Condition Assessment of Belted PILC Cables After 7 To 68 Years of Service

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Abstract **- This paper summarizes results of laboratory evaluation of eight service aged PILC belted cables, produced by different manufacturers in the period between 1937 and 1998. Cable performance was evaluated from different perspectives, including partial discharge pattern, ionization factor at room temperature, dissipation factor at elevated temperatures, up to 90 °C, dielectric strength of the cable insulation, analysis of the laminated insulation structure, moisture content, etc. Overall results indicate that, unless cable insulation is affected by moisture intrusion, most of the cable characteristics still meet requirements for new cables. The only exception is dissipation factor at elevated temperature, which suggests that cable ampacity is reduced by cable aging.**

Index Terms – PILC cables, field aged, partial discharge, dielectric losses, ionization factor, dielectric strength, ampacity.

I. INTRODUCTION

Paper insulated lead covered (PILC) cables have long been a backbone component of urban medium voltage distribution systems. Several leading North American utilities, in collaboration with the Electric Power Research Institute (EPRI), recently removed a number of PILC cable lengths from their systems. Cables that had been in service for 7 to 68 years were subjected to a series of laboratory tests to evaluate their conditions and analyze the aggregate of the overall results. The testing was conducted at Cable Technology Laboratories (CTL). Guidance and direction were provided by Consolidated Edison Company of New York and Pacific Gas and Electric Company of California.

In total, 8 cables were evaluated. They had been removed from a 4 kV distribution system due to replacement of the cable system. Individual reports, issued on each cable, are available at EPRI. This paper does not list all test results; it rather concentrates on typical performance and most significant findings.

The main objectives of the project were:
- to collect data on performance of service aged cables;
- to assess the condition of particular cables;
- to analyze cable characteristics in relation to their use in cable diagnostic testing;
- to elaborate test approaches for use in assessing similar cables.

TABLE I
CABLES EVALUATED

No.	Vintage	Manufacturer	Rated voltage, kV	No. of cond.	Cond. size	Length, m
1	1937	Okonite Cable Co.	7	4	No. 1/0 AWG	70
2	1940	Habirshaw Cable & Wire Corp.	7	3	350 kcmil	61
3	1957	John A. Roebling's Sons Corp.	7	3	350 kcmil	76
4	1957	John A. Roebling's Sons Corp.	6	3	350 kcmil	87
5	1971	Phelps Dodge Cable & Wire Co.	6	3	No. 1/0 AWG	52
6	1972	General Cable Corp.	6	3	350 kcmil	150
7	1992	The Okonite Co.	7	3	350 kcmil	48
8	1998	The Okonite Co.	6	3	500 kcmil	90

II. DESCRIPTION OF SAMPLES

A brief description of the cables evaluated is provided in Table 1. Manufacturers and vintages are based on imprints found on marker tapes.

The cables have construction design variables including; number and size of conductors, insulation thickness, possible differences in oil and papers used, thickness of the lead sheath. All test cables were of the belted design. The oldest cables were unjacketed; more recent cables, starting from 1957, had a jacket covering the lead sheath. Individual cable sample cross-sections are shown in Figure 1

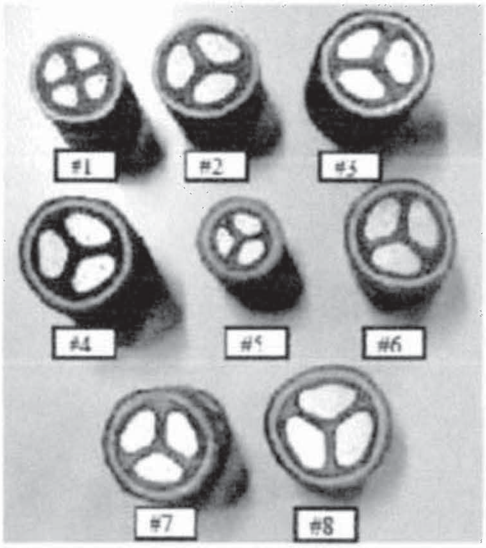

Fig. 1. Cross section of cables tested.

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Each sample was submitted to CTL in one continuous length. These were straight cable lengths, with no accessories installed. Due to the fact that the condition of cables may vary along their length, tests were performed on three sections of the same cable, each approximately 15 m long. The three sections were taken from the ends and the middle of the available cable lengths (Table I), so that the distance between the test specimens varied from 0 to 52 m.

III. TEST PROGRAM

The test approach was based on earlier experience gathered by CTL personnel in testing paper insulated cables [1-7]. The following tests were performed on each specimen:

a) Inspection for general overall condition and presence of mechanical damage.
b) Partial discharge at ambient temperature.
c) Power factor vs. voltage (ionization factor).
d) Dielectric power loss and dissipation factor at ambient temperature, 70 and 90 °C.
e) Impulse test at cable conductor emergency temperature.
f) Six hours high voltage withstand test at 8 kV/mm (200 V/mil), followed by a similar test for up to 7 hours at 16 kV/mm (400 V/mil), both executed at ambient temperature.
g) Dissection, paying special attention to the distribution of butt spaces, registrations, presence of wrinkles, ridges, torn tapes, wax, deficiency of oil, etc (if present).
h) Hot oil tests performed during dissection for the presence of moisture in the paper insulation.
i) Folding endurance of paper tapes on cable adjacent to the breakdowns to establish if insulating tapes had thermally degraded.

Tests b), c) and d) were performed between each individual phase and the other two (or three) phases connected to the lead sheath, as well as between all three (four) phases connected together and the lead sheath. Test e) was performed between each individual phase and the other phases connected to the lead sheath. Test f) was performed with all phases connected together, against the lead sheath.

Test procedures were based on AEIC CS1-1968 [8]. Although cables were manufactured at different times, the 1968 issue was used for testing all samples, to provide a common base for their comparison. In addition, to account for different insulation thicknesses, the cables were tested in accordance with their voltage ratings, as shown in Table I, this in spite of the fact that they all were used in a 4 kV distribution system.

IV. TEST SET UP

The specimens were set-up for electrical evaluations by removing the lead sheath from the cable ends. On each end, the oil impregnated paper belt was removed and tapered, while the individual phases were separated and terminated in an oil-filled cylindrical enclosure. The enclosures were adjusted, at their lower end, to the cable diameter with the help of rubber reducers.

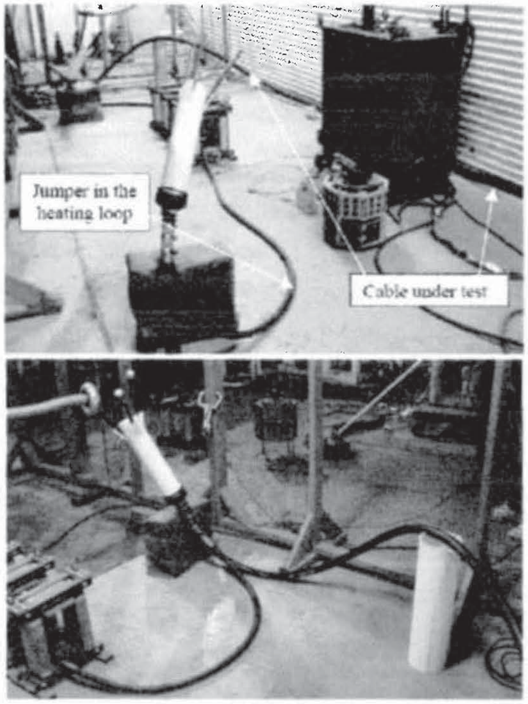

Fig. 2. Test set up.

The length of the cable between terminations was about 13.5 m. Passing current through the lead sheath provided uniform temperature distribution throughout the cable cross-section. A general view of the set up is provided in the upper picture in Figure 2.

To minimize the possibility that oil, being used in the terminations, would mix with the cable impregnating oil, the sample ends were shaped into an open S (lower picture in Figure 2). In this arrangement the termination oil could not enter the main part of the cable. On the other hand, elevated sections of the test specimen, undergoing evaluation at high temperatures, had oil moved to lower locations, so that a local deficit of oil developed. Therefore, times to breakdown obtained within the project were somewhat conservative (rather than being too optimistic).

V. TEST RESULTS

To ease comparison of overall performance of the cables tested, most of the results are summarized ~~at the end of the paper~~, in Table V. ✓

Visual Examination

Cables were thoroughly examined during their removal from the reels, as well as during preparation of the end terminations and during dissection of laboratory and field breakdowns. Three of the cables (No. 1, which was the oldest one and did not have a jacket, Nos. 5 and 7) were in good shape, with no peculiarities to be mentioned. Cable 4 had an opening, at approximately 15.5 m from one of the section ends, all the way through one of the conductors, probably made to ground the cable during removal. The affected section, about 20 m long, was discarded; the test sections did not appear to be affected by this opening.

Since one of the main factors limiting PILC cable life is lead corrosion, special attention was paid to the condition of the lead

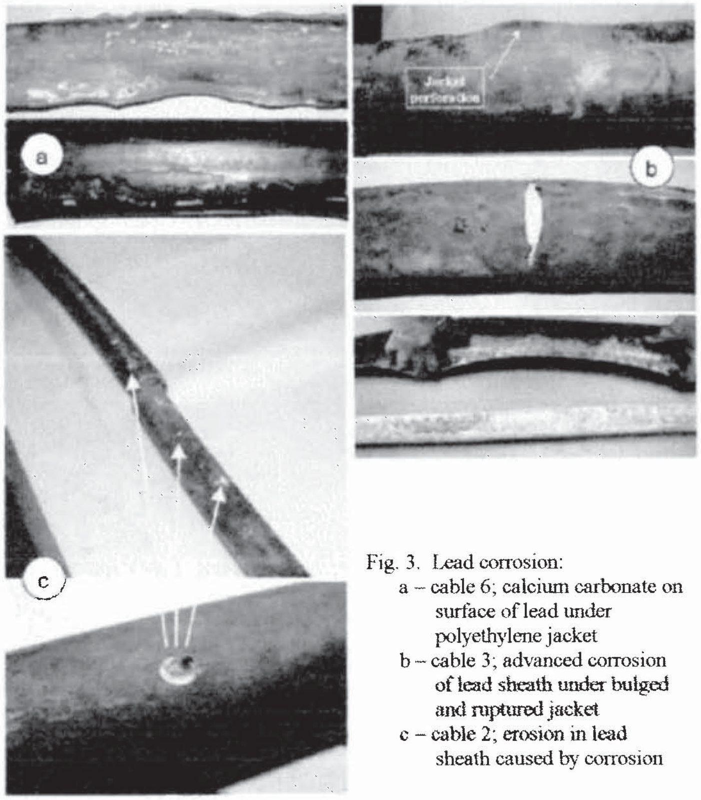

Fig. 3. Lead corrosion:
a – cable 6; calcium carbonate on surface of lead under polyethylene jacket
b – cable 3; advanced corrosion of lead sheath under bulged and ruptured jacket
c – cable 2; erosion in lead sheath caused by corrosion

sheaths. Figure 3 provides examples of different degrees of corrosion, from mild (cable 6, relatively young in the population examined, with a polyethylene jacket) to well pronounced (cable 3, of 1957 vintage, having rubber jacket and covered overall with insulating tapes). The inside of the sheath of these cables was clean and shiny.

The worst condition was that of cable 2, the only sample that incorporated a field failure. Figure 3c shows severely corroded (pitted) spots in the lead sheath, found in cable sections adjacent to either side of the failure.

Corrosion of metals can be divided into two major types: uniform and localized. Uniform corrosion involves oxidation of metal in the presence of a small amount of water (for example, moist air). In this case corrosion products cover the metal with a uniform layer of usually hydrogenated metal oxide, which protects the metal underneath from further corrosion. The other type is characterized by discreet pitting. It occurs when the metal is immersed in water and corrosion never stops. All cases shown in Figure 3 represent the second type, at different stages of corrosion progress.

Other findings were related to discolored paper insulating tapes at the ends of sample Nos. 3 and 4. Interestingly, in sample 3 the belt and outermost tapes in the phase insulation were discolored, while in sample 4 the innermost tapes were affected the most, and the discoloration diminished towards the outside. Despite this difference, the origin of the discoloration appears to be the same: tar-like compounds used to fill joint casings. These compounds permeate over time into the paper insulation, either through the conductor interstices (staining the inner tapes), or under the lead sheath (causing discoloration of the outer tapes). In neither case did this phenomenon affect the performance of the cable system. However, this finding was of interest to justify that the cable sections had been removed from locations adjacent to joints and therefore to visualize as to from where moisture also could have entered the cables (both samples 3 and 4 were affected by moisture intrusion).

Partial Discharge

Tests were started by gradually increasing voltage, until partial discharge (PD) inception took place, holding at this voltage for about 30 seconds, followed by a gradual decrease in voltage, until PD extinction. The entire voltage exposure cycle did not exceed 3 minutes. The test sensitivity was better than 5 pC for single phase testing, and between 8 and 10 pC for all phases connected together.

PILC cables are characterized by unstable parameters of PD, changing significantly over time. Therefore, the tests were repeated several times (at least 3) on each individual cable phase and also with the three (or four) phases connected together. A few minutes were allowed between successive applications of voltage for dissipation of space charges accumulated in the cable insulation during the preceding test.

All PILC cables tested had a complicated performance: PD started at low intensities (10-20 pC), converting abruptly to strong discharges (hundreds to thousands pico coulombs) with further voltage rise. It appears that small voids in butt spaces of the cable insulation evolve into large empty spaces (possibly due to displacement of oil by elevated gas pressure developed by initial discharges) conducive to a significant increase in the discharge intensity.

Partial discharge between a few hundred and maybe even a few thousand pico coulombs, applied during a limited test duration, is of no consequence to the PILC insulation. This type of insulation can support PD for a long time. In other words, PD testing at the beginning of a test sequence is not expected to affect subsequent results.

With exception of the two oldest cables (Nos. 1 and 2), all other cables had extinction voltage above the operating stress of the system from which they had been removed (2.3 kV phase-to-ground), so that they essentially had operated in a PD-free environment (Table V). Test results for the worst performer (in relation to PD activity) are shown in Table II. In each case the lowest reading for several voltage applications is reported.

TABLE II
PD CHARACTERISTIC VOLTAGES
CABLE 2

Phase	Voltage, kV	
	Inception	**Extinction**
Section 1		
A	7.1	6.7
B	>10	---
C	8.1	6.6
A+B+C	7.5	6.2
Section 2		
A	2.2	2.1
B	6.5	5.8
C	7.0	6.2
A+B+C	4.0	2.8
Section 3		
A	8.3	5.0
B	8.4	5.5
C	8.5	6.0
A+B+C	8.5	5.0

A substantial difference between individual sections of the same cable needs to be noted. In addition, despite the fact that individual phases of belted cables are in intimate contact to each other, their characteristics differed significantly.

Power Factor vs. Voltage (Ionization Factor)

The tests were performed in accordance with Section 10.1.3 of the AEIC CS1-68 at average voltage stresses ranging from 20 to 100 V/mil (0.8 to 4.0 kV/mm). Power factor was measured between each individual phase and the other phases connected to the lead sheath, as well as between all phases connected together and the lead sheath. Ionization factor was calculated as a difference between the maximum and minimum values of the power factor in the indicated voltage range.

Table III summarizes the maximum power factors, measured at room temperature and nominal operating voltage stress of 1.6 kV/mm on different phases and sections of the same cable, as well as the maximum differences between sections and phases within the same cable (the difference between phases might be helpful in distinguishing bad performers during on-site diagnostic testing). Figure 4 provides a visual presentation of the data for cable 4 that had the highest ionization factor.

A wide spread of results should be noted, with some cables well within industry specification requirements for new cables, the others exhibiting relatively poor condition. It is interesting to note that the power factor values were not as indicative of a poor cable condition, as was the level of ionization factor.

Significant variation in the performance of different sections of the same cable needs to be noted. As with other properties tested, this indicates a pronounced non-consistency of the cable performance along the feeder length. It is commonly recognized that PILC cables, as manufactured, are pretty uniform, so that the non-uniformity apparently has developed during cable service. It is also of interest that the difference between cable phases was not that pronounced; however, it was still noticeable, and in most cases (where moisture was not involved) there was a good correlation between PD parameters and ionization factors of individual cable sections and phases.

Further, it needs to be noted that, in relation to old cables, the term "ionization factor" does not necessarily mean that there is a lack of oil, which could create a void that is subject to discharge activity in the insulation structure. It could mean, for example, that the high values of this characteristic could be due to high levels of moisture and/or the formation of wax.

Capacitance and Power Factor vs. Temperature

Tests were performed at the cable rated voltage (as listed in Table 1) and at three temperatures: ambient, 70 and 90 °C. The cable was evenly heated through its length and cross-section by circulating current through the lead sheath. Each section was held at constant temperature for at least one hour after the required temperature was achieved at the cable outside.

TABLE III
POWER FACTOR AT ROOM TEMPERATURE AND OPERATING VOLTAGE AND IONIZATION FACTOR AT STRESSES UP TO 4 KV/MM

No.	Vintage	Power Factor at 1.6 kV/mm, %			Ionization Factor, %
		Variation between sections	Variation between phases	Max	
1	1937	0.34	0.03	0.41	0.09
2	1940	0.35	0.01	0.42	0.10
3	1957	0.22	0.13	0.67	0.89
4	1957	0.15	0.29	0.64	3.10
5	1971	0.26	0.02	0.30	0.03
6	1972	0.17	0.03	0.41	0.89
7	1992	0.20	0.02	0.23	0.05
8	1998	0.22	0.03	0.27	0.16
AEIC CS1-68 requirements for new cables				≤ 0.6	≤ 0.3*

* In accordance with AEIC CS1-68 there are no requirements for belted cables. The requirement for new shielded cables is 0.3%, maximum

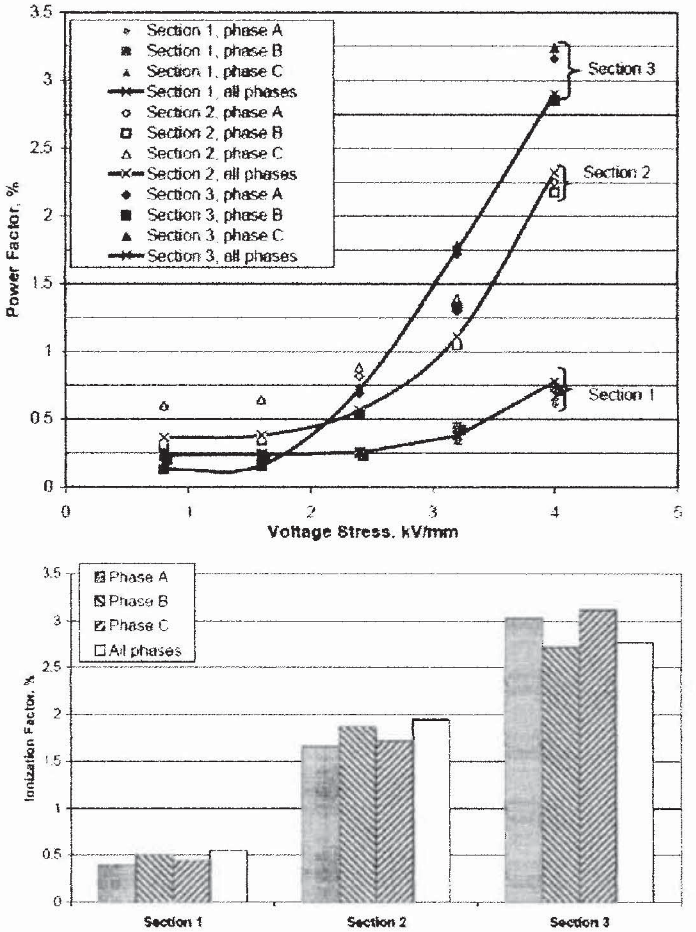

Fig. 4. Power factor at room temperature (upper picture) and ionization factor (lower picture) in cable 4 (worst performer of all cables).

Variation of cable capacitance versus temperature was very minimal (even in bad performing cables) and not worth of discussion. In contrast, dielectric loss at high temperatures provided significant information on the cable condition. A summary of the results is provided in Table V. The table incorporates the maximum value of power factor measured at each temperature on all cable sections and phases (including the configuration with all phases connected in parallel). An example of temperature dependence of power factor (for the worst performing cable 3) is shown in Figure 5. Extreme data for each section of this cable is provided (the worst and best performing phases of each sections of this cable).

As with previously described characteristics, there was also a great variation of dielectric loss at high temperatures between different sections of the same cable. Subsequent evaluations revealed that in two of the cables (Nos. 3 and 4) there had been moisture ingress in the end sections, which was one of the reasons for inconsistency of cable performance. In particular, cable 3 (Figure 5) had section 3 affected by moisture, while the other two sections tested appeared to be in a significantly healthier condition. Still, these two last sections had pretty high power factor at elevated temperature.

VI. CONCLUSIONS

The condition of eight PILC cables, rated 6 to 7 kV, removed from a 4 kV distribution system after 7 to almost 70 years of service, was evaluated by laboratory testing. Cables were mainly removed due to system replacement; only one of them contained a field failure. A series of test methods, including measurement of partial discharge, power factor at different voltage and temperature levels, dielectric strength under impulse and ac stresses, structural analysis, etc., were employed.

Most of the cable sections tested, including the oldest ones, appeared to be in good condition, indicating that cables with similar characteristics can provide further long and reliable service. Out of eight cables tested, only one should probably have been considered for immediate replacement. Even the failed cable, after removal of a short section containing the failure, was still in a reasonably good condition.

Among mechanisms of cable degradation, noted on older cables, were lead corrosion (in one case conducive to moisture penetration and cable failure), elevated moisture content (likely, due to a number of reasons), local deficit of oil, formation of wax; both moisture and wax are conducive to elevated dielectric losses in the insulation. Signs of different degradation mechanisms could sometimes be recognized in the same cable length.

Results of laboratory tests confirmed the worthiness of field diagnostic testing. However, a large number of variables, governing PILC cable condition, may not allow for designing a set of criteria, which can warrant a clear differentiation between "bad" and "good" cables. A complex testing approach may need to be adopted, if a comprehensive assessment of the cable condition is sought.

A loss of ampacity (up to 17 %) was noted on aged PILC cables. This loss was due to elevated dielectric losses in the cable insulation at the maximum operating and emergency temperatures. Considering typically low or moderate loading of Utility feeders, this factor might not be critical; however, it must be recognized and considered for cable operation.

VII. ACKNOWLEDGEMENT

The authors are indebted to several of their associates who have contributed to the laboratory investigation.

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X. BIOGRAPHIES

Vitaliy Yaroslavskiy was born in Russia on September 21, 1950. Received an MS degree in Thermo-Physics from Moscow Power Engineering University in 1973.

Until 2000 he worked for the Russian Research Institute for Metrological Services, Moscow, developing methods and measurement standards for precise high voltage measurements. He has been associated with Cable Technology Laboratories since 2001 as a Senior Test Engineer and VP Technology, with expertise in testing and performance evaluation of medium and high voltage cables and accessories. Mr. Yaroslavskiy is the author of over 60 technical papers.

Carlos Katz (M'70-SM'78-F'87) was born in West Germany on August 18, 1934. He received an Electrical Engineering degree from Polytechnic Institute of Quito, Ecuador in 1961 and an MS degree from Stevens Institute of Technology, Hoboken, New Jersey in 1970.

From 1962 to 1971 he was associated with General Cable Corp. Research Center and from 1971 to 1974 with the laboratories of Phelps Dodge Wire & 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 more than 40 technical papers and holds 16 U.S. patents related to high voltage cables. He is a voting member of the ICC, a member of CIGRE and of JICABLE. He is recipient of the ICC Dr. George Bahder Memorial Award and of the IEEE 2010 Herman Halpering Award.

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