and semicons and combinations. I think some possible diagnostic techniques were rated low in the questionnaire because of lack of knowledge rather than lack of merit. For example, space charge measurements have developed greatly in recent years and should be very seriously considered for both wet and dry insulation systems. We need a good system to collect failure statistics, to help develop accelerated aging tests. A good in-situ diagnostic test is needed. Harry Orton did an excellent job as my secretary. He made my job a lot easier last night and I just wish to thank him.

L. Deschamps

I wish also to thank my secretary, Pierre DeJean. I think this kind of exchange is very fruitful. We obtained, these two days, a lot of information on the aging of cables. One objective of our work was to answer the question: Is our present knowledge sufficient to optimize cables in terms of long life, reduction of costs and good reliability? 1) For medium voltage cables under wet conditions, we have seen some utilities go to water-tight systems. Today there are new developments in the insulation, interfaces and water tree retardant materials, and new technology for voids control and inhibition of water penetration. These developments have a cost and the decision as to whether or not to use water tight sheaths will depend on which is the most economic system with good reliability. To do this evaluation, we need more functional standards. 2) For very-high-voltage cables, we have good procedures to eliminate early failures. Because these cables show no property changes in service we are considering increasing the operating stress. We have discussed possible problems with this action, like generation of new defects. Increasing the stress on VHV cables is too important a decision for our working group. Once more, I thank Ralph Samm very much for the organizing of this workshop.

R. Samm

Some experiences which were not entirely pleasurable are significant in that you can say, 'I was there and I survived.' One example is the recent earthquake. It was not a pleasure, but at least I do have the unique distinction of saying I was there and I survived. I believe this has been a very fruitful and beneficial workshop and I think you've all had the pleasure of being here. Not only that, I think you have the distinction of being able to say that last night you had the toughest duck ever served, and you survived!

I would like to thank Mr. Bernstein, Dr. Densley, Mr. Deschamps, Dr. Broadhurst, Dr. Kelley and Ms. Farrell for all they've done for the workshop and above all, I would like to thank you, the attendees and the workers for all your suggestions, help and hard work. We intend to send each of you a copy of the proceedings in the first quarter of next year. And without further ado, thank you.

Section 5a

AGING - LIFE PREDICTIONS

by T. DAKIN

Dr. Dakin died on April 1, 1990, at his home in Florida. His technical contributions to understanding the nature and behavior of electrical insulation have been outstanding and guide much of the work of those who followed him. We are fortunate to have had his leadership in this field, and will miss his participation. An obituary can be found in Electrical Insulation Magazine.

Dr. Dakin reported on his extensive experience with aging tests and life time prediction. He pointed out the importance to Westinghouse of lifetime prediction to assure customer confidence and maintain a reputation of quality. He discussed three different areas: long term outdoor environmental testing, accelerated indoor salt fog testing and thermal testing.

Outdoor tests were conducted by exposing insulators to outdoor environments at test sites in different parts of the country. Data gathered outside the Westinghouse laboratory, where sample condition and aging events could be continually monitored, were especially important in obtaining experience with the service performance of insulators. These tests were done on bushings, pot heads, disconnect switches and similar components, made of cast epoxy and polyester. There was no good way found to extrapolate the environmental results at short times to longer times.

For partial discharges, the arcing that occurred intermittently outdoors could be made to occur continuously in an indoor salt-fog chamber. The salt-fog testing showed how well a component would withstand the erosive effects of arcing on the material surface. No organic material would survive continuous surface arcing. Organics that carbonized under arcing conditions were not used as insulators. Other materials etched at various rates. The solution to the arcing problem was to design the components to avoid arcing. Such tests were performed on films of materials used for capacitor dielectrics. (Westinghouse did not make cables. Capacitor and cable dielectrics share similar problems.)

Thermal life tests were done by measuring lifetime at several relatively high temperatures and extrapolating to longer lifetimes at lower temperatures using the

Arrhenius equation. These extrapolations were successfully done and the method was used with confidence world wide.

DISCUSSIONS

E. Brancato: Are thermal aging extrapolations under control because we know their basis in chemical laws? **T.D.**: Yes, they are pretty reliable. **E.B.**: Is salt-fog testing reasonably reliable? **T.D.**: Yes. **E.B.**: But how to accelerate voltage aging is still in question? **T.D.**: Yes. But we can accelerate partial discharge and tracking tests. **E.B.**: Apart from partial discharges and tracking, are there other mechanisms of voltage aging (in the laboratory)? **T.D.**: Yes. For dc stress, one gets electrolysis. DC stress is important in capacitors. **J. Tanaka**: The Arrhenius equation can be derived from physical mechanisms. Does it still apply if the system is not at thermal equilibrium? And have you applied statistical methods to partial discharge aging tests? **T.D.**: For engineering, I think the statistical approach is alright, but as a scientist, I want to know something about the mechanism and its rate of change with temperature and time. **M. Broadhurst**: For salt-fog tests, does the total number of arcs or the total current in arcing determine the lifetime? **T.D.**: It's the total amount of arcing, provided the mechanism does not change. **M. Broadhurst**: Did you use numbers and actually test it? **T.D.**: We were doing this sort of thing. It's simple because the leakage current is usually low, and could determine how much arcing we had on insulators outdoors and also in salt-fog tests. **N. Srinivas**: I agree we partially understand aging in electrical equipment in general, but mechanisms in cables are not understood.

Section 5b

AGING OF SOLID ELECTRICAL INSULATIONS

by R. EICHHORN

One of the earliest accounts of the installation of underground cable which I have heard, was presented by Earl Hazen after he had retired from Simplex and become the Eastern Editor of T & D Magazine. He attributes the story to Theodore O. Rudd, Chairman of the Kerite Company, who recounted it during a review of the first century of cable making in the United States. "The first telegraph lines between Philadelphia and Baltimore were laid in 1846. One of them consisted of a single iron wire and the specifications directed that the wire be insulated with tar. In conformance with the specification, a workman was hired to carry a bucket of tar, slung to his side and with the aid of a monster sponge to tar the wire. The foreman reported that the worker got as far as Wilmington, Del. when the tar proved too much for him. He went to sleep and never woke. We buried him there. After that the record ceases, history does not record the fate of that particular cable."

An incomplete list of the dielectrics which have been used for the electrical insulation of power and communication cables is presented in the Figure 5b-1. The first ten materials listed are by no means all replaced by newer ones in commercial practice. Some are still used in certain applications where they have special advantages. This situation illustrates the fact that there is no one material which is best for all electrical insulation applications. Each has advantages which are unique and fit it for certain uses.

The material with the best overall combination of physical, chemical and electrical properties is pure thermoplastic polyethylene. With polyethylene as a starting point many other materials are adapted, each by emphasizing or exaggerating one of polyethylenes properties. Thus many other polyolefins, polar and nonpolar copolymers, blends and filled materials have been developed each with one or possibly two advantages over polyethylene and all others. This is seen by the disappearance of polyethylene as a power cable insulation. However it is extremely important to understand that this game of formulation is really based upon compromise. To emphasize or improve any one property of the basic polymer always requires sacrifice of others. The greater the improvement, the greater the

TAR
GUTTA PERCHA, BALATA 1881
BITUMIN
FABRICS PLAIN, WAX, OIL, Pb Jacket
RUBBER ALWAYS THE UNIVERSAL GOAL
NEOPRENE
PVC GERMANY 1927
POLYISOBUTYLENE
BUTYL RUBBER
CHLOROPRENE 1931

POLYTHENE 1933, REPLACED PVC ABOUT 1960
1934 - 1936 800 NEW ORGANICS FOR INSULATIONS
EPR, EPDM
XLPE
SILICONE RUBBER 1945
CHLOROSULFONATED PE 1950
TR XLPE 1979
SILANE CROSSLINKED POLYOLEFINS (HOH CURE)
LLDPE
FLEXOMERS ρ = 0.88 - 0.915

Figure 5b-1. Electrical insulating materials for use in cables.

sacrifice. For example, even the chemical crosslinking of polyethylene, shown in Figure 5b-2, which is a minor change, decreases the electrical breakdown strength and increases dissipation factor. Greater changes such as copolymerization or introduction of polarity can improve flexibility and the ability to hold fillers but these changes result in more serious degradation of physical, chemical and

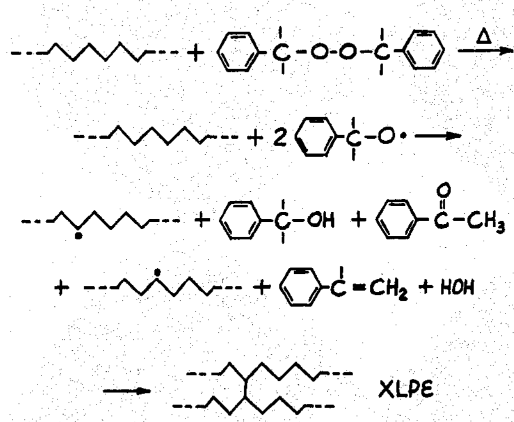


Figure 5b-2. Peroxide crosslinking of polyethylene to make XLPE.

electrical properties, for example elongation, toughness, oxidation resistance, chemical stability, electrical breakdown strength, impulse strength and dielectric losses.

In recent years the pace of improvement in insulations has increased substantially and new materials are appearing at an increasing rate. This is partially due to observations of early failures in some direct buried cables made many years ago before the importance of purity, jackets, smooth interfaces, strand fillers, and tree resistance were appreciated. In fairness however, it must be remembered that there are many cables insulated with thermoplastic polyethylene still in service after twenty or more years and most of the early failures can be traced to certain makers and certain years of manufacture. In Europe, where the same materials were used but quality was more important than price, the experience with early polyethylenes was very good. In France the shift to crosslinked polyethylene is only recently underway and other European countries use crosslinked polyethylene but not because of dissatisfaction with the thermoplastic material. A similar situation existed with ethylene-propylene insulations when they were new. The occurrence of failures due to voids and cavities limited application for many years and caused the first high-voltage EPR insulated cable tested at Waltz Mill to blow up. The

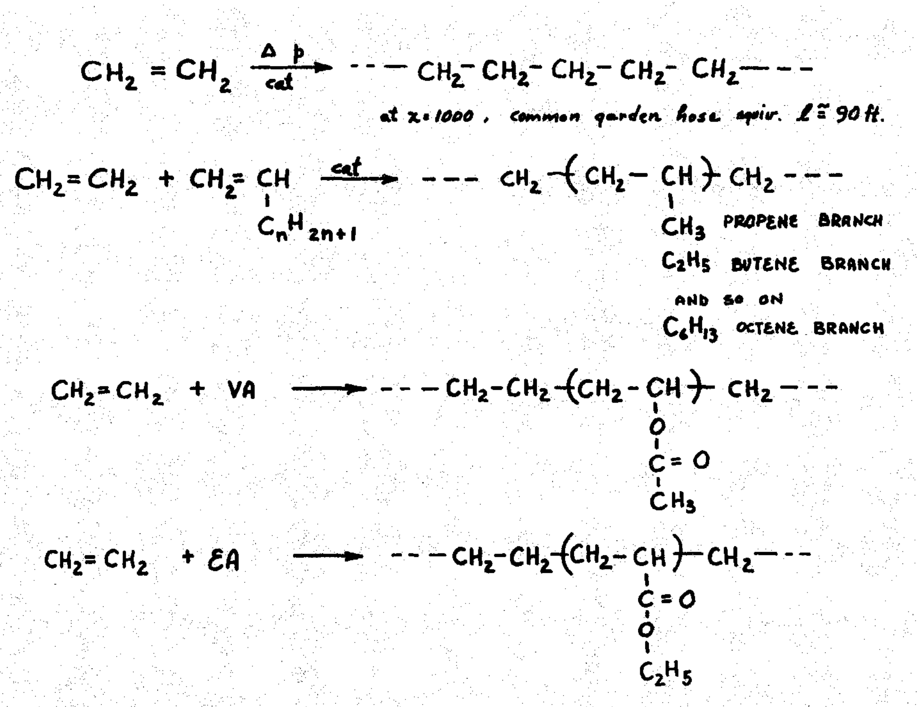


Figure 5b-3. Chemical structures and polymerization reactions of a few common resins that are important to polymer insulated power cables.

discovery that surface treatment is required to make the several components compatible was the improvement which made these materials practical and commercial.

Figure 5b-3 shows the structures in approximate schematic form of a few common resins which are not new but perhaps not familiar. The first shows polymethylene or an unbranched section of a polyethylene molecule. Conventional polyethylene made in a high pressure and high temperature reactor contains many branches of varying lengths on the backbone chain. High density polyethylene made with any of several catalysts has the unbranched structure shown. The second structure is typical of EPR where the methyl branches appear randomly along the chain. The new materials called LLDPE are of the second type and are available from two suppliers, UCC and DOW although the two materials are prepared by quite different methods. Flexomers are a new class of materials which can be made with any of the side chains shown or combinations. The range of properties in these materials is extensive. The last two structures show polar copolymers which are not new but are often used as the base for semiconductive shield materials. They are not too good for insulation

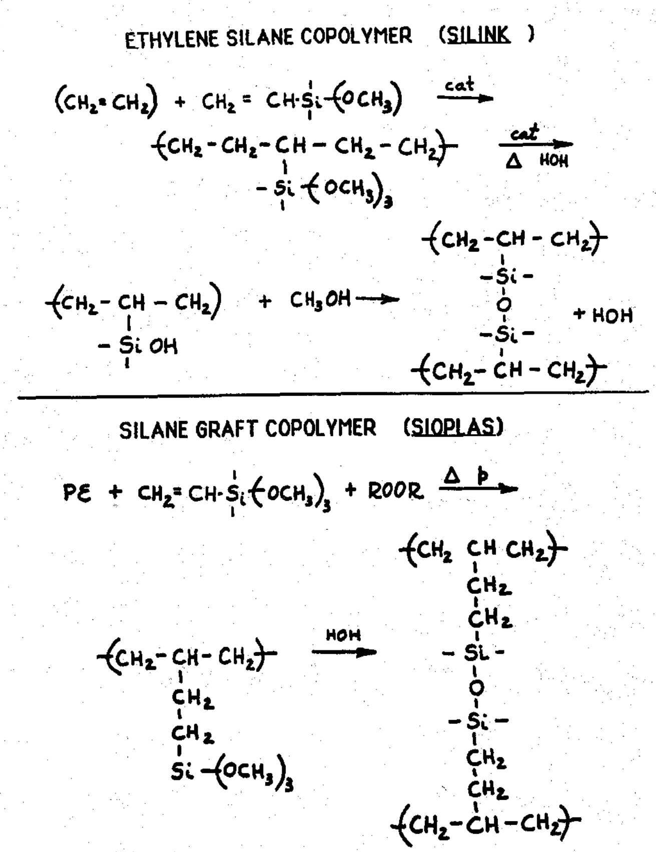


Figure 5b-4. Two variations of polymers that are crosslinked with a silane and water.

because their polarity renders them electrically lossy and susceptible to oxidation. A new class of polymers which has been accepted in Europe are crosslinked by use of a silane and water. The formation of two variations is shown in Figure 5b-4. The first is a silane copolymer in which the vinyl silane becomes part of the main chain; the second is a silane graft copolymer in which the vinyl silane grafts to the main chain as a branch. The differences between these materials is that while the latter crosslinks more rapidly it has a limited shelf life. It can crosslink before use if unreacted peroxide and silane remain. Another technique called Monosil is a process for charging polyethylene, silane, peroxide and catalyst to a special extruder and making a Sioplas in one step.

Papers on the aging of electrical insulations have not changed very much since the one by Kiss, Doepken, Srinivas and Bernstein (1) which was presented at the Symposium on Durability Of Macromolecular Materials in Miami in 1978. As Kiss, et al. said in their paper "Aging and lifetime are terms based upon biological analogies, and, though widely used, describe the investigated phenomena with limited accuracy." Kelen suggested the term "endurance" which may be better. In either case it is reasonable to assume that the lifetime of a cable commences when it is put into service, first exposed to the conditions which will eventually lead to its failure. Included among these conditions are the presence of contaminants, highly divergent stresses, water and impulses and they are due to imperfections in cable construction, materials used, and the conditions of installation and operation.

Looking deeper into the phenomenon of aging, in search of mechanisms and explanations, we find a common observation in recent work, that is either electrical or water treeing, sometimes both. The response to this observation varies with the background of the observer and sometimes with the amount of experience he has with the problem. Responses following the observation of trees may be tabulated as follows:

- After the observation of trees, count and measure the trees and attempt correlations with other variables.
- Since the mechanism of organic degradation is oxidation, measure it and attempt the correlation of oxidation with treeing.
- Consider first things first, measure and correlate functional properties with aging.

In the tree counts which are usually done, distributions of tree populations in several size ranges for both vented and bow-tie trees are most common. Considerably less time consuming are the estimation of average and maximum tree

$$RH \rightarrow R\cdot + H\cdot$$
$$R\cdot + O_2 \rightarrow ROO\cdot$$
$$ROOH \rightarrow RO\cdot + OH\cdot$$

$$ROO\cdot + R'H \rightarrow ROOH + R'\cdot$$
$$RO\cdot + R'H \rightarrow ROH + R'\cdot$$
$$OH\cdot + R'H \rightarrow R'\cdot + HOH$$
$$R'\cdot + O_2 \rightarrow R'OO\cdot$$
$$ROOH \rightarrow RO\cdot + OH\cdot$$
$$2\ ROOH \rightarrow RO\cdot + ROO\cdot + HOH$$

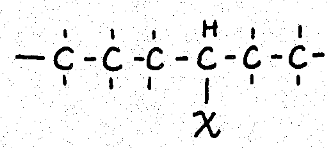


Figure 5b-5. The oxidation
process in a polymer.

sizes in a given specimen. Correlation is usually with the age of a laboratory specimen or the service life of a real failed cable. Oxidation of long-chain organic molecules usually commences with an attack upon a tertiary carbon and abstraction of its H atom, as shown in Figure 5b-5. This can be done in various ways but the most common result is chain scission and it represents the first step in degradation. After the first event the reaction has many varieties, liberates a range of low molecular weight materials and is autocatalytic so that it accelerates with time. However oxidation is not a rapid reaction in underground insulations because the concentration of oxygen is limited and an antioxidant is always used to postpone its onset. A subject of real interest is the observation of visible or ultraviolet light emission from dielectrics under electrical stress. Papers by Nitta (2) (3) report emission of light from specimens during water-tree growth. This has been used, by Dakin (4) as well as Nitta, as evidence to suggest the possibility of undetectably low levels of partial discharge. The emission of light during water treeing from exactly the same locations where the water trees grow has been reported by Tanaka (3) et al., and they consider electroluminescence or chemiluminescence as well as partial discharge as a possible cause. Certainly oxyluminescence has been shown to be a real effect in polyolefins. On the other hand using more modern equipment, Densley et al. have tried unsuccessfully to observe light emission which could not be explained as an artifact of the experimental technique. A definitive experiment which answers the question about the origin of the light would be most helpful at this point in our investigations. We need to know whether oxidation is required as a precursor to water tree growth or if it accompanies the tree growth.

Certainly we do know that oxidation occurs on the inside of the water tree cavities and channels. One of the first observations of water treeing was that water trees could disappear visually after removal of the electric stress and water supply only to reappear after soaking in warm water for a few hours. This indicates that in polyolefins the original hydrophobic nature of the material has changed or refilling of small channels would never be possible. The most likely explanation is oxidation and this conclusion has been analytically verified.

If aging of insulations is considered in the narrower context of high-voltage cables, we find much less information available and our knowledge more shallow. Most high-voltage cables are protected against the ingress of water so that water treeing is not a serious problem unless leaks occur at joints, connectors or the sheath. If this occurs the problem is serious since the operating stresses are higher than in distribution cables. It is of interest, however, that the first application of PE, in the days of rudimentary, low-temperature, low-pressure extruders, was for insulation of a short submarine cable.

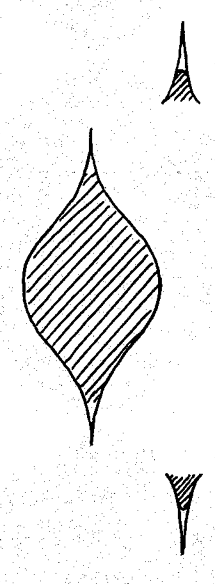


Figure 5b-6. A partially water-filled void in a polymer showing gas trapped in the tip of the void.

Probably the most important problems which could lead to premature failures in high voltage cables are the presence of contaminants, voids, protrusions from the semicon shields into the insulation, high power factor and overloading. A partially gas-filled void is pictured in Figure 5b-6. The reasons are that at higher operating stress, a stress enhancement due to contaminant or interface roughness could generate more stress than in a medium voltage insulation. This could initiate electrical trees which lead to failure more rapidly than water trees do. Also if the power factor is high, tree-type failures can grow as a result of localized overheating within the tree. Gas-filled voids are under greater stress than the surrounding solid material and the breakdown strength is lower. Therefore, discharging can commence when the Paschen conditions are fulfilled.

Aging of electrical insulations is not a simple subject. It has been studied for years and hopefully the information which is discovered now is that which will lead to understanding rather than just lead to more questions. In either case there is much more work to be done before the ultimate insulation is produced and validated, if in fact that is possible.

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2. Y. Nitta, S. Suzuki, Y. Takahashi, Y. Kawasaki, S. Tanaguchi, Y. Suzuki, "Water Tree Resistive Polymer Blend" IEEE Trans., Vol. EI-9, No. 3, 1974, p109.

3. T. Tanaka, T. Fukada, S. Suzuki, Y. Nitta, H. Gotoh, K. Kubota, IEEE Trans., Vol. PAS-93, No. 2, 1974, p 693.

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DISCUSSION

S. Verne: Thank you for an excellent presentation. Your comprehensive list of materials did not include impregnated paper. Impregnated paper has proved outstandingly successful, and oil-paper cables which have been in service for 50 years do not need replacement. There is an analogy between this historic experience and filled polymer insulation called EPR. EPR cables may perform very well and may exceed PE in just one or two properties. You mentioned that EPR cables blew up at Waltz Mill, but there are many EPR cables in service which haven't blown up. **R.E.:** I think EPR is a good practical dielectric material with a few unique advantages over PE. The thing I like about paper is there is no decrease in dielectric strength as the dielectric section increases. However this symposium was planned to cover solid dielectrics only. **E. Favrie**: I agree that impregnated paper gives good service, but it is possible to obtain very good results with polymer insulated cable. It depends on the quality of the material. It is now possible to have very good material. Three other important factors are: the design of the cable, and the process for manufacturing the cable, and the environmental conditions of the cable. In France, we find cables with a water barrier have given very good high-voltage service for 27 years. **C. Katz**: I'd like to emphasize that Mr. Verne is correct that paper cable has lasted in excess of 50 years. We tend to overlook that polymeric cables are not protected from the environment. Once moisture is removed, I'm quite sure that those cables will last significantly longer than we are accustomed to these days.

Section 5c

CABLES/ACCESSORIES

L. Deschamps

The dictionary defines aging as the action of growing old, the changes that happen as time passes and the action of allowing or causing these changes. In this workshop, we are concerned with materials, cables and cable structures. The three most important materials are thermoplastic polyethylene, cross linked polyethylene and ethylene propylene rubbers (EPRs). Cables are subdivided into MV ($\leq$ 5 kV/mm), HV (5 kV/mm $<$ E $<$ 10 kV/mm) and VHV and EHV ($\geq$ 10 kV). The cable structure of primary concern is whether or not the cable is waterproof. Aging factors can be internal or external. Internal factors include processing conditions, insulation morphology, type of semiconducting layer, moisture barriers, strand fill, adhesion, interfaces, residual byproducts, strains and moisture, contaminants in the semiconductor and insulation, level and frequency of electrical stress, temperature, temperature gradients, temperature cycling profile, oxidation and partial discharges. External factors include damaged insulation and faulty joints, mechanical aggression, water penetration, contamination and local heating.

Aging mechanisms that can work together or separately include thermal, dielectric, mechanical and thermomechanical and corrosion. Aging phenomena are complex and require three types of tests. These are tests on materials, laboratory tests on cable samples and long term full scale tests involving simultaneous electrical, thermal and mechanical stresses.

THERMAL AGING

Thermal aging results from oxidation of the carbon chains which may induce an increase in dielectric losses and a drop in mechanical characteristics. An Arrhenius type law is usually applied to thermal aging. According to I.E.C. Publication 216, the lifetime L at a given absolute temperature, T, is

$$\text{Log } L = A + E/RT, \qquad (5c\text{-}1)$$

where A is a constant, R = 8.314 J/molK is the perfect gas constant and E is the experimental activation energy (100 kJ - 130 kJ). An example of the application of this equation to XLPE aged at various temperatures and using a 20% decrease in the initial elongation to break as the end of life criterion is shown in Figure 5c-1.

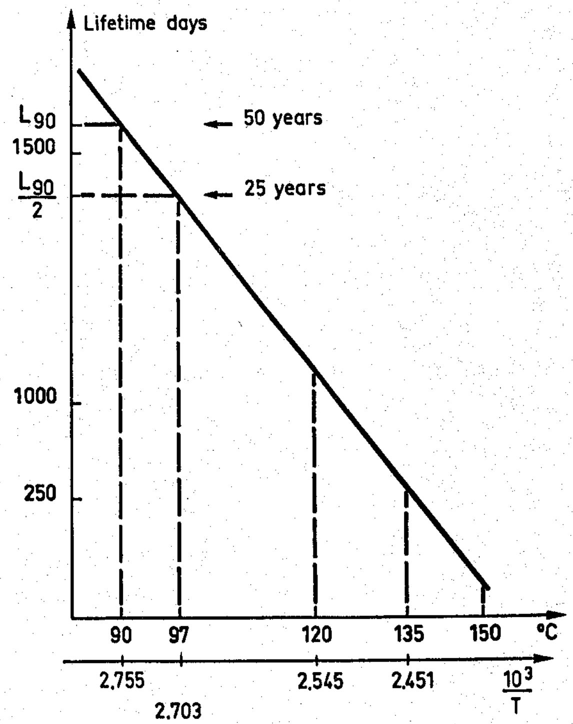


Figure 5c-1. Lifetime for thermal aging of XLPE at various temperatures. This data gives A = 11.47, E/k = 5730 for the constants in Eq. 5c-1.

Figures 5c-2 to 5c-4 show the effects of thermal aging on variations with time of elongation to break and tensile modulus at 100°C, 110°C and 135°C and loss tangent at 135°C. These data are presented for a variety of samples from different manufacturers. It is apparent that there is a wide variation in the properties and aging behavior of the materials tested. The complexity of the phenomena involved reveals the difficulty of extrapolating the results obtained at a high temperature to lower temperatures. However, the general behavior observed can be summarized in terms of four time zones of aging. In zone I, materials tests show the material is improving, and we interpret this as the elimination of polar crosslinking residues. During zone II, the material is not changing due to high efficiency of the antioxidant. During zone III the antioxidant provides only partial protection, and the material starts to degrade. Finally, in zone IV, the antioxidant is fully consumed and loss of desirable properties accelerates. These aging zones are

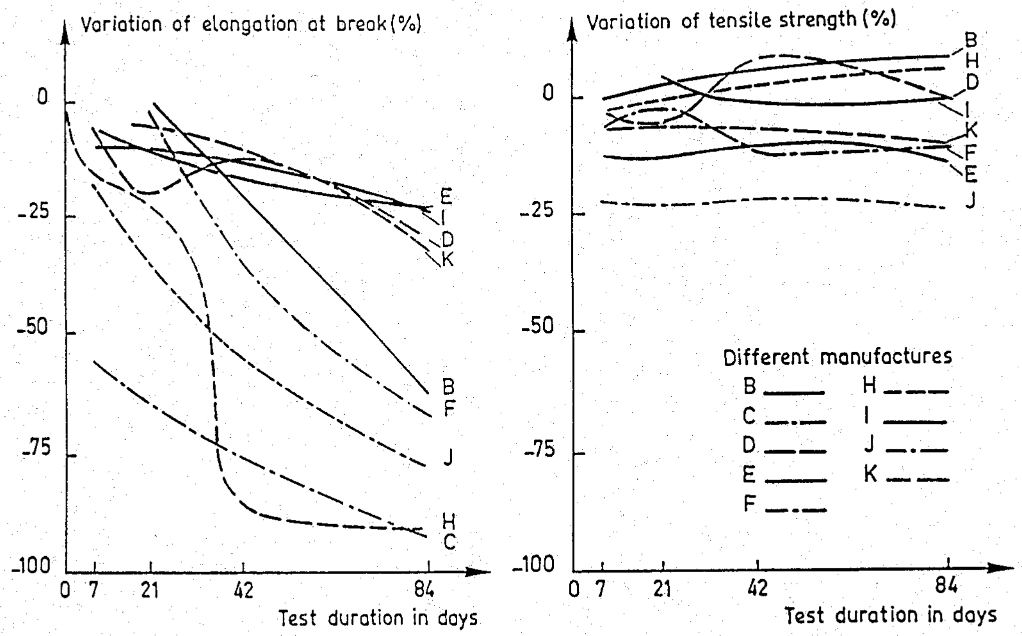


Figure 5c-2. Variation of mechanical properties of XLPE with time at 100°C for a variety of samples from different manufacturers.

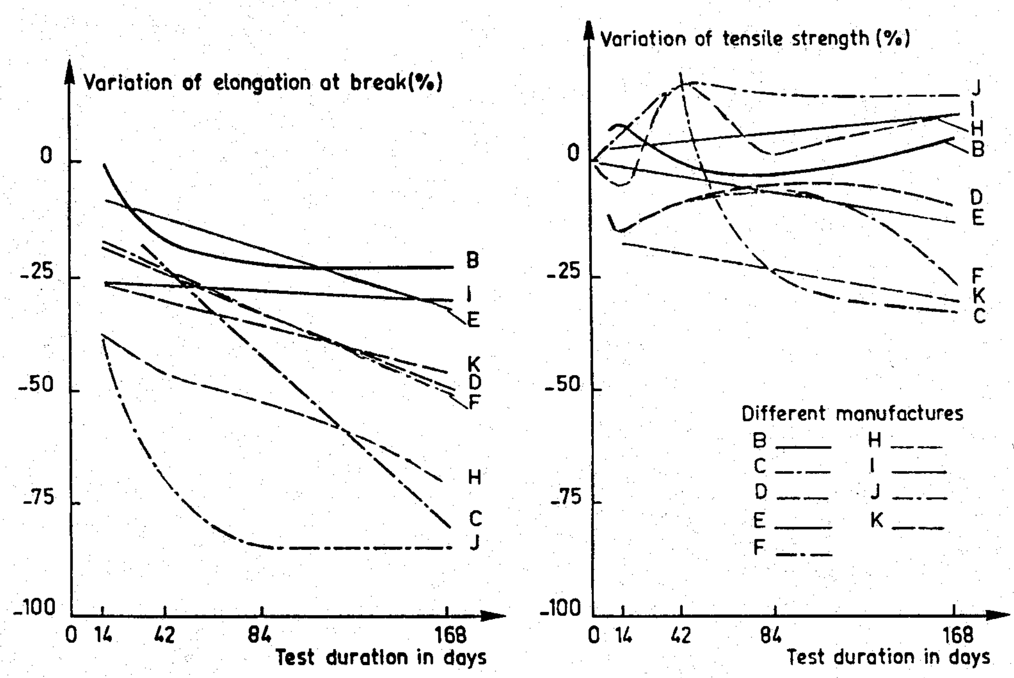


Figure 5c-3. Variation of mechanical properties of XLPE with time at 110°C for a variety of samples from different manufacturers.

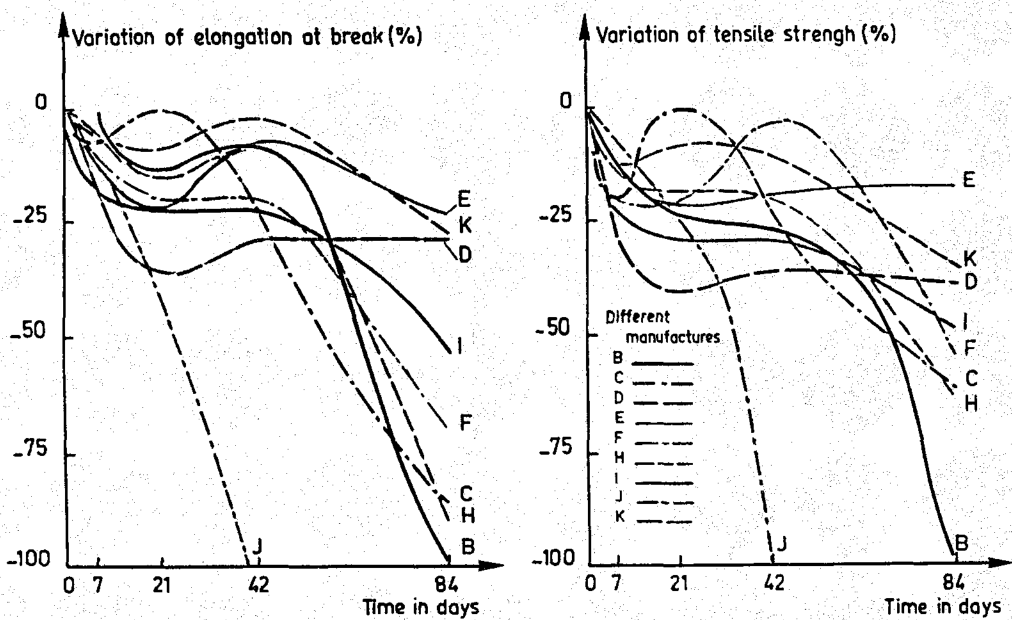


Figure 5c-4. Variation of mechanical properties of XLPE with time at 135°C for a variety of samples from different manufacturers.

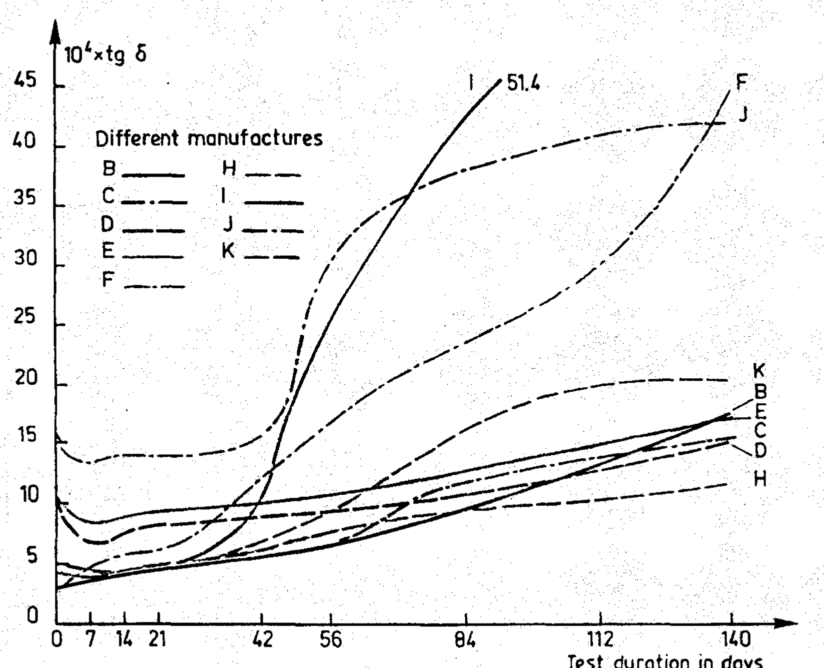


Figure 5c-5. Variation of dielectric loss tangent of XLPE with time at 135°C for a variety of samples from different manufacturers.

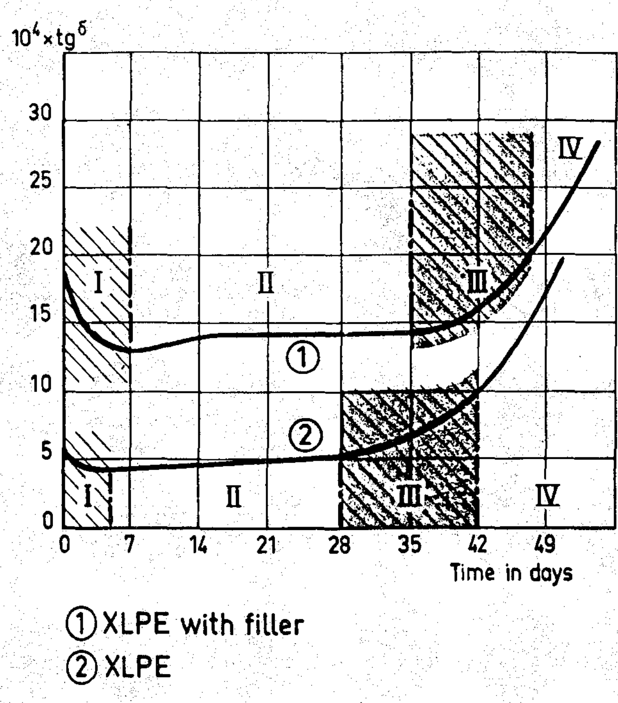


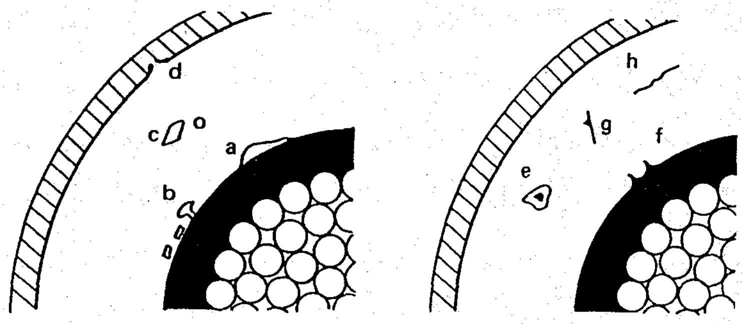
Figure 5c-6. Dielectric loss tangent of XLPE with time at 135°C, showing the four zones of aging.

illustrated schematically in Figure 5c-5.

Long-duration aging tests permit the integration of electrical, thermal and thermomechanical aging. The advantages of this kind of test are threefold. They evaluate diverse installation and mounting constraints. They simultaneously test the cable and its accessories. And they check the performance of the cable and its accessories under overload conditions in terms of both thermal and thermomechanical performance. An example of a set of test conditions for a long term aging test for 20-kV cables are the following. A 35-m loop of cable is buried directly in the ground, 80 cm deep. Twice the normal voltage (40 kV phase to phase) is applied for 5000 h and the temperature is cycled from 8 h heating to 16 h cooling. 125 of these heating cycles are done with the conductor at 100°C and 85 are done with the conductor at 120°C.

DIELECTRIC AGING

The intrinsic dielectric strength of PE and XLPE is probably greater than 1000 kV/mm. This intrinsic strength is reduced by the presence of impurities, voids and water in the material. Some examples of such defects are shown in the schematic cross section of cable in Figure 5c-7.



a) loose semi-conductive screen,
b) bubbles caused by gas-evolution in the conductive screen,
c) cavities due to shrinkage or gas-formation in insulation,
d) defects in the core-screen,
e) inclusion of foreign particles that separate gases,
f) projections or points on the semi-conductive screen,
g) splinters and
h) fibers.

Figure 5c-7. Cross section of a cable containing a variety of identified defects of the type that lower the breakdown strength of the cable.

The homogeneous nature of extruded insulation causes impurities to have a greater influence in extruded cables than they have in cables with tape-type insulation. A statistical approach has therefore been adopted for assessing the dielectric quality of these materials. This approach is based on the following four assumptions, all of which have been confirmed experimentally. 1) Insulation protected by a water-tight sheath does not undergo any modification due to external influences (particularly humidity) during the life of the cable. 2) Breakdown is a phenomena characterized by a random variable in three dimensions: the time t to failure, the electric stress and the volume of material submitted to the electric field. 3) Breakdown originates in a very small domain of the insulation. This microscopic rupture leads to failure through the entire thickness of insulation. 4) The law of cumulated probability of failure, p(t), at time t, voltage V, and for cable length L, follows the generalized Weibull law:

$$p(t) = 1 - \exp\left[-(t/t_o)^a (V/V_o)^b (L/L_o)\right], \qquad (5c\text{-}2)$$

where a and b are the time and voltage scattering parameters respectively. For a given probability of failure we obtain the following lifetime law:

$$t/t_o = (V/V_o)^{b/a} = (V/V_o)^n, \qquad (5c\text{-}3)$$

where the larger the value of n the greater the lifetime. Eq. 5c-3 is shown graphically in Figure 5c-8.

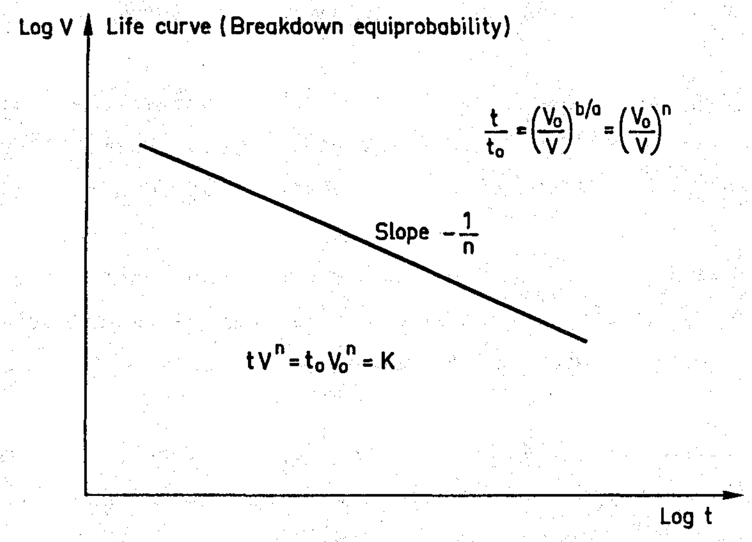


Figure 5c-8. Plot of the life curve given by Eq. 5c-3.

A plot of failure rate as a function of time is shown in Figure 5c-9. This Figure shows three different regions of failure.

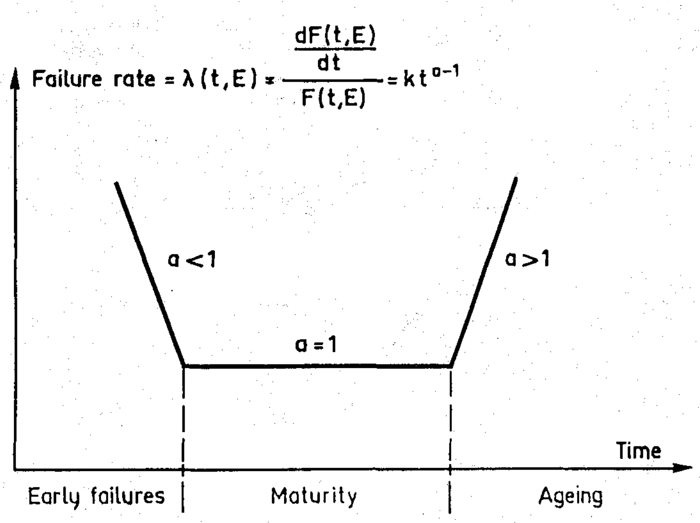


Figure 5c-9. Failure rate as a function of dielectric ageing time.

Trees play the major role in dielectric aging. The two types of trees are electrical and water trees, and the three stages in the development of trees are incubation, propagation and breakdown.

Electrical trees propagate with a channel diameter of approximately 100 μ, and exhibit light emission due to partial discharges. Electrical trees are bush type if the local field is greater than 1000 kV/mm, and branched if the local field is less than 1000 kV/mm. If the median field is greater than 4 kV/mm, electrical trees grow at about 10 μm/min, the partial discharges contain some hundreds of picocoulombs of charge and breakdown occurs as soon as the tree connects the two electrodes. If the median field is less than 4 kV/mm then the growth is not continuous, a few picocoulombs of charge are contained in a partial discharge and breakdown occurs some hours after the electrodes are connected by the tree.

Water trees incubate at impurities due to the high local fields. Incubation depends on the quantity of water present. Water trees propagate by non interconnected microvoids partially filled with water. Water tree shapes include bow-tie, tree and bush shapes. They do not exhibit partial discharges, and they propagate such that their length is proportional to some power, n, of time. Usually n is between 0.2 and 0.5. The mechanisms of water treeing involve electromechanical forces, diffusion of water and chemical action including oxidation. While water trees do not lead automatically to breakdown, they do lead to degradation of the insulation, possibly due to partial discharges in the partially-water-filled voids. In HV

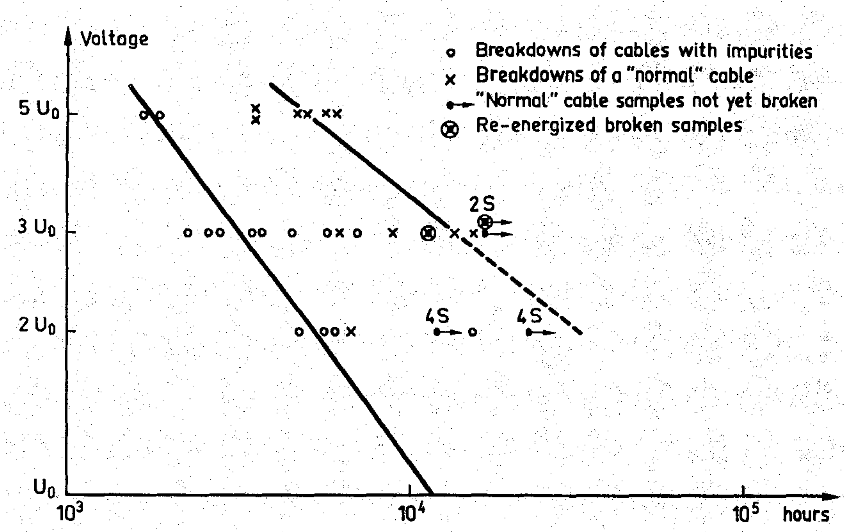


Figure 5c-10. Life durations versus testing voltage of 20-kV cables, the conductors of which are filled with water.

cables, bow-tie trees of 10 μm - 15 μm in size pose no danger to the operation of the cable while trees growing some hundreds of μm from the insulation/semiconductor interface do pose danger. Figure 5c-10 shows the results of life tests on 20-kV cables where the conductor is filled with water.

MECHANICAL AND THERMOMECHANICAL AGEING

Mechanical tests are carried out on dumb-bell samples with a spacing between jaws of 50 mm, at a tension rate of 2 mm/min for a time of 2 minutes. These conditions correspond to nearly 100% elongation for the narrow part. The sample is then held stretched for 60 min. The modulus at 10% elongation equals ten times the stress at 2 min. of test. Figure 5c-11 shows a test bar, and Figure 5c-12 shows the stress

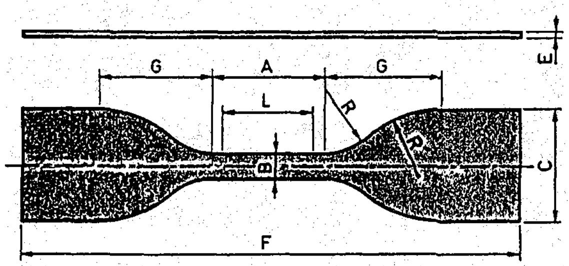


Figure 5c-11. A test bar for mechanical testing of insulation.

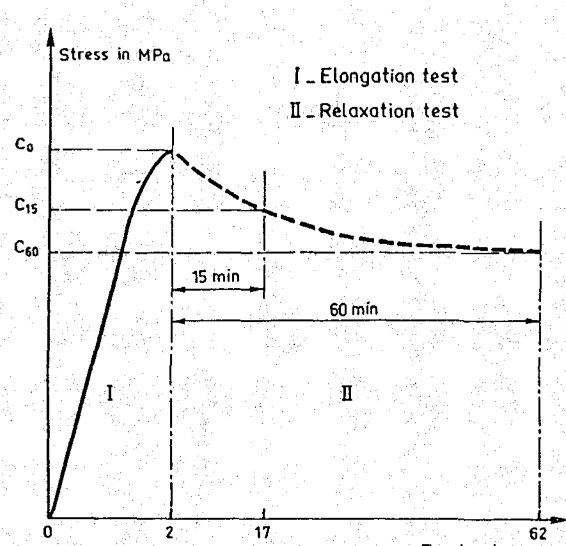


Figure 5c-12. Plot of stress versus time for mechanical testing of cable insulation.

versus time that one typically measures from the above test procedure. The modulus as determined from the mechanical test is plotted as a function of temperature for four different polyethylenes in Figure 5c-13.

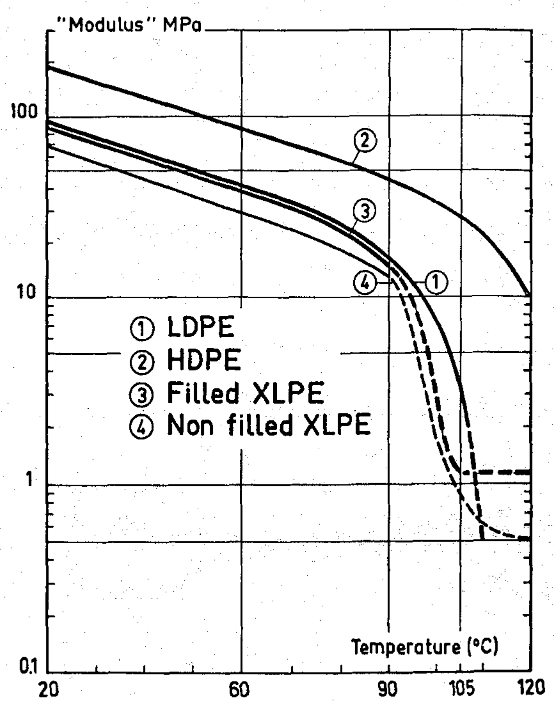


Figure 5c-13. The modulus of four types of polyethylene as a function of temperature.

When an XLPE-insulated cable is heated above the crystalline melting point of the XLPE and then cooled back to ambient temperature, the XLPE will tend to contract parallel to the cable length unless there is something to hinder such movement. In the radial direction, under the effect of temperature the material dilates, with an increase in the dilation rate during melting of the crystallites. On the whole, when the material returns to ambient temperature, it has expanded. This situation is illustrated schematically by a spring model in Figure 5c-14, and by thermal mechanical analysis data in both the transverse and longitudinal directions in Figure 5c-15.

The mechanical behavior of polyethylene is closely related to the crystallinity and inorganic fillers (which affect the modulus) and to the crosslinking (which effects the elasticity). During temperature overages, low density PE retains its normal characteristics at 80°C, and high density PE retains a significant part of its

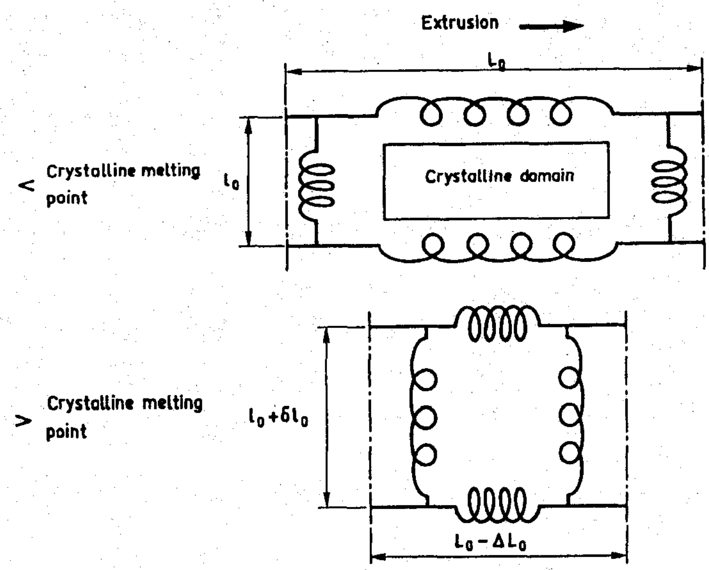


Figure 5c-14. Spring model showing how crystallite melting affects the dimensional changes in polyethylene.

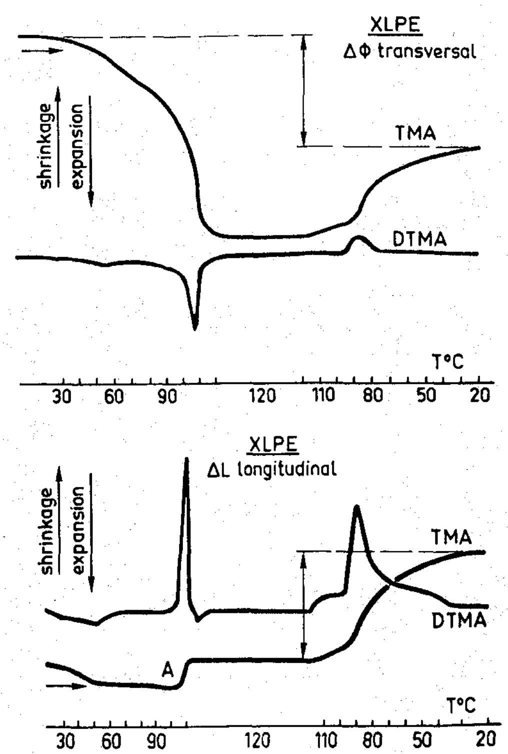
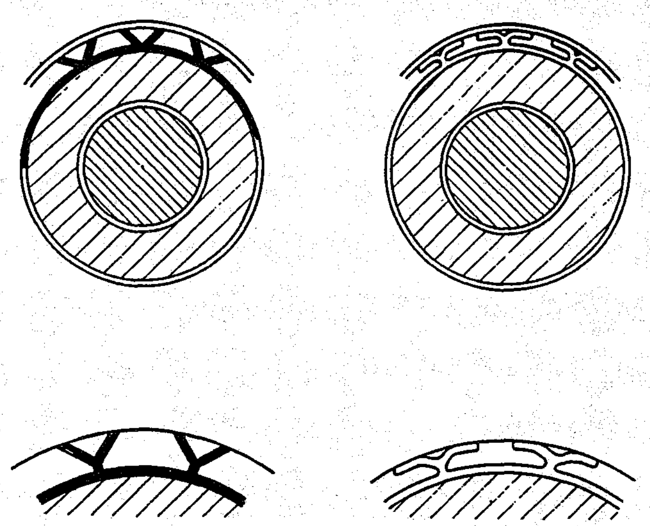


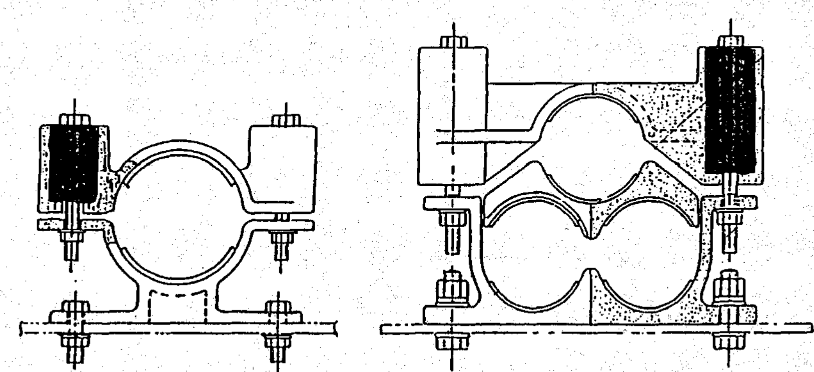
Figure 5c-15. Small-load thermal mechanical and differential mechanical data on XLPE from an extruded cable.

modulus at 90°C. In the case of XLPE, fixing an overload temperature should be done carefully because of significant modulus loss near the crystalline melting temperature of about 103°C.

Thermomechanical stress can be determined by equating the thermal strain (the coefficient of expansion, α, times the temperature change, $d\Theta$), to the modulus of elasticity divided by the stress, S. The stress due to unrelieved thermal strain is then, $\alpha S d\Theta$. For polyethylene with a modulus of 30 MPa and a coefficient of expansion of 0.0007, a temperature change of 50°C produces a stress of about 1 MPa. Two examples of cable systems designed to relieve thermomechanical stresses in extruded cables are shown in Figure 5c-16.



Compressible grooved shield

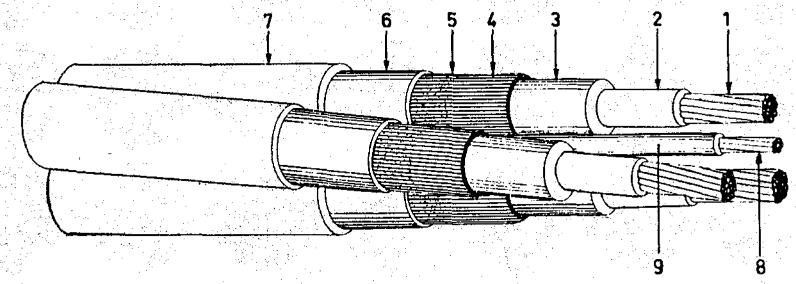


Cable cleats incorporating springs

Figure 5c-16. Two designs for relieving thermomechanical stresses in cables.

CABLES

Figure 5c-17 is a drawing of a 12/20-kV rated, XLPE cable.



1. Circular stranded aluminium conductor
2. Extruded semi-conducting screen
3. Cross-linked polyethylene insulation
4. Extruded semi-conducting screen with grooves
5. Sealing product
6. Metallic shied: aluminium tape, laid longitudinaly and bonded to the oversheath
7. Thick protective oversheath in polyvinyl chloride
8. Stranded aluminium conductor of the earthing conductor
9. Earth-conductor lead covering

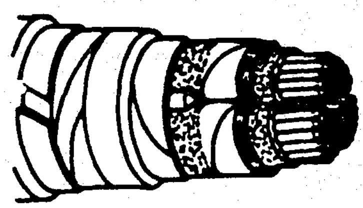
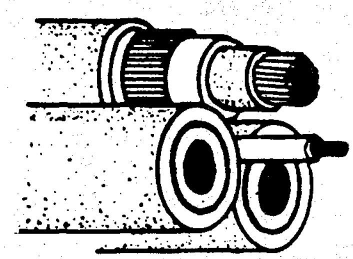
Figure 5c-17. XLPE insulated cables of 12/20-kV rated voltage for EDF distribution networks.

A comparison of the performance of HN 33-S-23 cable to impregnated paper insulated cable is shown in Table 5c-1.

The remaining Figures and Tables give data on the performance of cables and accessories in service in France. These are self explanatory and are presented without further comment.

Table 5c-1

COMPARISON OF A XLPE CABLE WITH A PAPER CABLE

	Impregnated paper insulated cable (ancient cable).	XLPE insulated cable HN 33-S-23
		
Aluminum conductor cross-section.	3x150 mm^2	3x150 mm^2
Nominal current, buried installation, winter.	355 A (12.3 MVA)	400 A (13.8 MVA)
Emergency overload current	370 A (12.8 MVA)	450 A (15.6 MVA)
Mass.	10 kg/m	4.75 kg/m
Relative costs	110%	100%

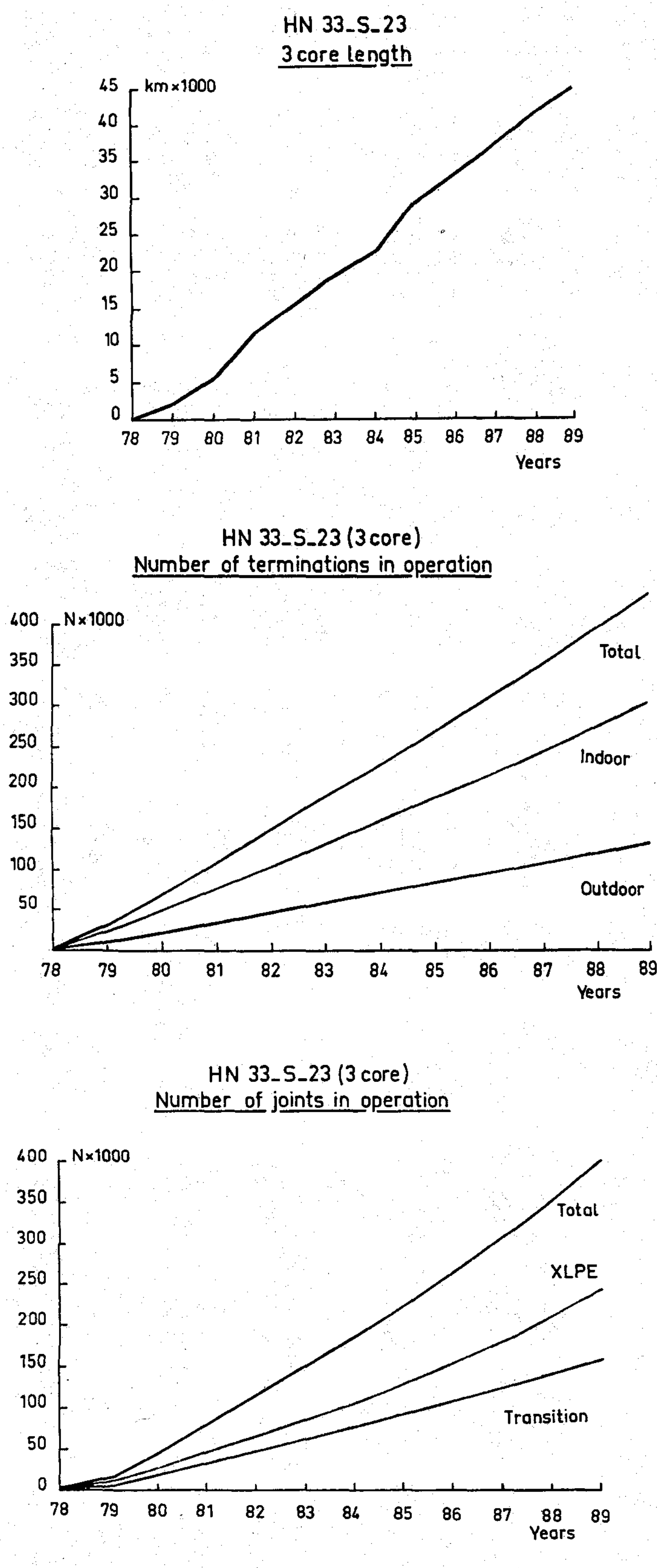
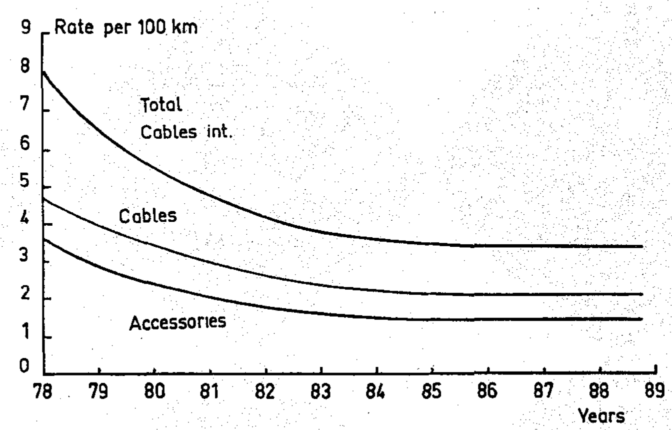


Figure 5c-18. Quantity of HN 33_S_23 cable, terminations and joints in service by year.

HN 33_S_23 XLPE (3 core)
Failure rates



HN 33_S_23 (3 core)
Failure rates per 1000 accessories

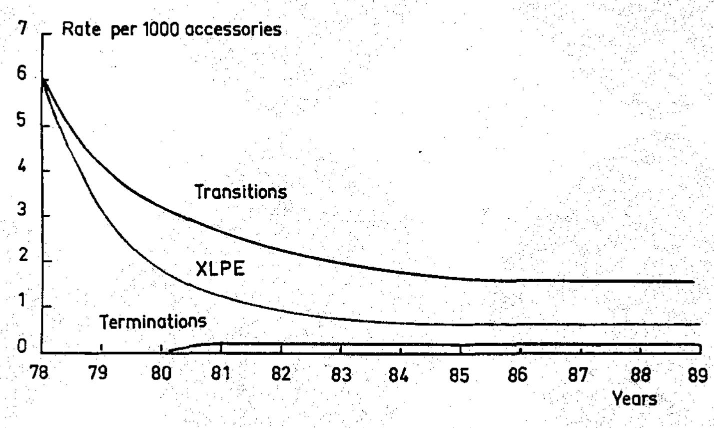


Figure 5c-19. Failure rates for HN_S_23 (3 core) cable and accessories by year of service.

Main characteristics of HV and VHV synthetic insulated cables used by EDF.

		Rated voltage			
		36/63 kV	52/90 kV	130/225 kV	230/400 kV
Conductor	Nature	Al or Cu	Al or Cu	Al or Cu	Al or Cu
	Cross sections mm^2	240 to 1600	240 to 1600	240 to 1600	630 and 1200
Insulation	Nature	LDPE,HDPE,XLPE	LDPE,HDPE,XLPE	LDPE HDPE	LDPE
	Max. voltage gradient kV/m	6	6	10	15
	Max. tg δ	8.10^{-4}	8.10^{-4}	8.10^{-4}	3.10^{-4}
	Max. thermal resistivity °C.cm/W	350	350	350	350
Short circuit current capability	Single phase	8 kA/2,5 s	10 kA/2,5 s	31,5 kA/0,5s	63 kA/0,5s
	Three phase	20 kA/1s	20 kA/1s	31,5 kA/1s	63 kA/1s
Example of characteristics for 1200 mm^2 Al conductor:					
Max power transmission capacity MVA		105	145	340	570
Weight per unit length kg/m		16	18	20,5	24

Limiting temperatures on conductor	Nature of insulation		
	LDPE	HDPE	XLPE
Permanent service condition	70°C	80°C	90°C
Overload condition	80°C	90°C	100°C
Short-circuit condition	150°C	180°C	250°C

Rated voltage	Total length of three phase circuits	Paper insulation (% increase)	Extruded insulation (% increase)	Share of extruded insulation on total length
63 kV	1050 km	550 km (-3%)	500 km (+7%)	47 %
90 kV (and 150 kV)	100 km	15 km (0%)	85 km (+8%)	85%
225 kV	480 km	250 km (0%)	230 km (+7%)	48 %
400 kV	21.5 km	15 km (0%)	6.5 km (+15%)	30%

Insulated cables in service in EDF_Transmission networks (year 1989)

Figure 5c-20. Data on EDF service experience with extruded insulation cables.

LDPE and HDPE

Cumulated probability of failure

$$P(t) = 1 - e^{-\left(\frac{t}{t_0}\right)^a \left(\frac{V}{V_0}\right)^b \frac{L}{L_0}}$$

Reliability $F(t) = e^{-\left(\frac{t}{t_0}\right)^a \left(\frac{V}{V_0}\right)^b \frac{L}{L_0}}$

a = Time scattering parameter
b = Voltage scattering parameter
n = −1/Slope life curve

		EDF STANDARD HN 33 S 51 and HN 33 S 54	LDPE	HDPE
225 kV and 400 kV cables	a	≤ 1	0.6	0.4
	b	–	12	8
	n	≥ 17.5	≥ 20	≥ 20

	Total length* in service Total number in service (accessories)	Cumulated length × year number × year	Mean internal fault rates /100 km* × year /100 acc × year
Cables	230	1560	0.06
Terminations	1878	9165	0.09
Joints	1156	5802	0.17

*3 phase links

EDF Operating experience

130/225 kV Cables and accessories
Intrinsic fault rates – Up to 1989

Figure 5c-21. Data on EDF operating experience with extruded insulation cables.

DISCUSSION

D. Silver: It is incorrect to say one must exclude water with a metallic sheath to achieve long life. In the US we have 27 years service experience with XLPE cables, including 2 to 2.5 million feet operating at 69 kV and 0.35 million feet operating at 138 kV without a metal sheath and some without special efforts to exclude water from the conductor. The failure rate is very low. With proper construction (no significant contaminants, no water in the conductor, an overall jacket and tree retardant insulation), I believe one can achieve a 40-year life without a metallic sheath. The use of lead sheaths in Europe is a conservative approach. I've never seen data that show a moisture barrier is needed for a cable to perform properly. **L.D.:** All answers to the questionnaire were in favor of metal shields above 10 kV. **C. Katz:** Was the XLPE data you showed on the Arrhenius plot for cables insulated with XLPE or for the XLPE compound itself? And what is the effect on the data of excluding the environment? **L.D.:** The data were for prototypes with metal foil around the insulation at the beginning of our new technology. The materials used for these data were evolving as you could see from the mechanical performance curves. Those data are not for present technology. **B. Bernstein:** Thermal aging of PE is more than just oxidation. It involves morphology changes, void size and concentration, solubility and migration of antioxidants. This complexity of effects brings into question the meaning of the Arrhenius equation. Also I question the conclusion of JICABLE 84 that the maximum overload should be 103°C. Published data show phase separation occurs between 90°C and 105°C. This may not be a problem in dry aging but is a potential problem in wet aging.

Section 5d

INFLUENCE OF INSULATION MORPHOLOGY ON THE ACCELERATED AGING OF CABLES

by J-P. CRINE

Dr. Crine presented experimental evidence for a relationship between breakdown strength and morphology in PE and XLPE. Published data showed an increase in breakdown strength with density for HMWPE and both steam-cured and dry-cured XLPE, with all three materials plotted on the same curve. Other published data, consistent with the above, showed that impulse breakdown strength decreases with amorphous thickness. Dr. Crine then showed neutron scattering data on deuterated PE and both small-angle and wide-angle x-ray scattering data on XLPE plaques. He interpreted these data as showing that there was a critical field around 15 kV/mm, at which discontinuous changes occurred in the structure of PE. He noted the similarity in his observations and reports that capacitance, loss and conduction changes occur above 15 - 30 kV/mm.

From these observations he concluded: 1) AC fields above a critical value (≈15 kV/mm) may induce defects in PE and XLPE aged at 22°C. 2) The maximum size of the defects is related to the length of the amorphous phase. 3) There are resultant changes in electrical properties. 4) Above a critical field of 15-20 kV/mm, aging becomes irreversible.

DISCUSSION

T. Barlow: Could XLPE byproducts be reacting at high field (30 kV) but not at low field? **J-P.C.**: Perhaps, but I doubt it. We dried these samples overnight in vacuum at 50 °C. **S. Grzybowski**: Did you see morphology changes after thermal and electrical aging? **J-M Braun**: How does one get from a 50 Å defect or void to cable performance and life? **J-P.C.**: Good question. The initiation step is a few 50 Å voids. These grow in number and size with time to μm sizes and partial discharges start and eventually create a breakdown site. **R. Eichhorn**: When the small angle x-ray scattering curve indicates increasing spatial perfection is there any difference in the line width, any line narrowing, in the x-ray diffraction main peaks? **J-P.C.**: It is hard to see because the main peak is not well defined and the defects are so small. A published report by P. Phillips of U. Tennessee using SAXS shows defects generated in insulation from cables of different ages. **G. Matey:** We have done similar work on French cables and see morphology changes. Cables aged 6,000 hours under service conditions show a rearrangement of the crystalline phase that affects the lamellae. The cables operate at much lower fields than you have used, and at these rated field levels you can rest assured that the cables will not breakdown.

Section 5e

DIAGNOSTIC TESTS FOR SOLID DIELECTRIC CABLES

by W. BOONE

INTRODUCTION

The purpose of diagnostic tests is not primarily to eliminate production or installation defects, but rather to identify and evaluate degradation phenomena by applying certain specific techniques, preferably of non-destructive nature and preferably performed "at site" and "on line" (1). It is important to distinguish between: degradation under dry conditions and degradation under wet conditions.

DEGRADATION UNDER DRY CONDITIONS (2)(3)

The first category comprises the following measurements which may give information on the state of degradation:

- density
- oxidation content
- partial-discharge detection
- tanδ

Density measurements can be used to check the crystallinity which may influence the long-term electrical performance. The density of insulating material generally increases with aging time.

Oxidation is an aging mechanism affecting mechanical properties. Antioxidants are used to improve thermal stability. The oxidation content increases with aging time, especially near the conductor shield.

Partial-discharge (PD) activity is generally associated with defects already present in new cables or accessories. However non-detectable micro-discharge levels may contribute to aging in the long term. PD detection at site, using switching impulse voltage, is under consideration (4), although it is not very likely partial-discharge detection will soon become an important tool to identify degradation processes.

In general, the dissipation factor does not change significantly as a result of degradation mechanisms under dry conditions and is therefore not to be recommended as a method to judge cable aging.

At a recent CIGRE colloquium in Toronto (Sept. 1989) (3) it was concluded that, for the time being, the extruded cable insulations do not appear to exhibit property changes that can be measured easily or that can be said to be significant in terms of cable life reduction when contaminations from external sources, e.q. water, are excluded.

DEGRADATION UNDER WET CONDITIONS

The following list of relevant measurements or tests will be discussed:

- CIGRE-characterization test
- Dual polarity test
- Insulation resistance test
- tanδ
- DC-dielectric relaxation test
- Partial discharge detection
- DC-withstand test
- L.F.-withstand test
- Oscillating wave test

The CIGRE-characterization test (5) comprises breakdown tests on pieces of cable, taken from the circuit and subsequent visual inspections. The combination of data (the ACBD value and the size of the largest tree) gives a reliable indication about the quality of the cable in service and the related life expectancy (see Figure 5e-1). The 'bad' cables are located in the right hand part of the curve, the 'good' cables in the left hand part.

In the dual polarity test (6) cable pieces are subjected to impulse breakdown, while being pre-stressed with dc-voltage of opposite polarity. The degree of aging can be related to a threshold voltage $V_{th}DC$ (see Figure 5e-2).

The results of the insulation resistance test (dc-leakage current test and the dc-component measuring method in ac charging current) and the tanδ test appear to be related with the ACBD value and consequently with the degree of aging (7)(8)

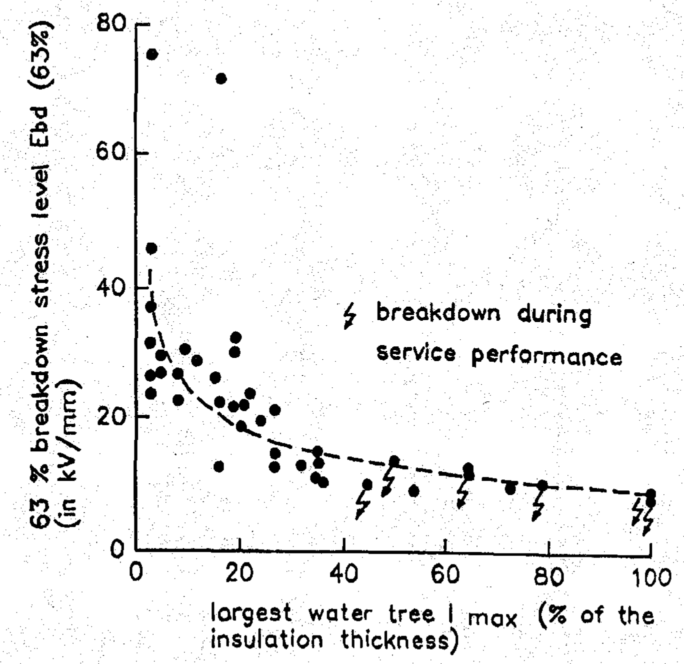


Figure 5e-1. The 63% breakdown field as a function of the size of the largest water tree.

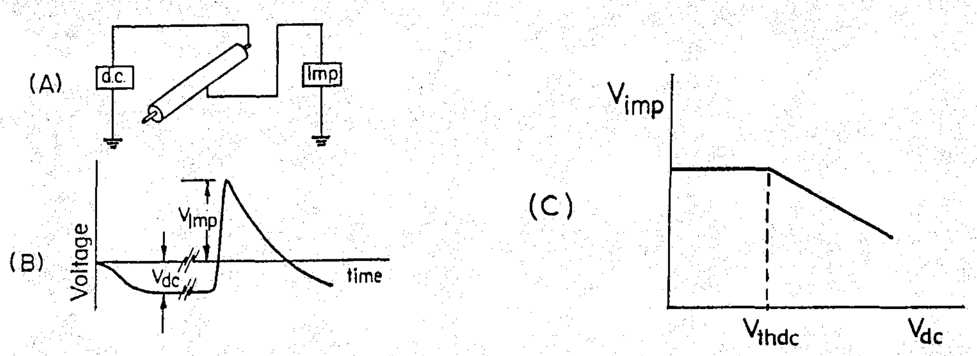


Figure 5e-2. (A) Diagram of circuit for determining threshold voltage. (B) Typical voltage transient. (C) Typical impulse breakdown voltage vs. dc prestressing voltage to establish threshold voltage.

(see Figures 5e-3 and 5e-4). The tanδ measurement is also recommended in a 1981 IEEE Paper (9) to quantify the remaining life. In (8) the dielectric relaxation method is mentioned, measuring the dielectric relaxation after dc voltage application.

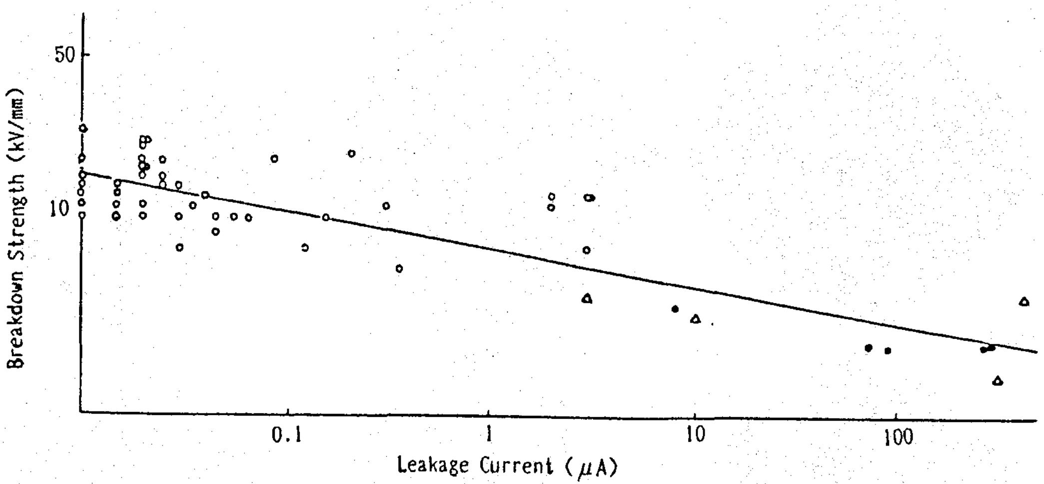


Figure 5e-3. The breakdown strength of XLPE power cables as a function of dc leakage current.

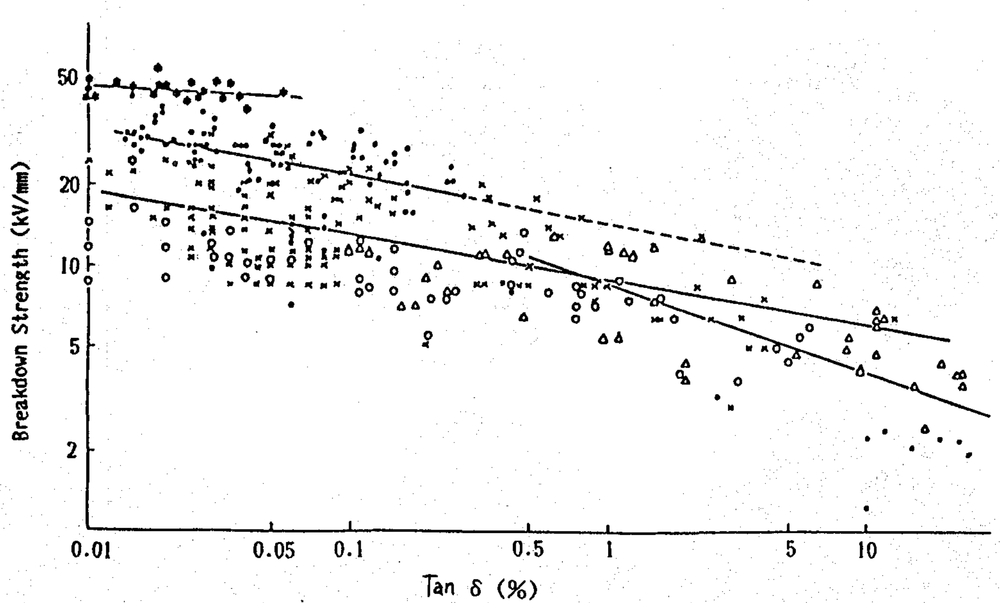


Figure 5e-4. The breakdown strength of XLPE power cables as a function of the loss tangent.

These tests, so far all suffering from a lack of practical experience, do not give any specific details but can only provide broad information about the level of degradation. Besides the strong impression is given that the tests will only be decisive if the level of degradation is already unacceptably high.

As the mechanism of water tree growth is not related to PD activity, PD detection can not be used for a diagnostic purpose with respect to cables suffering from water treeing.

Some authors (8)(1) report a much stronger reduction of dc-strength than ac-strength for cables affected by water treeing. From that point of view a dc-withstand test has diagnostic capabilities. However if a dc-breakdown occurs the combination of a travelling voltage wave and trapped space charge may be very dangerous (10)(12). The lack of effect of dc-stressing on ac-strength is generally confirmed (8)(10)(11).

The low-frequency withstand test, extensively dealt with in (12) is proposed as a diagnostic test, for long lengths of cable without the risks that have to be accepted when dc-voltage is applied.

The oscillating-wave test (13), in which the dc-charged cable is discharged through an inductance, developed as an after-laying test could be extended as a diagnostic test for aged cables.

CONCLUSIONS

Effective diagnostic techniques are not likely to be expected soon for cables aged under dry conditions. For cables aged under wet conditions a variety of techniques are mentioned in the literature but, most of them lack practical experience or international acknowledgement and are consequently not of immediate practical use. The CIGRE-characterization test is being widely applied and is certainly effective but is still complicated. The dual polarity test needs more practical experience, but is also very complicated. Site tests that are nearly non-destructive, like the insulation resistance test, the tanδ test and the dc dielectric relaxation test are still not very convincing as appropriate diagnostic tests, as long as no more statistical data about practical applications can be shown. Considering withstand voltage tests, the low-frequency test and the oscillating-wave test should need further attention.

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DISCUSSION

D. Silver: I suggest the power factor test in the field or the laboratory is the most significant non destructive diagnostic test. As power factor increases the size and density of trees in the cable insulation are increasing. You are not seeing the larger trees, but more smaller trees indicate higher probability of there being larger trees that will give breakdown. **W.B.:** One must be careful. Only the largest tree is of importance and I do not believe tanδ-measurements will give this kind of information. On the other hand dramatic changes in tanδ-value may indicate that something is wrong. It was suggested at the Toronto meeting of CIGRE that field tests which give rough indications and more detailed laboratory tests are a good combination. Statistical work should be done to be sure that this is really an effective tool. **C. Katz:** Mr. Silver is only partially correct because dissipation factor cannot be measured on one particular site, only. It's not only the tree that is important - it's also the moisture. Dried cable with trees has good dielectric strength. We have measured dissipation factor of long lengths of cable in the laboratory and see relatively small increases in tanδ. It's difficult to distinguish between tanδs of two cables which may have very different conditions. This was published eight years ago in IEEE. **B. Bernstein:** Doepken and Srinivas under EPRI contract showed it was very hard to relate power factor to residual breakdown strength. **J. Densley:** The Japanese find they can relate the non-linearity in the 60-Hz current waveform to treeing. This was published in Power Apparatus and Systems a couple of years ago and very good sensitivity to tree length with this measurement technique was claimed. **W.B.:** C. Katz tried to show a relation between tanδ measurements at the time of observation and the critical value, with the intention of giving a rough indication of remaining life.

Section 5f

CABLE SERVICE EXPERIENCE

How well are distribution power cables performing?

by D. Mintz

This presentation is based on Canadian Electrical Association Project 117 D 295, Survey of experience with polymeric insulated power cable in underground service. Resources for this work were drawn from EPRI, EEI, AEIC, NELPA, DEFU, UNIPEDE, European utilities publishing in CIRED, American utilities contributing at ICC, Canadian utilities participating in CEA survey.

For some utilities, the scene of a customer without power due to a cable failure is a rare occurrence; for others, it is all too frequent. The problems, that some utilities have encountered, have prompted many groups to start gathering data on service experience with polymeric power cables. The Canadian Electrical Association sponsored such surveys in 1983 and 1987, and the majority of the material discussed in this talk came out of the work for that project.

For the work on service experience to yield the results wanted, an international co-operative effort will be required. Many individuals and groups have supplied information on their experience either directly to data gathering groups or through published articles. I would like to thank those groups for allowing the general community of utilities to share their findings. I believe that the unprejudiced transfer of information will result in the fastest solution to cable problems.

I would like to point out in particular the work of the DISCAB working group of UNIPEDE (the Union of Producers and Distributors of Electricity in Europe), DEFU (the Danish group), AEIC (the Association of Edison Illuminating Companies), NELPA (the Northwest Light and Power Association), EEI (the Edison Electric Institute), EPRI (the Electric Power Research Institute) and CEA (the Canadian Electrical Association). In addition, I would like to thank those utilities in Europe, the United States and Canada that gather and release information on the performance of their underground systems.

WHAT DO WE WANT TO KNOW?

From the utility point of view, there are two main questions: How well will the cable perform, and what is the most cost-effective product that can be bought and installed? Utilities want to know if their cable system is performing as expected or if there are problems that need investigation. As well as the performance of the cable already installed, utilities are concerned about choices for new installations. Will the new product perform under service conditions as expected?

Manufacturers would like to be able to produce a long-lasting, relatively inexpensive cable which satisfies utility requirements. They have invested a considerable amount of money in new or renovated facilities to improve their product. New insulating materials and cable designs have been developed. Studies of service performance will help identify the important factors in cable design and will allow manufacturers to produce better, more competitive products.

One of the major research efforts is in the area of accelerated testing techniques. In-service cable performance has shown that the techniques previously used are not adequate. It will be the actual in-service experience that will confirm or refute the predictions of the new or modified tests.

SERVICE EXPERIENCE - THE ULTIMATE TEST

The results of the cable's performance in-service is the ultimate test of the cable's capabilities. It looks at the very long lengths of cable necessary to fully examine not only the materials and design of the cable, but also manufacturing

Table 5f-1

1986 CABLE FAILURE RATES PER YEAR

	XLPE			LDPE/HMPE		
	per 100 conductor km	per 100 conductor miles	per 100 circuit km	per 100 conductor km	per 100 conductor miles	per 100 circuit km
Canada (CEA)	**0.90**	1.45	2.70	-	-	-
US (AEIC)	0.90	**1.45**	2.70	4.08	**6.57**	12.25
EUROPE (UNIPEDE)	0.12	0.19	**0.37**	1.26	2.03	**3.79**

quality control. In actual practice, unacceptable failure rates (e.g., 10 faults/100 km/yr) are a very low probability occurrence (0.06%) when considered as an experiment on 6 m (20 ft) samples. Because in-service experience is gained over normal time and under a large variety of conditions, all aspects of the cable's performance will be tested without the use of questionable accelerating factors or fixed conditions. Lastly, service experience is the proving ground for all aspects of the cable system, including utility handling and installation practices which can have a great effect on the ultimate performance of the cable.

The cable failure rates were taken from the 1987 CEA report, from the AEIC presentation described in the minutes of the November, 1987 ICC meeting and from the UNIPEDE-DISCAB paper presented at CIRED 1989. These numbers are for the types of insulations indicated, including all voltage classes, cable constructions, ages, or methods of installation. So-called "dig-in" failures have been excluded from the data. The bold numbers in the Table indicates the statistic used by the group gathering the data. This points up one of the difficulties in comparing data from several sources.

The failure rate statistics were derived from the quantities of installed plant shown in Table 5f-2. These quantities are large enough to give a good definition to average performance.

Table 5f-2

QUANTITIES OF INSTALLED PLANT USED FOR THE FAILURE RATE STATISTICS

Country	Conductor km	Conductor miles	Circuit km
Canada	25,000	16,000	8,300
US	113,000	70,000	38,000
Europe	249,000	155,000	83,000

These types of statistics help define acceptable performance. In North America, the numbers for high molecular weight polyethylene (HMPE), would be considered unacceptable by many, if not most utilities, and those cables would be involved in some kind of replacement program. Clearly, the cross-linked polyethylene (XLPE) insulated cables are performing much better. Many of the utilities that I deal with in Ontario find those kinds of failure rates (i.e., below 1 fault/100 km/yr) acceptable.

DIFFICULTIES IN GATHERING AND INTERPRETING SERVICE PERFORMANCE DATA

Gathering and interpreting service performance information has many difficulties. An obvious difficulty is the choice of statistical parameter to use. As seen previously, the choice of measurement of "cable" length (kilometers, miles, conductor or circuit length) can lead to confusion. In addition, cumulative failure rates have been used in place of yearly rates by many researchers. Since most people feel that cable age is a factor, age-weighted cumulative failure rates have been proposed; however, they are not often used because of the difficulty in obtaining installed-plant age data.

A serious problem with service information is accuracy. Often the amount of cable installed can only be guessed at, and field personnel, interested in restoring the power, do not always have the time to report cable failures. It is often difficult to determine the cause of failure (i.e., determine "dig-in" type faults). In the case of some insulation types or cable constructions there is not enough installed plant to determine accurate failure rates. Since utilities with severe cable problems are more likely to keep accurate failure records, it is possible that the failure rates are biased.

Information on cable design, age, insulating material, method of installation are, for the most part, not available.

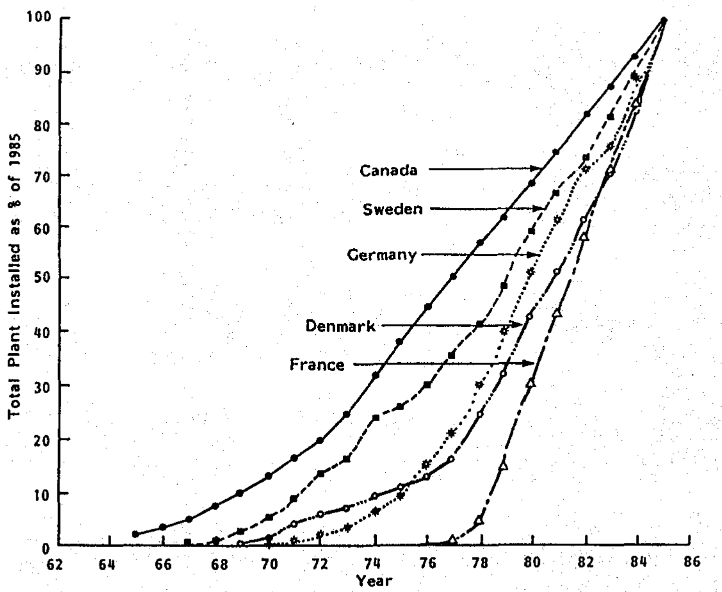

Figure 5f-1. Age profiles of XLPE cables (1985)

To illustrate how these problems can effect the interpretation of the data, Figure 5f-1, taken from (1), shows the age profiles of XLPE cables for several European countries as compared to Canada. It is easy to see that the Canadian experience is based on older designs of cable with longer service times. This may partially explain the differences in overall cable failure rates between Canada and Europe.

WHAT WE HAVE LEARNED FROM THE CURRENT INFORMATION

Examination of failure rate data has given us a perspective on average cable performance and has helped to point out problem cables to both utilities and manufacturers. The average failure rates give utilities a standard by which they can evaluate their own systems.

PART OF SYSTEM CAN DOMINATE FAILURE RATE

One interesting outcome of the study of cable system performance has been the realization that a small part of a cable system can be responsible for an overall poor cable performance record. Memphis Light and Power had poor experience with a cable made in the early 1970's that had a larger proportion of failures than would be expected from the proportion installed. Swedish utilities noticed a similar effect with cables of an early graphite shield design. In the CEA work, the five Canadian utilities shown in Table 5f-3 could define their installed plant and failures well enough so that a comparison could be made.

Table 5f-3

EXAMPLES WHERE SMALL PARTS OF A SYSTEM GIVE LARGE PERCENTAGES OF FAILURES

Location	Percentage of Installed Plant	Percentage of Failures
Ottawa	3%	81%
St. John	<1%	56%
North York	<5%	53%
Burlington	5%	30%
Windsor	22%	63%

Ottawa's failure rate goes from 4.4 to under 0.9 faults/100 km/yr if the bad cable is excluded. For the others, their failure rate is approximately halved by eliminating the problem cable.

IDENTIFICATION OF POSSIBLE PROBLEM CABLE

Service experience has also helped identify some cable designs and materials that are suspect. The failure rates that were shown previously, indicate that the cables insulated with high molecular weight polyethylene (US) or linear polyethylene (Europe) do not have as good a service record as XLPE. In Canada and the US, uncoated carbon-black-filled tapes have been shown to be very susceptible to water treeing and premature failure. In addition, two voltage classes of cable (5-kV XLPE in Canada and 30-kV XLPE in Europe) have been shown to be more at risk than others. The data demonstrating this last result are shown in table 5f-4. The data for the 5-kV and 15-kV cables comes from Canadian utilities in the CEA survey. These high failure rates are due to the old design (tape shields) and the age of the cable (up to 20 yrs). For both years, the cables' average ages were the same but the 5-kV cable had more than twice the failure rate. It may be that, for relatively thin-walled designs susceptible to water treeing, wall thickness is more important than increased stress (since the growth of water trees from local stress enhancements does not require a high average electric field).

Table 5f-4

XLPE CABLE FAILURE RATES BY VOLTAGE CLASS

Year	Voltage Class	Failure rate / 100 cond km/year	Length weighted average age (yrs)
1985	5 kV	8.5	12.0
	15 kV	3.8	12.4
1986	5 kV	8.0	13.1
	15 kV	3.5	13.1
1985	10 kV	0.12	-
	20 kV	0.10	-
	30 kV	1.11	-
1986	10 kV	0.09	-
	20 kV	0.13	-
	30 kV	0.84	-

On the other hand, the European XLPE cable data (CIRED 1989) shows, that compared to 10-kV and 20-kV cable, 30-kV cable has a far worse performance record. This was consistent for six years of data. Perhaps for larger wall thicknesses stress is more important because the water trees must be longer (i.e., further from the "stress enhancement") to affect performance.

EVALUATION OF NEW DESIGNS AND INSTALLATION PRACTICES

An important reason for looking at service experience is the evaluation of cable designs and practices. Two groups, who are trying to look at these factors, are NELPA and AEIC. Their results are still tenuous because of small sample sizes, relatively new cables and the difficulty in obtaining cable age data. However, the work of these groups should be applauded because their efforts will supply the type of information needed in the future. The variation of failure rates with cable age is a sought-after relation. Two attempts from the Canadian data are depicted in Figures 5f-2 and 5f-3.

The data for absolute cable age are depicted in figure 5f-2. The data available for this graph were limited so that the failure rates used were averaged over 5 years. The effect of the poor cable can be seen in the difference between the two North York Hydro graphs. The increase with age is obvious. Figure 5f-3 is based on length-weighted average cable age. Again the increase with age is evident. These two graphs combine the performance of many designs and voltages of cables, and they would not apply to today's cables. However, they offer some feel for the average performance of "older" designs.

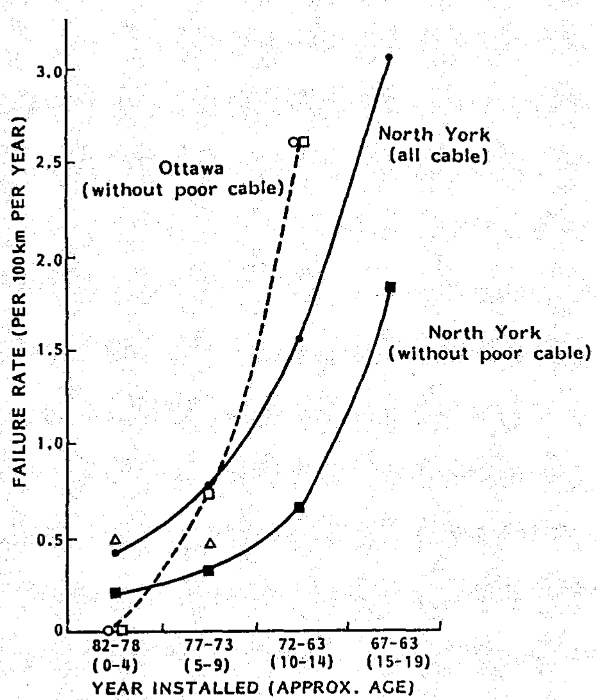

Figure 5f-2. Failure rate as a function of year of installation.

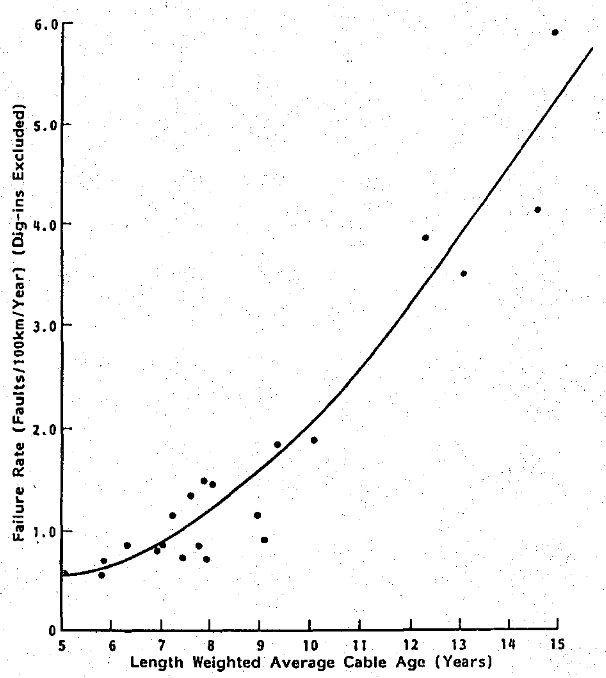

Figure 5f-3. XLPE cable failure rate versus average cable age.

SUMMARY

The results of examining service experience has helped define realistic cable performance expectations and gives a method for reevaluating future performance expectations. In the future we would like to learn the following from service experience:

- service life of cables
- evaluation of accelerated aging tests
- actual cost effectiveness of new cable designs
- confirmation of cable design improvements
- manufacturing process changes
- installation techniques
- and circuit designs.

Even though the difficulties in obtaining accurate service experience data are significant, it is essential to continue the work with further detailed studies to evaluate the large number of new insulating compounds and cable designs. It is only through the concerted efforts of many groups of utilities and manufacturers that the needed information will be obtained. It will be through our efforts today that future engineers will not have to say "We wish there were some in-service cable performance data available."

REFERENCES

1. J.D. Mintz, Principal Investigator. "Survey of Experience with Polymeric Insulated Power Cable in Underground Service." Phase III, CEA project 117 D 295, October 1987.

2. "International Cable Fault Statistics on Synthetically Insulated MV Cables", written by UNIPEDE DISCAB group, CIRED proceedings, 1989.

3. "The 1986 AEIC Cable Engineering Section Cable Operations Report", Appendix V-B, IEEE Insulated Conductors Committee Minutes, November 1987.

DISCUSSION

W. Boone: In the Netherlands, they replace cable after a certain number of failures. The rate of failure goes down as replacement rate goes up but the cost is large. Have you considered differences in replacement in terms of differences in failure rates reported by different countries? **D.M.:** The Americans are asked to say how much cable (mostly high molecular weight) is removed from the ground when they're reporting to AEIC. In Canada, cable replacement programs involve butyl rubber which doesn't appear in the statistics. For XLPE, even failure rates of 20 are cheaper to repair than to replace - there is a lot of cable involved. Only recently are there large-scale replacements (four to six million dollars). Yes replacement is an important part, but I don't think it affects my data much at present. **S. Verne:** Is the dramatic difference between European and North American statistics due mainly to jacketed cables or to other factors? **D.M.:** I don't have data on that. I suspect other factors. In Ontario Hydro some jacketed cables have performed very badly. I don't think even better jackets are the final answer. In the European data are French data with a true semi-impervious metal shield as well as a jacket. And newness makes a difference. We have better design and manufacturing quality now than 20 years ago. There are now cleaner materials, better shields, better controls on the lines - a lot of differences. Small quantities can dominate your statistics. The high North American number may be dominated by the older designs or poorer quality cables or one or two bad runs. It's very difficult to be sure. **J. Moran:** This is a very excellent paper. The missing element, and I'm sure it's due to politeness, in your paper is vintage and manufacturers. Manufacturers have bad and good years as chateaus do with wines. **D.M.:** I didn't put in manufacturers data because I can't get it. In the US and Canada cable makers are spread all over and no one knows how much cable comes from which manufacturers. I could get the dollars spent but not the lengths of cable.

It is more the difficulty than just politeness. **T. Dakin:** Is it possible to extract the effects of operating temperatures or loading levels from your data? **D.M.:** For Canadian and most other data the typical load is less than half the rated 90°C load. Most people run cool systems. That's not true everywhere, but is generally true of people who supplied data for this survey. **D. Silver:** I believe the most important reasons the European and North American statistics are different are: 1) Until recently most US cables were single conductor and unjacketed while European cables were three phase, conductor jacketed cables; and 2) at the time the cables for which we have data were manufactured and installed, there was much less awareness of the significance of water in the conductor, and fewer precautions taken to exclude it in the US than in Europe. I think overall jackets and water in the conductor can explain the difference.

Section 6

PERSPECTIVE OF THE SECRETARY

by M. Broadhurst

I was asked by the sponsors of this workshop to present my views on "Cable '89" and problems that the workshop addresses. I do this from my perspective as a polymer physicist, and within the framework of 30 years of materials research experience, primarily at the National Bureau of Standards (now National Institute of Standards and Technology) in the field of dielectric properties of polymers.

The electrical insulation problem is a complex and varied one. Entire careers have been spent solving some problems and working on others. Progress has come in increments with no quick or easy solution to insulation failures in power cables. The failure mechanisms are varied and complex, and changing technology places new demands on the properties of existing materials and creates new and modified materials to be evaluated as possible replacements for older ones.

As with any complex phenomenon, our state of knowledge can be divided roughly into three categories.

1. First, there are established scientific principles that can be described and verified quantitatively by well controlled scientific experiments.

2. Second, there is empirical knowledge gained through extensive experimentation and years of field experience. This knowledge is often the basis for current manufacturing practice and engineering improvements in practical systems.

3. Third, there is a body of commonly quoted principles and beliefs. These are often qualitative, loosely formulated and supported by a number of observations rather than well defined experiments. This category of knowledge is often the source of new hypotheses of material behavior or creative leaps away from the usual progression of technical development.

I found it increased my appreciation and understanding of the many topics addressed during Cable '89 to look at the type of knowledge involved. All three types of knowledge are useful, as I will try to show with simple examples from the workshop.

The Arrhenius equation is an example of a well established scientific principle. It is a well established relationship between time and temperature, and can be verified in the laboratory for many physical and chemical processes. It is also used in cable insulation aging studies where its applicability can not be rigorously defended. Dr. Dakin and Dr. Deschamps discussed its usefulness for paper-oil insulation that was structurally stable over the temperature range of testing and use (5a-1), and for elongation to break data for XLPE (5c-2). But, as pointed out in the discussions, the equation does not work for many processes where internal or external conditions change over the ranges of temperatures and times that this equation is used.

The idea that defects reduce cable performance illustrates a type of knowledge that came from years of experience. There have been many experiments and model calculations about the deleterious effects of particles, voids, and protrusions into the insulation. While one cannot test all situations involving defects in cables, the conclusion that imperfections are a major source of failures in cables (4d-3) successfully guides polymer and cable manufacturers to make better cables by reducing the sizes and numbers of imperfections. This general knowledge about imperfections also provides a rationale for over-voltage testing of finished cables.

A commonly quoted belief can be illustrated by the idea that partial discharges are involved with water tree growth. Such discharges have never been observed. The belief that they exist at levels too low to be detected with present equipment comes from our ideas about the most likely water treeing mechanisms. This belief suggests that we need more sensitive PD measurements. If water tree related partial discharges were found, they could form the basis of a new diagnostic test for water tree detection.

With these simple examples, I have tried to show how three quite different but complimentary types of knowledge are involved in a complex research program. Each type has advantages and disadvantage, and all three are needed for a well balanced research program. This perspective also makes clear the need for meetings like "Cable '89" that gather together practitioners of all three types of knowledge and keep the field vital, nourished and up to date.

Appendix A

ATTENDEES

PARTICIPANTS AT CABLE 89 WORKSHOP
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Appendix B

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CHAIRMAN OF THE WORKSHOP: Ralph W. Samm (EPRI)

ADMINISTRATIVE OFFICE: Shirley Ferrel (EPRI)

TECHNICAL COORDINATORS:

Lucien Deschamps (JICABLE)
Bruce Bernstein (EPRI)
John Densley (CEA)

SPONSORING ORGANIZATIONS:

JICABLE
EPRI (Electric Power Research Institute)
CEA (Canadian Electric Association)

WORKING GROUP CHAIRMEN AND SECRETARIES:

Materials Aging and Diagnostics
- Bruce Bernstein, Chairman
- John Tanaka, Secretary

Cable/Accessory Aging and Diagnostics
- Lucien Deschamps, Chairman
- Bernard Dalle, Secretary

Accelerated Aging - Service Experience
- John Densley, Chairman
- Harry Orton, Secretary

OVERVIEW PRESENTERS:

Aging/Life Predictions - Tom Dakin (Consultant)
Materials - Robert Eichorn (Union Carbide)
Cables/Accessories - Lucien Deschamps (EDF - DER - ERMEL)
Accelerated Aging - Jean-Pierre Crine (IREC)
Diagnostics - Willem Boone (KEMA)
Service Experience - David Mintz (Ontario Hydro)

WORKSHOP SECRETARIES:

Martin Broadhurst (Consultant)
Edward F. Kelley (Consultant)

Appendix C

JICABLE/EPRI/CEA Workshop "Cable 89"

FINAL PROGRAM

THURSDAY
November 2nd

7:30 a.m.	Registration & Continental Breakfast	
8:30 a.m.	Welcome	
8:40 a.m.	Overview Presentations with brief discussion:	
	Aging-Life Predictions	T. Dakin
	Materials	R. Eichorn
	Cables/Accessories	L. Deschamps
	Accelerated Aging	J-P Crine
	Diagnostics	W. Boone
	Service Experience	D. Mintz
Noon	Lunch	
2:00 p.m.	Three Working Groups:	
	Materials Aging and Diagnostics	
	Cable/Accessory Aging and Diagnostics	
	Accelerated Aging-Service Experience	
5:00 p.m.	Adjourn	
6:00 p.m.	Reception	
7:00 p.m.	Dinner	

FRIDAY
November 3rd

8:00 a.m.	Continental Breakfast
9:00 a.m.	Working Group reports and final discussions
Noon	Workshop summary and conclusion
1:00 p.m.	Adjourn

Appendix D

QUESTIONAIRE

WORKSHOP "CABLE 89"

Attachment #2

Introduction

A workshop has been organized prior to the November ICC meeting in St. Petersburg, Florida on November 2-3, 1989. The topic will be, "The Aging of Extended Dielectric Cables".

We would appreciate it if you would kindly participate in the workshop or suggest someone in your organization equally expert in the subject.

The workshop will last one-and a half days and will consist of a half day of introductory presentations on various aspects of cable aging. The remaining time will be spent addressing concerns expressed in the results of a specially prepared questionnaire which is enclosed. Many of the questions are in tabular form to make it easier for the organizing chairman to analyze the data. Space has been left in each question for you to add your comments or parameters you consider important and which have been omitted. For the purpose of the workshop and the questionnaire, the stress levels are: MV (≤5kV/mm), HV (5 to 10kV/mm) and EHV (≥10kV/mm). The data from the questionnaire will be the focus of the discussion at the workshop so that it is important that you fill it in and return it by September 1, 1989 to Ms. Shirley Farrell. It is intended to discuss the more controversial points by forming groups of participants and then have one session altogether to summarize our findings.

Materials Aging **1. What factor influence the aging of materials under dry conditions?**

Legend: None = 0
Low = 1 Med = 2
High=3

	INFLUENCE			
	MV	HV	EHV	COMMENTS
Residual Moisture				
Field				
Temperature				
Temperature Gradient				
Temperature Cycling				
Frequency				
Residual Strain				
External Strain				
Time				
Partial Discharges				
Others (Please List)				
Material Type				
Moorphology				
Antioxidents				
Additives				
Dissolved Gases				
Contaminants (Semicon)				
Contaminants (Insulation)				
Voids/Cavities				
Amber's				
SC/Insulation Interface				
Space Charge Injection				

Your comments on those parameters which have a medium or high influence would be appreciated.

What synergistic effects occur among the various parameters?

Is any particular material more or less sensitive to any of the parameters?

2. What factors influence the aging or materials under wet conditions?

Legend:
None = 0
Low = 1
Med = 2
High = 3

	INFLUENCE			
	MV	HV	EHV	COMMENTS
Residual Moisture				
External Water				
Ions in Water				
Field				
Temperature				
Temperature Gradient				
Temperature Cycling				
Frequency				
Residual Strain				
External Strain				
Time				
Partial Discharges				
Morphology				
Contaminants in Semicon				
Contaminants in Insulation				
Dissolved Gases				
Antioxidants				
Additives				
Cavities/Voids				
Ambers				

Please make comments.
Are there any synergistic effects?
Is there any particular material more or less sensitive to any of the parameters?

3. What methods are used for characterizing or detecting the aging of cable components, i.e. conductors, semiconducting materials, insulation and jackets?

	USEFUL				
CONDUCTORS	None	Low	Med	High	COMMENTS
Elongation					
Tensile Strength					
SEMICONDUCTING MATERIALS/INSULATOR					
Chemiluminescence					
Elongation					
Tensile Strength					
Density					
Contaminant Level/Nature					
Optical Microscopy					
SE M.					
SEM + EDS					
SEM + WDS					
FTIR Spectroscopy					
UV Spectroscopy					
PIXE					
NAA					
Ion Chrometography					
Contact Angle Measurements					
DSC					
TGA					
TMA					
DMA					
Tan δ (V)					
Dielectric Strength					
Tan δ (f)					
TSC					

4. What information on materials is needed to understand aging?

5. What new techniques have been developed in the last five years and which will aid in characterizing or detecting aging of materials?

6. What test geometrics do you consider to give the most realistic simulation of aging?

1= Least Effective 5 = Most Effective

W E T (LIQUID NATURE)		1	3	3	4	5
Needle/Plane	Liquid Electrodes					
Needle/Plane	SC Electrodes					
Uniform Field	SC Electrodes					
Uniform Field	Liquid Electrodes					
Scratched Surface	Liquid Electrodes					
Coaxial Geometry	Liquid Electrodes					
Coaxial Geometry	SC Electrodes					
D R Y						
Needle/Plane	Metal Electrodes					
Needle/Plane	SC Electrodes					
Uniform Field	Metal Electrodes					
Uniform Field	SC Electrodes					

7. What parameters do you use to assess your materials after aging tests?

	S E N S I T I V I T Y				
	None	Low	Med	High	C O M M E N T S
ACBD Test					
Time To BD Test					
Tan Δ					
Impulse Voltage BD Test					
DC Testing					
Analytical Techniques (Please Specify)					

8. Do morphological changes in the insulation/semicon occur during aging which can significantly affect the life? If so, what are they (Wet and Dry Conditions)?

9. Is diffusion of stabilizers (antitoxicolants and additives) and/or contaminants an important factor in aging? If so, what effects can occur? (Wet and Dry Conditions)

10. Do we have a good test to evaluate the retardant additives (Water and/or Electric Trees)?

11. **What factors do you think influence Cable Aging under Dry conditions?**

Legend:
None = 0 Low = 1
Med = 2 High = 3

	INFLUENCE			
STRESSES / FACTORS	**MV**	**HV**	**EHV**	**COMMENTS**
Field				
Temperature				
Temperature Cycling				
Frequency				
Residual Moisture				
Oxidation				
Residual Strain				
External Strain				
Compatibility (Materials)				
Contaminants in SC				
Contaminants in Insulation				
Shrinkback				
Processing Conditions (Dry/Cool)				
Adhesion				
Insulation Morphology				
Neutral Design				
Thermal Expansion Effects				
Residual Byproducts				
Interfaces				
Neutral Design				

PLEASE GIVE A BRIEF EXPLANATION OF MED/HIGH INFLUENCES

Partial Discharges					
Others					
Insulation Wall Thickness					
Extrusion Profile					

12. What factors influence cable aging under wet condtions?

Legend:
None = 0   Low = 1
Med = 2   High = 3

	INFLUENCE			
	MV	HV	EHV	COMMENTS
Field				
Temperature				
Temperature Gradient				
Temperature Cycling				
Residual Moisture				
External Water				
Contaminants in SC				
Contaminants in Water				
Contaminants in Insulation				
Presence of Jacket				
Type of Conductor (Sold/Stranded)				
Frequency				
Oxidation				
Residual Strain				
External Strain				
Processing Conditions				
Adhesion				
Interfaces				
Repeated Impulses				
Insulation Morphology				
Type of SC				
X-Linking Byproducts				
Partial Discharges				
Strand Fill				
Moisture Barriers				

13. Aging of Accessories

What factors influence aging of accessories?

Legend:
None =0 Low = 1
Med = 2 High =3

	INFLUENCE			
	MV	HV	EHV	COMMENTS
Field				
Temperature				
Temperature Cycling				
Frequency				
Compatibility of Materials				
Adhesion				
Residual Strain				
External Strain				
Thermal Expansion				
Connector Design				
Voltage Rating				
Current Rating				
Mechanical Vibration				
Partial Discharges				
Type of Material				

Please make comments about any Med/High Influence

14a. <u>Testing Accelerated Aging</u>

What test parameters should be used to accelerated aging of cables/ accessories?

DRY (EHV)

PARAMETERS	LEVELS LDPE		XLPE		EPR	
	Min	Max	Min	Max	Min	Max
Field (kV/m)						
Temperature (Celcius)						
Cycling (Temperature)						
Frequency Hz						
Repeated Impulses						
Mechanical Strain						
Time						
DC Application						

14b. **WET (HV)**

PARAMETERS	LEVELS LDPE		XLPE		EPR	
	Min	Max	Min	Max	Min	Max
Field (kV/m)						
Temperature (Celcius)						
Cycling (Temperature)						
Frequency Hz						
Repeated Impulses						
Mechanical Strain						
Time						
DC Application						

14c. <u>WET</u> (MV)

L E V E L S

PARAMETERS	LDPE		XLPE		EPR	
	Min	Max	Min	Max	Min	Max
Field						
Temperature						
Temperature Cycling						
Frequency						
Water Inside (Yes/No)						
Water Outside (Yes/No)						
DC Application						
Types of Contaminants						
Contaminants Concentration						
Mechanical Strain						
Impulses (Yes/No) [Repeated]						
Time						
Water Nature						

15. **What methods are used to analyze the data? (E.g. do you use Wiebull, Log-normal Statistics, GMTF or Other?)**

16. **What theoretical model of aging do you use?**

17. **What additional tests should be performed on accessories?**

18. **Is there a national standard for aging tests under wet or dry conditions? If so, please name them.**

19. <u>Diagnostic Tests</u>

What tests do you use to assess the degree of aging after accelerated aging tests or field aging?

Legend:
None =0 Low = 1
Med = 2 High =3

	SENSITIVITY			
TEST	MV	HV	EHV	COMMENTS
AC Ramp BD Test				
AC Step BD Test				
AC Constant Stress Test				
Impulse Voltage				
DC BD Test				
Tan δ (v)				
Tan δ (f)				
DC Leakage Current				
Partial Discharges				
Low Frequency Testing				
Oscillating Wave Testing				

20. Do you conduct in situ tests to measure aging? If so, which ones?

21. What factory and installation tests do you conduct for transmission class cables ($\geq$ 138-kV)?

22. Service Experience

a. What is your experience of aging or service of cables?
(Transmission and distribution [with and without a moisture barrier]).

b. What techniques are available to rejuvenate aged cables?

c. Have you tried any? If so, what is your experience?

d. Is there an in-situ test to predict remaining life? (Dry or Wet Conditions)

e. What kind of research would you suggest?

f. Can you relate cable failure to installation data of that cable?

23.

PRESENT PRACTICE

VOLTAGE kV	AVERAGE STRESS kV-MM	MATERIAL XLPE,LDPE,EPR,ETC	WATER IN CONTACT WITH INSUL YES/NO, LAM/SHLD	
15				
35				
69				
138				
275				
400				
500				

Appendix E

WORKING GROUP ON MATERIALS - DETAILED REPORT

by JOHN TANAKA, SECRETARY

The working group on Materials Aging and Diagnostics met at 2:00pm under the chairmanship of Bruce Bernstein.

Bernstein first asked for the number of people who wished to give reports. About four to five people responded. Bernstein then outlined the rules to be followed. He pointed out that this working group was to confine itself to materials since cables were being covered in a parallel working group. At the start, the results of the survey covering materials would be reviewed. Then after the presentations and discussion, it was hoped that objectives could be formulated toward the close of the session. With the procedures clarified, Bernstein went on the summarize the survey. In order to derive a feeling as to what items people considered important, Bernstein chose to count the number of people who rated a particular item a "3" or highly important. There were 18 responses tabulated for the dry condition (one was a faulty xerox copy which could not be read) and 19 responses tabulated for the wet condition. The separate items under the categories of aging, diagnostics, test geometry, assessment methods, and morphology changes were shown with the number of "3" responses for each sub-item.

Andras Farkas of NESTE reported on the lab testing of XLPE prepared with their water tree retardant. The uniform field approach using the CIGRE methodology known as EFI/Eb was used. The voltage stress was 15 kV/mm with temperature cycled 16 hours at 90°C and 8 hours at 7°C. The aging time was 3 and 8 weeks. There was a significant difference (a factor of 1000) in the number of bow tie trees when the water tree retardant sample was compared to a standard XLPE sample. When AC breakdown was used, the water tree retardant samples maintained a high breakdown value whereas the breakdown values for the standard XLPE were found to degrade. A typical breakdown for the water tree retardant samples after 16 weeks was about 78 kV/mm whereas 90% of the standard XLPE samples had failed and those surviving had dielectric strength of around 10 kV/mm. Finally, since electrical trees have been reported to grow from water trees and since electrical trees are more detrimental to the health of a cable than water trees, a double needle test was used at 50% and 80%

relative humidity to grow electric trees. The inception voltage showed better results for the tree retardant samples than for the standard XLPE.

Reinhard Schroth of Siemens reported on the aging experiments on full sized cables made with the same tree retardant material. The cables were made on a standard CV line. The construction included an insulation shield, a copper wire screen and a jacket. A CIGRE common test was run for 250 days. The results of the testing was compared with a XLPE cable of the type which has had 20 years of service experience. The bow tie tree count obtained by aging at 40°C for 1000, 2000, and 6000 hours was about four orders of magnitude lower for the cable containing the tree retardant. The number of vented trees in the tree retardant cable was about six times lower than for the standard XLPE. The AC breakdown degraded with aging for the standard XLPE but was not degraded as much with the tree retardant.

The cables were also tested using the AEIC test protocol for 300 days. There was a good correlation with the CIGRE test. The density and number of bow tie trees was much less in the tree retardant cable. The AC breakdown voltage was more stable to degradation with age for the tree retardant cable. It was concluded on the basis of comparison with the standard XLPE cable that the tree retardant cable will be long lived.

Jean-Pierre Crine of IREQ asked which type of trees are more important, the water trees or vented trees? Schroth said that he knew how to do the tests but was not as certain about interpretations. However, without making a judgement on which is important, it should be noted that both were reduced. Crine noted that the AEIC results did not show the results for vented trees. He asked whether differences were observed in the bow tie trees and vented trees. Schroth responded that the data had been collected. The results were similar to the CIGRE common test. The results of the CIGRE test should be considered to be representative.

Crine asked whether the tree retardant used was that developed by Siemens. Farkas responded that the tree retardant represented the combined technologies of Siemens and NESTE.

Bernstein asked whether the additive could be described as a partial discharge suppressant. Schroth responded by observing that the tree retardant material was highly dispersed in the polyethylene. The implication seemed to be that it was not a partial discharge suppressant.

Emmanuel Brancato, consultant, observed that the ratios of values obtained for the tree retardant cable and the water tree retardant cable were reported. He wondered whether the ratio of cable life could be obtained from these other ratios. Schroth felt that projections of this type are not necessarily valid.

Bob Eichhorn of Union Carbide observed that the data were very interesting but were only the final points. He noted that none of the fundamentals were being reported. For example, what is the system? How does it work? Without information of this type, the results are commercial rather than scientific. Farkas responded that there wasn't time in the schedule to discuss all the fundamentals. Briefly, the water tree retardants are selected from a series of active compounds which inhibit formation of hydroperoxides. The retardants suppress radical formation. In standard polyethylene, radicals form more rapidly than can be reacted with the antioxidants present. The tree retardant is more effective than the usual antioxidant for preventing peroxide formation. The hydroperoxide inhibitor is part of a copolymer system.

Ben Hwang of B.P. Performance Polymers asked whether the jacket was removed in testing. Schroth said yes. Bernard Dalle from EDF-DER-CIMA reported that insulated cables have been studied for a long time in France for thermal, dielectric, mechanical, and hydrolytic aging. These studies have shown that when humidity is prevented from getting into a cable by use of a lead sheath, there is no water treeing. However, EDF, the manufacturers, and materials suppliers have decided that diagnostic tools are needed to study the effect of morphology of the insulation and the interface between the semicon and insulation. To this end, the universities, manufacturers, and suppliers are evaluating a number of diagnostic tests to be applied to this problem. Work has been initiated, but the program is just coming to the end of its first year, and results have not been achieved.

Dalle also described the pressure wave propagation method of determining space charge in an insulating material. J. Lerwiner has developed this method and has succeeded in measuring the space charge in an intact cable insulation. Eugene Favrie of SILEC has applied this method to a cable system. Semicons can contain 1% zinc stearate and larger amounts of plasticizers. Zinc stearate was found to diffuse into the insulation and cause a large increase in the space charge. When the zinc stearate is eliminated from the semicon, the space charge did not increase very much. It was postulated that the plasticizer facilitated the diffusion of zinc stearate into the insulation.

Crine asked for the identity of the supplier of the shield material containing the zinc stearate. Dalle did not know the supplier. Bernstein asked whether the main point of the presentation was that the pressure pulse method was a new diagnostic tool. He noted, in any case, that it was a diagnostic tool not on the list. Crine noted that there was another important point in that a component of the shield had migrated into the insulation.

Brigitte Fallou of LCIE, France, noted that sometimes we look for something at a place that is convenient rather than where the problem might be located. She noted the change in the tanδ of high density and low density polyethylene with temperature and with aging. The unaged tanδ vs. temperature curves are rather flat. After aging, noticeable peaks form. Because of the shape of the curve, the measurement temperature is important. It was suggested that tanδ was an index of aging properties and probably could be correlated to other aging properties such as elongation to break. Another example of a criterion for accelerated aging as a function of combined stresses was the time needed to reduce the breakdown voltage by 15%. The temperature index available from thermal aging studies was suggested as a means of giving ranking to materials. The evolution of gases, namely CO, CO_2, and H_2 can be related to life for polyethylene terephthalate. Because short time tests are needed to project life data, diagnostic tests are important in measuring the beginnings of degradation. Christian Mayoux from Universite Paul Sabatier commented that the results of GC analysis must be used with care. He quoted results of hydrogen evolution from XLPE under two different conditions. The amount of hydrogen observed was quite different for the two experiments.

Roger Porter of the University of Massachusetts asked for a clarification. He noted that polymers do not spontaneously decompose. He wondered how the gases originate. Fallou said that high temperatures were not being used. The experiments were suggested by the gas analysis from transformers. The degassing was from initial decompositions (which by inference was from electrical stress).

Tom Dakin, consultant, asked whether hydrogen evolution parallels the gas evolution observed in transformers. Fallou responded that the gas evolution is a short term test to predict changes in longer term tests such as mechanical properties.

Bernstein asked whether the decompostion could be correlated to aging. Fallou said that the decomposition was a short term indication of aging. Porter pointed out that the amorphous regimes in a polymer can contain dissolved gases. He pointed out that these might complicate the gas decomposition studies. Martin Broadhurst, of the National Institute of Standards and Technology, said he had learned a lot from the EPRI and Union Carbide projects studying space charges. The space charges induced in a polymer were found to evolve with time. The flow of these charges in the polymer might be capable of carrying out chemistry. Bernstein commented that generalized changes were most easily measured. Gas evolution is a generalized change. Failures, on the other hand, are site specific. Generalized changes may not always reflect the changes at the failure site. Crine commented on the micro cavity formation. Some tiny spots are evaporated. Some gases are probably formed. What does this mean with respect to failure time?

Christian Mayoux from Universite Paul Sabatier described two experiments to study the degradation of polymers by partial discharge. In the first experiment, Mayoux creates a long channel (1 mm to 1.3 mm) in low density polyethylene by molding a wire in polyethylene and then extracting it leaving the hollow channel. A flat electrode is pressed against one end of the channel. A wire electrode is inserted from the other end of the channel leaving a gap between the point plane electrodes of 1 mm to 5 mm. A single pulse of 85-μs rise time and 200-μs decay was imposed on the gap in the channel. Different species were found to impinge on the surface of the channels. The surface of the channels were changed. Some antioxidants and oligomers were found. There was gas evolved. Light emission spectroscopy was done. The discharge occurs as in air until the ratio of the channel diameter to electrode gap is lower than 0.20. The surface of the channel was studied with IR. In the second experiment, an apparatus was constructed which contains ion and electron guns. These sources allow formation of ions and electrons with energies of 20 eV to 300 eV and current densities of 0.25 $\mu A\ mm^{-2}$ for ions and 0.50 $\mu A\ mm^{-2}$ for electrons. A polyimide sample was exposed to these corona like ions and electrons. The electrical characterization after the ion and electron bombardment was with thermally stimulated current. These two novel and interesting techniques are being used to study the nature of partial discharge degradation of insulating materials.

Bernstein asked whether the aging behavior or the life of the polymer was being studied. Mayoux said that the aging mechanism was being studied, not life. Armin Bruning of Lectromechanical Design asked about the energy of the discharge in the channel. Mayoux said that this could be determined, but had not yet been done. Argon ions of 25 eV, 45 eV, and 95 eV had been used in the second experiment. Also differences were found between argon ions and nitrogen molecule ions.

Tony Barlow, Quantum, commented on morphology and secondary crystallization. This latter was defined as polymer chains forming lamellae and spherulites at temperatures below the melting point in order to achieve a lower energy configuration than that produced in the extrusion process. When microvoids are measured by optical spectroscopy, they are found to increase. This is ascribed to the secondary crystallization. Because of the pseudo laminar flow during extrusion, it is expected that the center of the insulation would exhibit more secondary crystallization than the portion near the surfaces. This is borne out by the data. Another evidence that the polymer molecules are undergoing movement during secondary crystallization is the observation that when a slab of a virgin polymer and a slab containing antioxidant are placed in contact, the antioxidant is found to migrate from the antioxidant-containing slab into the virgin polymer. The next question is whether the same effect is observed for cross-linked polyethylene. It has been found that dry cured polyethylene do generate voids. These are about 2 μm in size with 47 voids/mm^3 being observed. Since the XLPE was prepared with a similar material and the same extrusion equipment, it would seem that the processing condition has an effect on the microvoid population.

Bernstein asked whether microvoids of this type are significant. Barlow said yes, they may coalesce and get larger. Bernstein asked what would happen to the hypothetical cable which operates at temperatures no higher than 40-50°C? Barlow felt that microvoids would also grow in these cables. Porter suggested an alternate hypothesis. He wondered if additives could phase separate and then diffuse away leaving a void. Eichhorn observed that in steam cured cables the water phase segregates and forms a halo. However, on the loss of water, the voids do not necessarily remain. He also observed that, with some antioxidants, there is an agglomeration. These remain and have been known to be the initiation point for trees. These two observations are thus counter to Porter's alternate hypothesis. John Tanaka, University of Connecticut, asked whether the halos which are often observed to be at the center of the insulation are related to the microvoid formation? Barlow did not have an answer.

Jean-Marie Braun of Ontario Hydro described a technique which is being developed for filled epoxy spacers used in switchgear. This is a diagnostic technique which can probably be applied to cable insulation. Very small voids do not initiate discharges in a consistent manner. In general, discharges are started by free electrons generated by cosmic rays which are then accelerated in the field causing collisions with the gas molecules present and generating secondary electrons and ions. Very small voids are less apt to be hit by cosmic rays and insufficient electrons are created to enable discharges to initiate. The technique being developed for the epoxy spacers is to irradiate the microvoid with X-rays. This creates a sufficient number of electrons so that a true inception voltage is observed for microvoids. The X-ray can be focussed to find the site of a microvoid. If the beam is irradiating a microvoid, a partial discharge is detected. If the X-ray is turned off or moved, the partial discharge ceases. If there are no microvoids, no partial discharge is detected. The technique has been shown to work by using a 0.1-mm void purposely put in an epoxy spacer.

Bernstein asked whether the X-ray would degrade polyethylene. Braun said that the X-ray was tunable and that the energies could be adjusted to appropriate levels. Eichhorn asked about the target. Braun believed that it was the K_α lines of tungsten. Brancato asked about the inception voltage. Braun said that the inception voltage was sufficient to give partial discharge in large voids. It was not so high as to give a glow discharge.

At this point, Bernstein initiated the wrap-up for the session. The survey results were put on the overhead and the audience was asked whether any of the parameters should be reevaluated. The first survey results to be discussed were the categories under Aging.

Brancato noted that time was the most important parameter. There would be no aging without time. Mayoux felt that field and time were related and should be yoked. Hwang felt that external water and field needed to be combined. Neither stress by itself would cause appreciable deterioration of the insulation. Bruning asked about the effect of water in the field. Eichhorn noted that polyethylene saturates at about 0.1% water. When there is a field present, more water enters the polyethylene. This is due to the electrophoretic effect under either an AC or DC field. The temperature rise and thermodynamics tend to counter this effect and will push the water out. Joe Dudas, consultant, in response to the low score given temperature gradient, said that he had a problem with this. Temperature and temperature gradient are always a significant factor and they should go together. Tony Doepkin, Cablec, commented that he agreed but that he had not given it a "3" rating. Only "3" ratings were counted for the overhead being shown. Eichhorn commented that Densley had observed in accelerated life tests that room temperature effects were greater for polyethylene than high temperature effects. Eichhorn said that he had made the same observations. However, EPR shows opposite effects. Bernstein wondered whether this was a temperature gradient effect.

Tom Rodenbaugh, EPRI, noted that for studies of semicon contamination, temperature gradients would be needed. Bernstein commented that Phillips' work and Katz's work showed that microvoids increased with temperature of thermal load cycling treatment and that there was a relationship between aging and breakdown. Fallou pointed out that the magnitude of the temperature was important. Tests run in France show that at certain elevated temperatures, new phenomena appeared. These were not necessarily real world phenomena. It is important to recognize the temperature of the transition points.

Eichhorn asked about temperature cycling. This should be added to the list. Bernstein noted the low score for high frequency testing. Eichhorn thought it might be important, but no other comments were made. Bernstein noted the low score for morphology. Perhaps many people were not aware of the results of the work on morphology. With the introduction of the subject of contamination, Hwang commented that he was surprised that it did not get more votes. Broadhurst wondered about contamination and field enhancement. Should these be coupled? Eichhorn pointed out that residual moisture does not belong in the wet environment testing. Barlow concurred saying that since the sample was placed in water the residual moisture was insignificant.

The next category to be discussed was Diagnosis Techniques. Bernstein observed that the survey seemed to indicate that the diagnostic techniques for 1970 are adequate. The lower significance placed on some of the more exotic techniques might be due to unfamiliarity. Fallou asked whether the diagnostic methods listed were only for materials. Bernstein said yes. Bernstein commented that chemiluminescence was so sensitive, it was difficult to interpret the results. Work done under EPRI contract seemed to indicate that for dry aging the most important aging parameter was oxidation resistance which was followed by elongation to break and then electrical properties (ACBD). For wet environments, the order was electrical properties, oxidation, and then elongation.

Crine noted that density changes slowly over time due to increased crystallinity. Tanaka pointed out that Sandia had found density changes a useful way to follow oxidation. Broadhurst noted that perhaps the modulus and yield properties of polyethylene would change 10% for a 1% change in density. Eichhorn observed that DSC is an important tool for materials development. For example, the effectiveness of an antioxidant can be quickly evaluated. Micro IR and FTIR are useful. The micro IR, in particular, enables a small spot to be analyzed. Porter asked about the use of microscopy for determining the number and length of trees.

Willem Boone, KEMA, felt that the life of a cable is correlated to the size of the trees. Doepkin responded that in a study of 7 or 8 HMWPE field aged cables, they did not get a correlation of cable life with tree size. Doepkin felt that, in general, it was difficult to get this type of correlation. Bernstein noted that TGA and TMA were both rated low. He felt that this is as it should be. Porter agreed. Bernstein wondered if anyone had looked at tanδ as a function of frequency. Was there a possibility that as a diagnostic tool a frequency different from 60 Hz should be used? Brancato felt that the results would be the same at different frequencies.

Bernstein noted that dielectric strength had been used by Neste as their criteria of a desirable material. Rodenbaugh asked Doepkin whether the tanδ obtained in the laboratory correlated with field experience. Doepkin said that there was a correlation and that it was datum which an engineer needed to know. Hwang pointed out that there was a Sumitomo paper in which voltage life had been determined by tests on a plaque.

The discussion meeting was adjourned at 5:00 pm.

Appendix F

ACRONYMS AND ABBREVIATIONS

ACBD - ac breakdown
AEIC - Association of Edison Illuminating Companies
AWG - American wire gauge
BD - breakdown
CEA - Canadian Electrical Association
DSC - differential scanning calorimetry
E - field
EDF - Electricite de France
EEI - Edison Electric Institute
EHV - extra high voltage
EPDM - ethylene-propylene-diene monomer
EPR - ethylene-propylene rubber
EPRI - Electric Power Research Institute
FTIR - Forier transform infrared spectroscopy
HMPE - high molecular weight polyethylene
HMWPE - high molecular weight polyethylene
HV - high voltage
ICC - Insulating Conductors Committee (of IEEE Power Engineering Society)
IEC - International Electrochemical Commission
IEEE - Institute of Electrical and Electronics Engineers
IR - infrared
IREQ - Institut de Recherche d'Hydro-Quebec
LDPE - low-density polyethylene
MV - medium voltage
NELPA - Northwest Light and Power Association
PD - partial discharge
PE - polyethylene
PVC - polyvinyl chloride
SAXS - small angle x-ray spectroscopy
SC - semiconducting material or layer
semicon - semiconducting layer
TR - tree retardant
TRXLPE - tree-retardant cross-linked polyethylene
TSC - thermally stimulated currents
UNIPEDE - Union of Producers and Distributors of Electricity in Europe
UV - ultraviolet
VHV - very high voltage
WAXS - wide angle x-ray spectroscopy
XLPE - cross-linked polyethylene