FIELD MONITORING OF PARAMETERS AND TESTING OF EP AND TR-XLPE DISTRIBUTION CABLES

C. Katz and B. Fryszczyn
Fellow, IEEE Non-Member
Cable Technology Laboratories, Inc.
New Brunswick, NJ 08903 USA

A.M. Regan and W.A. Banker
Member, IEEE Member, IEEE
Orange & Rockland Utilities, Inc.
Pearl River, NY 10965 USA

B.S. Bernstein
Fellow, IEEE
Electric Power Research Institute
Washington, D.C. 20036 USA

Abstract: Five commercial ethylene-propylene rubber (EP) and one tree-retardant cross-linked polyethylene (TR-XLPE) 15 kV cables are being aged in the laboratory, and in field service on a utility distribution system. The cables were obtained from six different manufacturers. This study subjects commercially available, widely used EP cables, and one TR-XLPE cable to similar conditions at three different sites. Two test sites are located at Orange and Rockland Utilities' (O&RU) distribution system. The first is in normal 15 kV service; the second is a normal 35 kV service site, with the cable aging under accelerated voltage conditions. Line voltage, voltage surges, load current, earth, duct and cable temperatures on the systems are being field monitored. Cable Technology Laboratories (CTL) has provided an accelerated aging set-up for the third site. This paper describes the methodology, characterization testing and some preliminary results from this project.

Keywords: Cable, 15 kV, ethylene-propylene rubber, tree-retardant cross-linked polyethylene, field and laboratory accelerated aging, field monitoring, characterization testing.

I. INTRODUCTION

While the in-service degradation of primary XLPE cables has received significant coverage, little work has been reported on the analysis of in-service aged EP and TR-XLPE insulated cables [1,2,3,4]. Accumulated data on aged cables suggest that XLPE and EP cables undergo aging and loss of life via rather different mechanisms, and that the aging of EP cable is much more complex [5,6,7]. It is not surprising that mineral-filled elastomers (EP) would respond differently from semi-crystalline unfilled polymers (XLPE), under the same aging conditions. Manufacturers use different proprietary compound formulations for EP cables, which makes it difficult to draw conclusions regarding the general performance of these cables.

II. PURPOSE AND OBJECTIVE

There are two primary objectives to this project. The first is to determine if a generalized accelerated aging procedure for EP cables can be established. For this purpose, a field aging study was set up, and laboratory aging conditions are being modified based on field results. In this manner, it is anticipated that the laboratory conditions will provide a more representative aging environment. The second objective is to determine if the performance and life expectancy of different types of EP cables can be generalized and estimated. This project also includes TR-XLPE cable as a control, so that the results can be compared with previous aging studies. Additionally, research has improved testing techniques and diagnostic equipment, to make measurements of in-service performance of cables less difficult. This project, sponsored by EPRI, ESEERCO, O&RU, and CTL, aims to take advantage of these new techniques, as well as to supplement present research.

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III. TEST CABLES AND AGING SITES

Test Cables. Five EP, and one TR-XLPE 15 kV cables, having similar designs, were acquired by O&RU for this study. Each cable was made by a different manufacturer during 1994 - 1995. The cable construction requested was 107 mm^2 (No. 4/0 AWG), 19 strands compressed copper conductor, 0.38 mm extruded semiconducting conductor shield, 4.45 mm (175 mils) EP or TR-XLPE insulation, 0.76 mm extruded semiconducting insulation shield, and 20 - 5.26 mm^2 (No. 10 AWG) tin coated copper concentric neutrals.

Field Aging Setup. Two sites were chosen to age the cable while operating on the distribution system at O&RU. At the first site, the 15 kV cables are operating at 13.2/7.62 kV, grounded wye. At the second site, they are installed on a 34.5/19.9 kV grounded wye system (operating at $2.5V_0$). A description of each test site follows.

15 kV Aging Site. The site is located along a local roadway, across a golf course. The installation is a 670 m underground section of circuit mainline, installed in three manholes connected by 2 - 15 cm concrete encased PVC conduits, and buried 0.75 m below grade. The cables are paralleled per phase, and terminated on 200 A load break connectors (LBC's) in the manholes, and on 600 A disconnect switches at the riser poles. Underground metal oxide varistors (MOV's) provide surge protection for the cable system at each riser pole. Monitoring thermocouples are installed on each cable insulation shield, on the exterior of the conduits, and outside the duct system in the earth, approximately 15 m in from each riser pole. One three-phase circuit was installed in each of the conduits. A diagram of the 15 kV system is shown in Fig. 1, which shows the cable in the conduits, by section.

35 kV Aging Site. The site is located at an existing condominium subdivision. The cables provide an underground express feed to the rear of this subdivision. The project cables comprise approximately 760 m of the express feed, paralleled on each phase. The system is installed in three boxpads connected by 2 - 15 cm, and 1 - 10 cm, PVC conduits, direct buried to 0.75 m below grade. Monitoring thermocouples were installed in similar locations as on the 15 kV

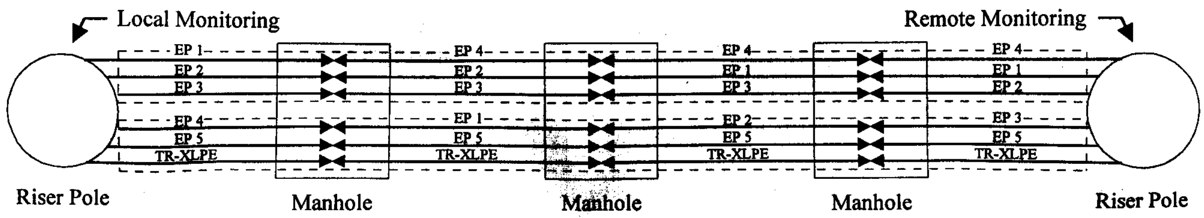

Fig. 1 - 15 kV Site Diagram

system. One three-phase circuit was installed in one of the 15 cm conduits, while the other circuit was installed in the remaining 15 cm and 10 cm conduits. There was concern that one of the cables, with a higher dissipation factor, would cause excessive heating. This cable was installed by itself in the 10 cm conduit. The cables are terminated on 35 kV, 200 A LBC's in the boxpads, and at padmounted switchgear at the remote ends. Underground MOV surge protection was provided at the riser poles, and at the system open points. Underground padmounted breakers, with overcurrent and undervoltage protection, were installed at both ends of the cable system. The protection consists of a selective and coordinated tripping scheme utilizing a fiber optic communications system. A diagram of the 35 kV system is shown in Fig. 2.

Laboratory Aging Setup. The cables were formed into coils, each 27.5 m in length, and placed into polymeric tanks filled with water [8]. Tap water temperature initially was 30^{o} C ± 5^{o} C. Water was also placed in the conductor interstices. De-ionized water is used to make up for evaporated water from the tanks and the conductor. Voltage is applied continuously at 20 kV to ground ($2.5V_O$). The setup is equipped to apply standard 1.5 x 50 µs voltage impulses [9], and to adjust water tank temperatures, to reflect monitored field conditions.

IV. DATA ACQUISITION SYSTEM

Temperature Monitoring System. An automated data acquisition and communication system, utilizing thermocouples at various locations, provides temperature monitoring at both field sites. There are 48 thermocouples installed at each site, with 24 active and 24 spare, as detailed in Fig. 3 for the 35 kV site (installation at the 15 kV site is similar). The monitoring system consists of 6 temperature recorders at each site. Three are AC powered units, and the other three run off batteries. The battery powered recorders provide backup in the event of a possible loss of AC power. Each recorder has 4 input channels. Data are sampled at a rate of 1 event per second. The units permanently record the minimum, maximum, and average temperatures on an hourly basis, and have a storage capability of 44 days before needing to be downloaded. The AC units are remotely downloaded via a telephone line and modem. The DC units are downloaded using a portable computer.

Voltage/Current Monitoring System. All 3 phase voltages and the 6 line currents are continuously recorded at each field site with 2 line recorders. Each recorder has 3 voltage and 3 current input channels. The units are AC powered, and have battery backup to hold data in case of power failure. Voltage is measured 16 times each half cycle, and the true RMS value is stored. The units permanently record the minimum, maximum, and average levels on an hourly basis. These recorders have a storage capability of 270 days before needing to be downloaded. In addition, events such as sags, swells, and impulses, with the exact time-stamp of the event, are captured. Each unit holds 150 events before overwriting the oldest data. All of these units can be remotely downloaded via a telephone line and modem.

Field Results. Fig. 4 shows partial temperature data from the 35 kV field site, from January 1996 to June 1998. All cables follow a similar to ambient temperature pattern, at slightly different levels. They are lightly loaded like many typical URD subdivisions. Cable temperatures at the 15 kV site also follow an ambient pattern, and on average are 3 to 5^{o} C cooler in the winter, and 0.5^{o} C warmer in the summer. Line voltages at both field sites are operating between 1.0 and 1.04 of nominal. On average, line currents on each of the cables at the 15 kV site was 10 A, and at the 35 kV site, 2.5 A. All recorded voltage transients can be related to system events such as switching and lightning.

Use of Field Data in the Laboratory. Data collected at the 35 kV site is analyzed to adjust laboratory aging parameters as close to field conditions as possible. The 35 kV site was chosen since the field and laboratory cables are operating under the same $2.5V_O$ voltage conditions. As a result, the temperature of the water in the laboratory tanks is regularly adjusted to approximate the actual cable temperatures measured at the field site. The number of impulses applied in the laboratory is based upon the number of voltage transients experienced at the 35 kV site, during a set period of time. Presently, 80 kV, standard 1.5 x 50 µs surges are being applied twice a month in the laboratory.

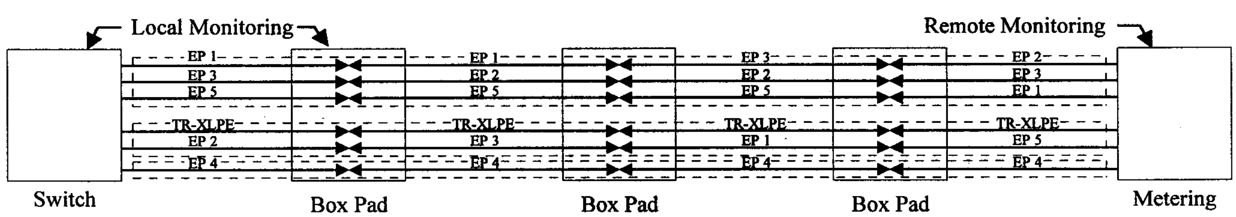

Fig. 2 - 35 kV Site Diagram

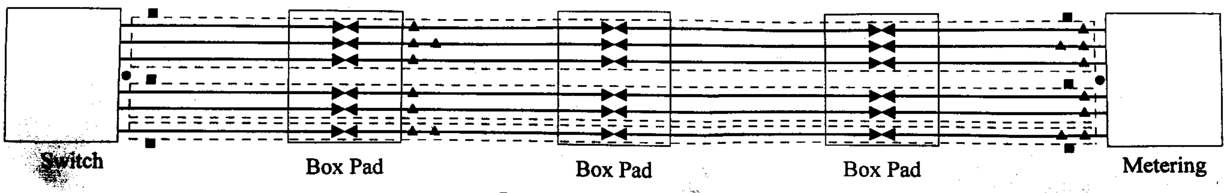

Fig. 3 - Active Thermocouple Locations at the 35 kV Site

V. EVALUATION OF CABLES

Characterization of New Cables. Cables were ordered to comply with AEIC Specification requirements [10,11]. CTL performed tests on samples from the delivered cables, as follows: dimensional analysis, microscopic examination for voids, contaminants and protrusions, insulation shield stripping, moisture content of the insulation, hot creep, partial discharge, volume resistivity of conductor and insulation shields, dissipation factor, AC and impulse voltage breakdown strength. Some deviations from the specifications were found, but were not considered significant.

Data on Aged Cables. Results are provided for the cables as received, after 7 months aging in the laboratory, and after 23 and 26 months in the field, at the 35 kV and 15 kV sites respectively. At the time this paper was prepared, the cables had completed in excess of 30 months of aging in the laboratory, however, only 7 month aging data were available. In addition to characterization tests, similar to those performed on the new cables, a water tree analysis was also done on the aged cables. Results of tests on cables from all three sites show that the stripping strength of the insulation shields, volume resistivities of the shields, and partial discharge did not change significantly from when new. However, in most cases water content, water tree analysis, AC and impulse voltage breakdown strengths changed. The results are provided as follows:

Stripping Strength: Except for the insulation shield of one cable, the insulation shield of all others, as received, met AEIC requirements. The exception showed none, or very limited adhesion to the insulation. Negligible changes were observed with aging of the cables at the three sites.

Dissipation Factor: Tests were performed at ambient temperature and rated voltage. The differences in the dissipation factor between new and aged insulation, for five of the six cables, were negligible. The exception is one EP cable that changed dissipation factor substantially when aged immersed in water, especially in the laboratory.

Partial Discharge: With the exception of one of the EP cables, the others tested below 5 pC, up to 35 kV. Negligible changes occurred with aging.

Volume Resistivities of Shields: All of the insulation shields, and all but one conductor shield, met AEIC requirements. Negligible changes were recorded with aging.

Water Content of Insulation: The water content was measured in the outer and inner 25% portions of the insulation of each cable, prior to aging, immediately after removal from the laboratory tanks, and immediately after receipt from the field sites. An automatic Karl Fischer type of moisture analyzer was used. Each value in Table 1 is the average of three measurements performed at each of two locations along the cable. It should be noted that: a) there is a greater increase in moisture content close to the insulation shield, as compared with the conductor shield, and b) two of the cables have a significantly greater increase in moisture content with aging than the others.

Water Tree Analysis: Thirty slices of insulation from each cable, cut close to the point where AC voltage breakdown occurred during laboratory tests, were examined. The insulation slices were dyed with methylene blue and examined with 15 to 60 times magnification. For the EP cables, the number of water trees observed at both surfaces of each slice is reported. For the TR-XLPE cable, the number of trees in the bulk of the insulation is reported. Most of the trees observed were bow-tie type. The results of the bow-tie water tree analysis are shown in Table 2. It is likely that more bow-tie trees exist in the EP cables than are depicted in Table 2. Only one vented water tree was found on EP cables aged 23 months at 2.5 V_0 in the field. None were found in the cables aged 26 months at V_0. For the laboratory aged cables, five vented trees were found in the TR-XLPE cable, and one in the EP cables.

AC Voltage Breakdown Strength: Tests were conducted at ambient temperature on individual 9.2 m samples. The effective length between terminations was approximately 6.2 m. Samples from the laboratory were promptly tested after removal from the aging tanks. Samples from the field were shipped promptly to the laboratory upon removal, placed in ambient temperature water, and tested as soon as possible, thereafter. During AC breakdown tests, the voltage was slowly increased to 17.5 kV, then increased every five minutes in steps equivalent to 1.6 kV/mm, until achieving breakdown. For each cable, five tests were performed. The AC breakdown strengths are based on the insulation thickness at the point of breakdown. The results were utilized to prepare statistical Weibull distributions, and the characteristic AC breakdown of each cable. Figures 5, 6, and 7 provide the AC voltage breakdown results. The EP values are shown as a range, encompassing all five types.

TABLE 1 - MOISTURE CONTENT OF INSULATION

	Water Content (weight/weight, %)			
Cable Identification	**New Cable**	**7 Mo. in the Lab at 2.5 V_o**	**23 Mo. in the Field at 2.5 V_0**	**26 Mo. in the Field at 1.0 V_o**
Close to the Insulation Shield				
EP	0.09	0.13	0.13	0.09
EP	0.11	0.13	0.13	0.10
TR-XLPE	0.04	0.25	0.26	0.17
EP	0.06	0.10	0.11	0.09
EP	0.13	0.40	0.35	0.21
EP	0.10	0.14	0.15	0.12
Close to the Conductor Shield				
EP	0.10	0.12	0.11	0.10
EP	0.10	0.12	0.11	0.10
TR-XLPE	0.04	0.23	0.11	0.12
EP	0.07	0.11	0.10	0.10
EP	0.15	0.37	0.29	0.21
EP	0.11	0.13	0.15	0.10

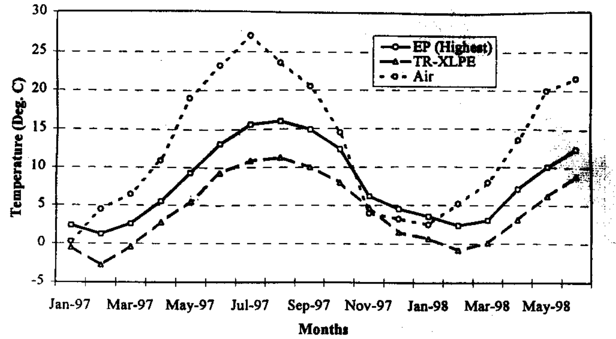

Fig. 4 - 35 kV Site - Field Temperature Data

Impulse Voltage Breakdown Strength: Impulse voltage breakdown strength tests were performed starting at Basic Impulse Level (BIL), applying three impulses of positive polarity followed by three impulses of negative polarity. Next, the voltage was increased in steps of 30 kV. At each level, three negative impulses were applied until achieving breakdown. The results were utilized to prepare statistical Weibull distributions, and the characteristic impulse breakdown used for preparing Figures 8, 9, and 10. The impulse breakdown stresses are based on the insulation thickness at the point of breakdown.

VI. DISCUSSION

Cables manufactured for utility use, without their normal jackets, were employed. The purpose was to use the same design of cables, and accelerate the diffusion of moisture from the environment into the insulation. The cables were obtained from six different manufacturers. Each EP cable is believed to be made with a different compound formulation. Also, the conductor and insulation shield materials may be different with each manufacturer. It is believed that this study includes the complete range of EP cables commercially available in the marketplace. To our knowledge, this project represents the first time that accelerated aging of extruded cables, at 2.5 V_O, is being conducted in the field. When combined with other accelerating factors, as for example the same average temperature, it provides a fair comparison between field and laboratory aging. It is of interest to note that in the field,

TABLE 2 - BOW TIE TREE ANALYSIS

Cable	EP	EP	TR-XLPE	EP	EP	EP
Range of Lengths (mm)	**Number of Trees**					
Aged 7 Months in Laboratory at 2.5 V_O						
0.05 - 0.12			149			
0.13 - 0.25		3	4			
0.26 - 0.50	1	2		9		3
Aged 23 Months in Field at 2.5 V_O						
0.05 - 0.12			4			
0.13 - 0.25		1	7	1		1
0.26 - 0.50	2		7			1
0.51 - 0.75			1	1		
Aged 26 Months in Field at 1.0 V_O						
0.05 - 0.12			10			
0.13 - 0.25			8			
0.26 - 0.50		1	1			

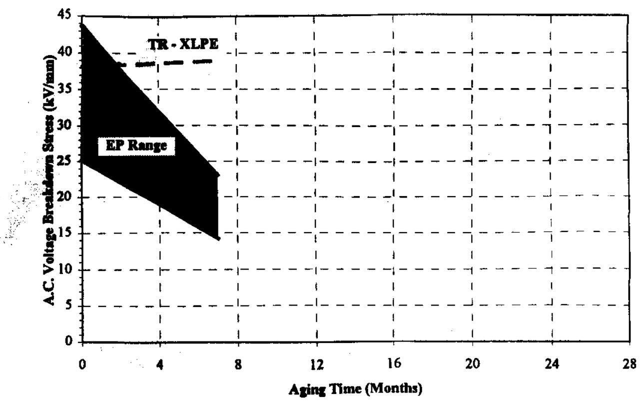

Fig. 5 - AC Breakdown Strength of Cables Aged in Lab at 2.5V_o

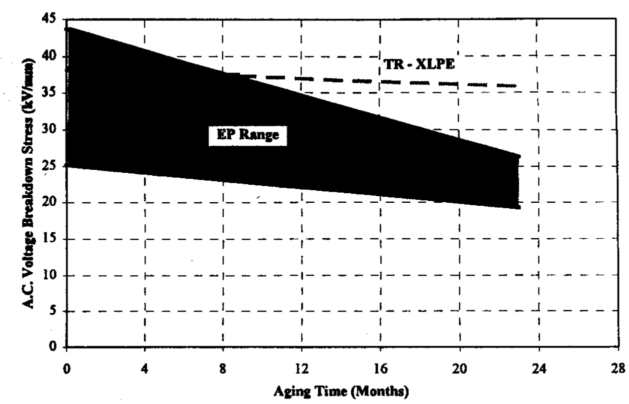

Fig. 6 - AC Breakdown Strength of Cables Aged in Field at 2.5V_o

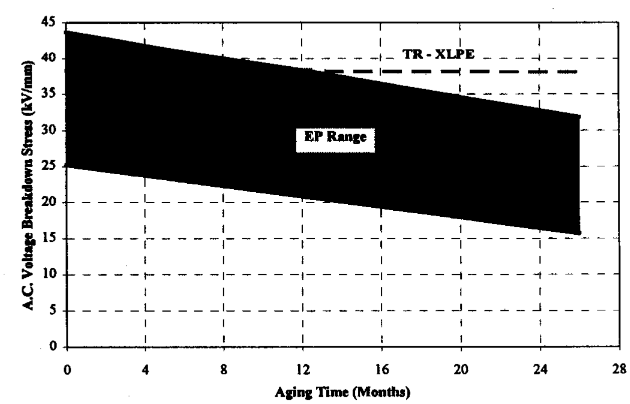

Fig. 7 - AC Breakdown Strength of Cables Aged in Field at V_o

temperature variations of the local environment are the overwhelming factor in the temperature change of the cables.

Although the cable conductor goes through daily temperature variations, the loads are not sufficient to significantly raise the cable temperature. This appears to be typical of suburban URD systems. The temperature of the water in the laboratory is periodically adjusted to be approximately that of the average cable temperature in the field.

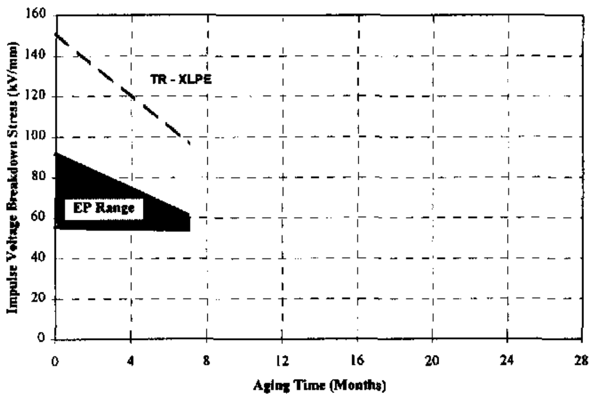

Fig. 8 - Impulse Breakdown Strength of Cables Aged in Lab at 2.5V_0

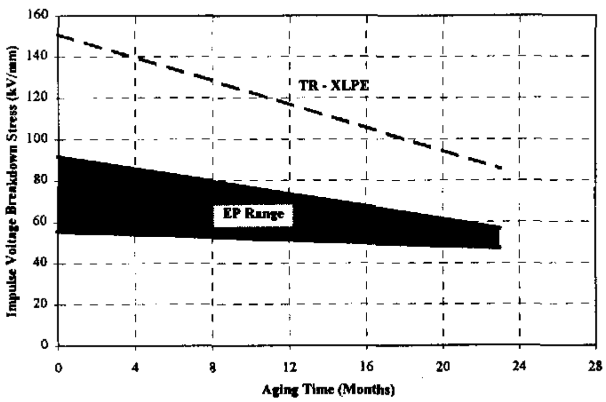

Fig. 9 - Impulse Breakdown Strength of Cables Aged in Field at 2.5V_0

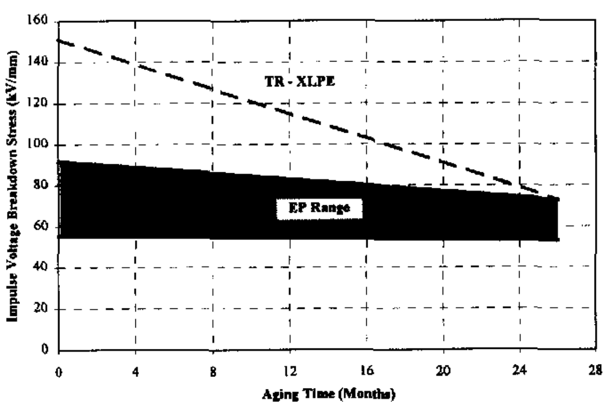

Fig. 10 - Impulse Breakdown Strength of Cables Aged in Field at V_0

The cables in the laboratory are aged with water in the conductor interstices, while immersed in water. This procedure gives maximum acceleration to the aging process. The cables at the 35 kV site, and to a lesser extent those at the 15 kV site, are in a terrain where the elevation varies. Therefore, there is a variation in the amount of water (if any) in contact with the cables along the route, and at different times of the year. This no doubt influences the aging of the cables, however, they have absorbed moisture, as shown in Table 1. Generally, moisture penetration into the insulation seems to be the overwhelming factor changing the characteristics of the cable, and lowering AC and impulse voltage breakdown strengths.

Tables 3 and 4 show the retention of AC and impulse voltage breakdown strength of the EP and TR-XLPE cables at the three test sites. With respect to AC voltage breakdown strength, except for one EP cable at the 15 kV site, all the other EP cables drop significantly. There is only a minor drop for the TR-XLPE cable at all three sites. With respect to impulse voltage breakdown strength, except for one EP cable which did not change its impulse voltage breakdown strength, all of the other EP cables dropped. The TR-XLPE shows a reduction of impulse breakdown strength, however, it is still above the EP cables. Although there was limited laboratory aging data (7 months) at the time of this report, the following comparisons can be made; in the laboratory, the AC voltage breakdown strengths of the EP cables have decreased more severely than those of the two field sites after approximately 2 years, and the impulse voltage breakdown strengths of these cables is close to that experienced in the field, also after 2 years. It should be noted that the moisture content of both the laboratory and field aged cables appears to be similar. Additional aging data will be reported as the study progresses.

TABLE 3 - Retention of AC Voltage Breakdown Strength

Cable Insulation	7 Mo. in the Laboratory at 2.5 V_0	23 Mo. in the Field at 2.5 V_0	26 Mo. in the Field at 1.0 V_0
EP Range	77 - 49 %	78 - 60 %	92 - 45 %
TR-XLPE	100 %	94 %	99 %

TABLE 4 - Retention of Impulse Voltage Breakdown Strength

Cable Insulation	7 Mo. in the Laboratory at 2.5 V_0	23 Mo. in the Field at 2.5 V_0	26 Mo. in the Field at 1.0 V_0
EP Range	100 - 58 %	93 - 58 %	96 - 67 %
TR-XLPE	64 %	57 %	48 %

VII. CONCLUSIONS

1. No EP or TR-XLPE cable failures have occurred at any of the three aging sites.
2. The insulation shield stripping tension, partial discharge and resistivity of the extruded shields have changed very little with aging.
3. Dissipation factor of one EP cable, and water content in the TR-XLPE cable and one EP cable, increased after aging at all three sites. All other cables show no significant change in these properties.
4. Most of the water trees found were of the bow-tie type. The TR-XLPE cable had the most trees. It is likely that more trees which may exist in the EP cables were not visible, since only slice surfaces can be examined.
5. With respect to the EP cables, except for one, the AC and impulse voltage breakdown strengths decreased at all three sites. With respect to the TR-XLPE cable, there is only a minor decrease in the AC voltage breakdown strength, while the impulse voltage breakdown strength decreased significantly, at all three sites.

VIII. ACKNOWLEDGEMENTS

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X. BIOGRAPHIES

Carlos Katz (M'70-SM'78-F'87) Born in West Germany on August 18, 1934. Received an Electrical Engineering degree from Polytechnic Institute of Quito, Ecuador in 1961, and a MS degree from Stevens Institute of Technology, Hoboken, New Jersey in 1970. From 1962 to 1971, he was associated with General Cable Corporation Research Center, and from 1971 to 1974, with the laboratories of Phelps Dodge Wire and Cable. In 1974, he became Assistant Director of R&D at General Cable Corp., and later Technical Director Power and Control Cables for General Cable International. He has been with Cable Technology Laboratories as Chief Research Engineer since its founding in 1978. Mr. Katz's special field of activity is the investigation of extruded and laminar dielectric high voltage power cables, the manufacture and properties of such cables, and the extension of service life of installed cables. Mr. Katz is the author of 33 technical papers, and holds 16 U.S. patents related to high voltage cables. He is a voting member of ICC and a member of CIGRE.

Bogdan Fryszczyn Born in Poland on April 24, 1943. Received his M.S. and Ph.D. degrees in Nuclear Physics from the University of Warsaw in 1965 and 1974, respectively. From 1965 to 1978, he worked as a Research Associate at Warsaw University, Warsaw, Poland. While associated with Warsaw University, he performed research work at the Joint Institute for Nuclear Research in Dubna, USSR (1966-1971) and at the University of Groningen, Holland (1973-1974). He has been associated with Cable Technology Laboratories since 1979, where at present he is a Senior Research Engineer. Dr. Fryszczyn's special field is the investigation of extruded distribution cables and their components, the behavior of cables in service, and the extension of life of these cables. Dr. Fryszczyn is the author of numerous technical papers on high voltage extruded power cables, and of several related U.S. patents.

Angelo M. Regan (M' 85) was born in Athens, Greece on August 23, 1963. He received his B.S. in Electrical Engineering in 1985, and his M.S. in Management Science in 1987, both from Fairleigh Dickinson University, Teaneck, New Jersey. Mr. Regan has been employed with Orange and Rockland Utilities, Inc., since 1987. As an Electrical Engineer in the Distribution Engineering Department (1988-1995), he was responsible for the standards, reliability, design and construction of high voltage underground transmission and distribution systems. Presently, as Manager of Retail Service Planning, his responsibilities include planning, protection, power quality, metering, reliability of both overhead and underground distribution, and design and construction of underground mainline distribution and transmission. Mr. Regan is a member of IEEE, a member of the AEIC Meter and Service Section, and a Registered Professional Engineer in the State of New York.

Wayne A. Banker (M'92) was born in Sugarloaf, NY, on May 1, 1966. He received his B.S. in Electrical Engineering from Clarkson University in 1991. Mr. Banker has been employed by Orange and Rockland Utilities, Inc., since 1992. As a Delivery Technology Strategist, his present responsibilities include protection, underground material standards, and the reliability, design, construction and maintenance of underground mainline distribution and transmission systems. Mr. Banker is a member of IEEE, a member of the Insulated Conductors Committee, a member of the AEIC Cable Engineering Section, and a Registered Professional Engineer in the State of New York.

Bruce S. Bernstein (F'92) Mr. Bernstein was Born in New York City, attended City University of New York, Brooklyn Polytechnic Institute, and has a M.S. degree from Iowa State University. He is technical advisor with the Energy Delivery Utilization Division (EDU) of the Electric Power Research Institute (EPRI), head-quartered in Washington, DC. He joined EPRI in 1977, and has been involved in guiding extruded cable and material studies for several EDU programs, and for the Strategic Science and Technical Group. He has coordinated numerous EPRI workshops on extruded cable subjects. Before joining EPRI, Mr. Bernstein was Materials Section Manager at Phelps Dodge Cable and Wire Co., in Yonkers, New York. Earlier, he guided contract research on the subject of radiation effects on polymers, including efforts to efficiently crosslink polyethylene. He is a Fellow of IEEE, previously served as US representative to CIGRE Study Committee 15 (1989-1996), and is a former member of DEIS ADCOM. He presently serves as convenor of a CIGRE working group on "advanced materials." He is also a member of the American Chemical Society, and the Society of Plastic Engineers. He has authored or co-authored about 45 publications and patents on polymeric materials.