Underground Cable Diagnostic Testing Utilizing Partial Discharge Technique

(An Update to the April 29, 2001 Report)

Potomac Electric Power Company

Reliability Services
(Asset Management)
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Background:

Partial Discharge (PD) generally occurs when dielectric properties of a cable insulation system under high potential are not sufficient to withhold applied electrical field. PD measurements are usually performed at electrical stresses that exceed the normal steady-state service stress. As the test voltage is increased above the in-service voltage level, the detection and location of PD sites along the test cable run are sought. According to a technical report published by EPRI, several utilities are commonly using two methods for cable diagnostic purposes:

- Off-line measurement of the partial discharge inception voltage (PDIV) at the system operating frequency and location of individual PD sites and
- Measurement of the low frequency dissipation factor of the cable.

In 1999 and 2000, Pepco began conducting PD tests on paper insulated lead covered cable (PILC), cross link polyethylene cable (XLPE), and ethylene propylene rubber cable (EPR) utilizing four contractors; KEMA, Ultra Power Technologies (UPT), DTE and Baur Test Equipment. The testing began on July 6, 1999 and was completed on July 27, 2000. During this period, the contractors tested approximately 184,000 feet of cable on 26 underground feeders. Upon completion of testing, it was recommended that approximately 33 joints and approximately 88,000 feet of cable be replaced immediately or within one year to prevent cable and joint failures with the majority of the remaining cable to be re-tested within two years.

Since the completion of cable and splice testing, several segments of URD cable in Montgomery County and splice joints within the Leisure World Subdivision have been replaced. The replaced cable and splice joints were selected due to PD test results, multiple service interruptions and customer complaints. Additionally, in an effort to examine selected components showing excessive partial discharge, approximately 400 feet of underground cable was replaced along Watkins Mill Road in Montgomery County. The removed cable was not satisfactory for electrical testing purposes due to the force applied to the cable during its removal. Since there was no correlation between the contractor's test results and actual cable performance, the recommended cable and splice joints replacement was not continued.

Objective:

On April 29, 2001, Reliability Services issued a comprehensive report entitled 'Underground Cable Diagnostic Testing Utilizing Partial Discharge Technique'. The report outlined the Partial Discharge application and summarized diagnostic testing performed by several contractors; analyzed results, examined cost, and presented five recommendations as follows:

- Develop a database to capture all test values and related information.
- Monitor performance of all tested cable.
- Remove and examine selected components showing excessive partial discharge. Record subsequent findings in database.
- Select five feeders utilizing the current criteria for selecting diagnostic cable testing and initiate PD testing using more than one contractor. Compare and contrast results of tests. Monitor feeder activities for two years.
- Maintain technological awareness of PD developments affecting the electric utility industry.

This paper is an update to the April 29, 2001 report. The purpose for this report serves to discuss recommendations listed in the April 29 report and to further determine the accuracy of the contractors' analyses, which include recommendations for cable and splice replacement.

Summary of Investigation:

A database has been developed to capture historical data on the tested underground and URD cables. In order to conduct a detailed analysis and determine if the suggested areas of replacement are feasible and necessary, three years outage history was extracted from three separate databases- Daily Feeder Report, Reliability Data Mart and Underground Cable Activities. According to the outage history, during the period July 6, 1999 through April 15, 2002, a total of seventy five (75) cable failures and nine (9) joint failures occurred on the feeders that were tested utilizing PD techniques. Of the identified outages, only two interruptions occurred on the segments of the cable recommended for replacement.

Recommendation:

Ensuring the reliability of the underground cable system and striving to minimize the costs associated with outages have prompted interest in utilizing the PD technique. Pepco has tested a considerable amount of cable using several PD techniques with several contractors. However, based on the test results and the outage history, with the exception of two incidents, there is no correlation between the contractor's test results and actual cable performance.

Contractors typically recommended instant replacement, scheduled replacement or periodic repeated costly testing to monitor suspect stretches of cable and splice joints. Industry experience and contractors' test results have failed to provide sufficient physical verification of impending failures identified by PD techniques to warrant replacement. Reliability Services will continue to maintain industry progress awareness. EPRI is currently conducting research on the estimation of the remaining life of PILC cable, estimation of future performance of solid dielectric cable accessories and non-destructive distribution system diagnostics. Therefore, it is concluded that future testing or vendor presentations are unwarranted at this time.

Details of Investigation:

The following information details the activities performed by the contractors on specific Pepco underground radial feeders, network feeders and underground residential distribution feeders, followed by a detailed three year outage history.

<u>Feeder 59</u>

This 4KV feeder originates from Substation No. 12, which is located in the District of Columbia and it provides a total load of 1,359 KVA to 344 customers. DTE performed partial discharge testing on August 10, 2000. A total of 4,800 feet of cable was tested. Test results concluded one joint replacement. Since August 2000, nine (9) cable failures and one joint failure occurred on this feeder; however, there were no signs of a direct outage or fault detected on the joint recommended for replacement.

Feeder 233
This 4KV feeder originates from Substation No.126 located in the District of Columbia. Fifty six (56) customers are served by this feeder and it provides a total load of 3,889 KVA. DTE conducted PD testing on this feeder on August 13, 2000. A total of 5,505 feet of cable was tested. Test results recommended replacement of 3,225 feet of cable and two joints. One cable failure and five joint failures occurred on this feeder, since the test date. However, no outages were detected at locations that were recommended for replacement.

Feeder 14156
This 13KV feeder originates from Substation No. 27 to Substation No. 40 located in the District of Columbia. This feeder had been de-energized since 1996 and was selected for PD testing to evaluate the condition of the cable. KEMA tested 3,091 feet of PILC cable on May 11, 2000. Test results recommended replacement of 750 feet of cable and one joint. According to the outage history, this feeder experienced no cable or joint interruptions.

Feeder 14248
This 13KV feeder originates from Substation No.155, located in Prince George's County. Approximately 1,199 customers are served by this feeder, and it serves total load of 14,199 KVA. UPT completed partial discharge testing on 16,600 feet of cable on November 29, 1999. UPT recommended immediate replacement of 5,637 feet of cable and one joint. Additionally, UPT recommended scheduled repair (taking action within three months to a year) for 3,346 feet of cable along with two joints. Since November 29, 1999, six cable failures occurred on this feeder. One cable fault was detected on the segment that was recommended for replacement; Refer to Appendix B for further details.

Feeder 14381
This 13KV feeder originates at Substation No. 56, located in Montgomery County. Approximately 524 customers are served by this feeder, and it provides a total load of 14,867 KVA. Three contractors performed partial discharge testing as follows:

- On December 1999- UPT recommended replacing 1,115 feet of cable and one joint.
- On August 2000- DTE recommended replacing 950 feet of cable and one joint.
- On May 2000- KEMA recommended replacing 2,500 feet of cable and two joints.

In order to remove and examine selected components showing excessive partial discharge, a work order was completed to remove and replace approximately 400 feet of underground cable along Watkins Mill Road in Montgomery County. The replaced cable was not satisfactory for electrical testing purposes due to the force applied to the cable during the pulling process. In order to produce cable that is suitable for testing purposes, an excavation method should be used. According to the outage history, three cable failures and no joint failure occurred on this feeder. There were no faults detected on the segments recommended to be replaced since May 8, 2000.

Feeder 14602
This 13KV feeder originates at Substation No.117. This is a dedicated feeder serving three high voltage customers; the National Archives, the Smithsonian Institute and the Museum of American and Natural History. KEMA conducted two tests on this feeder; the first was from the

Natural History Museum to the National Archives; the second being from Sub No. 117 to the American History Museum. Two contractors performed partial discharge testing as follows:

- On May 24, 2000, KEMA recommended retesting or replacing 1,500 feet of cable and five joints.
- On July 12, 2000, DTE tested a total of 4,205 feet of cable. The results indicate 2,880 feet of cable and one joint be replaced.

There were no outages detected on this feeder since May 24, 2000.

Feeder 14749

This 13KV feeder originates from Substation No. 9. Approximately 54 customers are served by this feeder, and it provides a total load of 7,118 KVA. On May 10, 2000, KEMA conducted a test on this feeder; recommending replacement of 350 feet of cable and one joint. Although this feeder experienced four cable failures, none were linked directly to the segments recommended for replacement.

Feeder 14909

This 13KV feeder originates at Substation No. 169. Approximately 742 customers are served by this feeder, and it provides a total load of 16,490 KVA. On September 2, 1999, UPT recommended immediate replacement of 2,152 feet of cable. Although this feeder has experienced one cable failure and one joint outage, neither was directly linked to the segments recommended for replacement.

Feeder 15122

This 13KV feeder originates at Substation No. 158 and it serves 1,124 customers, providing a total load of 15,062 KVA. On October 22, 1999, UPT recommended immediate replacement of 947 feet of cable. Although ten cable failures occurred on this feeder, none were linked directly to the segments recommended for replacement.

Feeder 15294

This 13KV feeder originates at Substation No. 18, which is located in the District of Columbia, Southwest. Approximately 1,100 customers are served by this feeder, and it provides a total load of 4,945 KVA.

- On July 1999, UPT recommend scheduled repair for 872 feet of cable and two joints.
- On July 1999, UPT conducted further test and recommended 1,259 feet of cable and three joints for immediate replacement.
- On July 1999, UPT also recommended scheduled repair (taking action within three months to one year) for 5,541 feet of cable and three joints.

Although, seven cable failures have occurred on this feeder, only one cable fault occurred on a segment recommended for replacement; Refer to Appendix B for further details.

Feeder 15295

This 13KV feeder originates at Substation No. 18, which is located in the District of Columbia. Approximately 809 customers are served by this feeder, and it provides a total load of 5,037 KVA. UPT conducted several tests on this feeder and recommended:

- Immediate replacement of 3,877 feet of cable and four joints.
- Scheduled replacement of 4,373 feet of cable and two joints (take action within three months to one year).

- Immediate replacement of 2,537 feet of cable and three joints.
- Scheduled replacement of 8,038 feet of cable and twenty splice (take action within three months to one year).

Although four cable failures occurred on this feeder, none were at locations that were recommended for replacement.

Feeder 15678

This 13KV feeder originates at Substation No.159, which is located in the P.G. County. This express feeder serves the Branch Avenue Traction Power Station, and it provides a total load of 3,337 KVA. This feeder was energized on March 10, 2000. On October 22, 1999, UPT conducted a partial discharge test reflecting that 10,717 feet of cable and one joint be replaced with scheduled repair priority.
No outages have occurred on this feeder since March 10, 2000.

Feeder 15679

This 13KV feeder originates at Substation No.159 which is located in the P.G. County. This express feeder also serves the Branch Avenue Traction Power Station, and it provides a total load of 3,337 KVA. The feeder was energized on March 10, 2000. On October 1999, UPT conducted PD test and recommended that 10,712 feet of cable and one joint be replaced with scheduled repair priority. No outages occurred on this feeder since March 10, 2000.

Feeder 15834

This 13KV feeder originates at Substation No.31, which is located in Montgomery County. Approximately 1,074 customers are served by this feeder, and it provides a total load of 12,089 KVA. On July 14, 2000, DTE conducted a PD test and recommended that 1,230 feet of cable be replaced. Eleven cable failures occurred on this feeder. However, no outages have occurred at locations that were recommended for replacement.

Feeder 15872

This 13KV feeder originates at Substation No. 18, which is located in the District of Columbia. Approximately 988 customers are served by this feeder, and it provides a total load of 7,404KVA. On September 15, 1999, UPT did not recommend any immediate replacement; however, they did recommend 230 feet of cable for scheduled repair (take action within three months to one year). On September 1999, an additional 1,987 feet of cable was recommended for scheduled repair. Two cable failures were reported on this feeder. However, no outages have occurred at locations that were recommended for replacement.

Feeder 15873

This 13KV feeder originates at Substation No. 18, which is located in the District of Columbia. Approximately 681 customers are served by this feeder and it provides a total load of 10,738 KVA. On October 1, 1999, UPT conducted a PD test reflecting 1,196 feet be immediately repaired, additionally 2,278 feet of cable and one joint were recommended for scheduled repair (take action within three months to one year). Three cable failures were reported on this feeder. However, no outages have occurred at locations that were recommended for replacement.

Feeder 15874

This 13KV feeder originates at Substation No. 18, which is located in the District of Columbia. Approximately 1,632 customers are served by this feeder and it provides a total load of 4,204KVA. UPT performer PD test on this feeder on August 20, 1999, recommending no immediate repair, however, they recommend scheduled replacement on 692 feet of cable. Four cable failures and one joint failure have occurred on this feeder. However, no outages have occurred at locations that were recommended for replacement.

Feeder 15875

This 13KV feeder originates at Substation No. 18, which is located in the District of Columbia, Southwest. Approximately 2,250 customers are served by this feeder and it provides a total load of 6,191 KVA. A PD test was conducted on July 30, 1999. UPT recommended replacing 2,289 feet of cable immediately and 857 feet for scheduled repair. Ten cable failures and one joint failure have occurred on this feeder. However, no outages have occurred at locations that were recommended for replacement.

Underground Cable Diagnostic Testing Utilizing Partial Discharge Technique

Potomac Electric Power Company

Reliability Services
(Power Distribution)
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April 29, 2001

Executive Summery

Objective:

Partial Discharge (PD) generally occurs when dielectric properties of a cable insulation system under high potential are not sufficient to withhold applied electrical field. "The ultimate aim of any PD test is to economically increase the in-service reliability of the cable system by reducing the risk of forced outage. As well, the aim is to provide economic alternatives based on actual technical data, which may be advantageously used when deciding to repair, re-test, rehabilitate, partially replace or retire a cable that can no longer be operated reliably and economically." (IEEE Guide 400-3). In 1999, Pepco utilized this technique to evaluate its effectiveness in identifying sites with installation defects and/or sites with defects induced by cable aging. This report addresses PD application, summarizes diagnostic testing performed by several contractors, analyzes results, examines cost, and presents recommendations for future testing.

Details of Inspection:

Four Contractors were utilized to test paper insulated lead covered cable (PILC), cross link polyethylene cable (XLPE), and ethylene propylene rubber cable (EPR). Ultra Power tested 160,000 feet of EPR and XLPE from June 1999 through January 2000 at a rate of $2.57 per foot. KEMA tested 16,300 feet of PILC during May 2000 at a rate of $2.45 per foot. KEMA performed on line testing of energized cables. Detroit Edison (DTE) tested 13,200 feet of PILC at a rate of $1.61 and 1,200 feet of URD cable at a rate of $2.20 per foot. Both Ultra Power and DTE performed off line testing with de-energized cable. Through separate contractor application, Pepco examined the use of Baur cable diagnostic testing equipment, at no initial cost, to perform partial discharge of cable, cable joints, and terminations. A total of 2,100 feet of PILC was tested off line with de-energized cable. Feeder 14381 was the only cable tested by all three contractors and Baur equipment.

Summary of Test Results:

Ultra Power recommended that 10,700 feet of cable (approximately 7% of tested cable) be replaced immediately or within one year to prevent cable failures with the majority of remaining cable to be re-tested within two years. A total of 107 cable joints were recommended for replacement. KEMA recommended that 4,900 feet of cable (approximately 30% of tested cable) be replaced immediately or within one year and six cable joints replaced to prevent impending cable failures. The majority of remaining cables was recommended for re-testing within two years. DTE recommended replacing immediately or within one year 2,700 feet of PILC (approximately 20% of tested cable) and 450 feet of URD cable (approximately 38% of tested cable). A total of five cable joints were to be replaced. DTE suggested re-testing the majority of cable within two years. Utilizing Baur test equipment, it was recommended to replace 1,700 feet of cable immediately or within one year. No cable joints were to be replaced.

Feeder 14381 was tested four times, December 13, 1999, May 8, 2000, July 11, 2000, and July 27, 2000, by four different contractors. There were many signs of partial discharge and evidence of potential cable and cable joint failure. Most were in agreement as to the degradation of the cable and the cable joints, with one contractor doubling the suggested cable replacement. As of this date, no forced outages occurred on Feeder 14381, either involving cable or cable splices, in the vicinity of the tested areas.

Recommendations:

PD testing techniques are still evolving and their long-term benefits are yet to be determined. The results of the testing performed during the past two years suggest further study and analysis is necessary before implementing various replacement programs. The following is recommended:

- Develop a database to capture all test values and related information.
- Monitor performance of all tested cable.
- Remove and examine selected components showing excessive partial discharge. Record subsequent findings in database.
- Select five feeders utilizing the current criteria for selecting diagnostic cable testing and initiate PD testing using more than one contractor. Compare and contrast result of tests. Monitor feeder activities for two years.
- Maintain technological awareness of PD developments affecting the electric utility industry.

Conclusion:

Ensuring the reliability of underground cable system and striving to minimize the costs associated with outages have prompted interest in utilizing partial discharge technique. Although Pepco has tested a considerable amount of cable using several PD techniques, there remains an insufficient correlation between contractor test results and actual cable performance. Therefore, further study and analysis is necessary before developing a meaningful cost/benefit evaluation and implementing various replacement programs.

The following presentation details activities by contractors on specific Pepco network and URD feeders. A cost analysis is reviewed; demonstrating expenses incurred utilizing contractor assisted cable diagnostics.

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Technology:

"PD refers to a localized electric discharge that is restricted to only a portion of a dielectric (insulating) material and, therefore, does not completely bridge between electrodes." (IEEE Guide 400-3). Thus, while a partial discharge does not indicate a cable failure, it does indicate a weak point in the installed cable.

Electrical discharge occurs when the dielectric strength of the insulation is exceeded. This could result from manufacturing error such as with impurities in the cable insulation or voids occurring in the insulation. In addition, any protrusion into the insulation or shield damage causes a stress area. Also damage to the conductor during cable installation can create voids via scoring. The effect of PD is seen as an electrical tree, erosion, space charge, or chemical change that eventually will lead to cable damage. Three major types of cable are our central focus; paper insulated lead (PILC), cross link polyethylene (XLPE), and ethylene propylene rubber (EPR). Through a means of detecting and localizing partial discharges, early identification of weak sections in the cable circuits may be used to support cable repair or replacement decisions.

Methods for measuring and analyzing PD vary among testing contractors. Pepco has utilized the services of three established contractors, Detroit Edison (DTE), KEMA, and Ultra Power Technologies. Costs vary per contractor for PD testing. Supplemental manpower requirements are different because of energized and de-energized testing conditions. Analysis reporting times and methods are also dissimilar. The most important contrast in PD testing lies in the detection results. Some methodologies claim that PD can only reveal insulation discharges, while others suggest multiple findings such as water trees. When moisture penetrates paper insulation (via leaking accessories, corrosion, mechanical punctures, etc.), breakdown by thermal instability could occur. Some contractors suggest that PD testing can not predict this breakdown and water treeing can not be detected and measured by PD. This can only be captured using the Dissipation Factor (tan delta measurement). Regardless, the absence of PD does not guarantee avoidance of cable failure. The following synopsis captures each contractor's approach.

Detroit Edison (DTE):
DTE measures partial discharge in time and frequency domains. They provide an on-line diagnostic approach to partial discharge measurements. This system detects partial discharge in extreme noisy environments and distinguishes between partial discharge generated in the cable under test and outside interference, generated from background RF noise and discharges generated in adjacent equipment.

DTE uses inductive couplers to detect PD pulses. Inductive couplers are high frequency current transformers that are placed around the cable. The magnetic field disturbance induced by the PD pulses traveling in the ground loop is detected by this coupler. DTE utilizes a spectrum analyzer to conduct the frequency domain testing. This testing process captures narrow frequency bands in the analyzers full range mode, as well as single frequency pulses in the zero range mode. In addition, a special sensor providing both inductive and capacitive coupling provides detection of PD frequencies above the 200 MHz range, thus, allowing the capability of identifying PD from the tips of water trees.

The DTE PD technique measures the magnetic field outside the cable resulting from the PD pulses. The magnitude of the magnetic field of the detected signal depends on the cable impedance and the cable geometry. The magnitude of the PD can not be used to estimate the life expectancy of the cable and its accessories. Additional information such as pulse repetition and pulse phase angle may be needed to determine the type of defect that produces a discharge. DTE uses a five level classification for partial discharge. Each level has a recommended action associated with the tested cable.

Level 1 - Represents system free of partial discharge magnitudes and pulse repetitions. No resulting action is necessary.
Level 2 - Yields a small level of partial discharge. This is considered an acceptable level and no resulting action is recommended.
Level 3 - Demonstrates a low probability of failure within 2 years. DTE recommends re-testing in one year.
Level 4 - Represents a Medium probability of Failure in 2 years. Replacement of cable is recommended.
Level 5 - Represents a high probability of failure in 2 years. Replacement is strongly recommended because of imminent failure.

DTE was involved in testing 7 feeder cables, feeders 59, 14381, 14382, 14384, 14602, 233, and 15834. (See table #1 for detail).

Test Date	Feeder(s)	Tot Cable (Feet) (A,B,&C) Phases	# of Sections Tested	Average Cable Section Length	Cable Sections Per Day	Total Number of Discharges Measured	Recommend # of Immediate Cable Section Replacement	Total # of Splices	Splices Per Section	% Splices With Discharge	Recommend # of Splices Replaced
7/10/2000	59	4,800	5	960	5	15	0	5	1	20%	1
7/11/2000	14381	9,375	8	1,172	8	24	0	8	1	25%	1
7/11/2000	14382	3,600	2	1800	2	3	0	3	1	0%	0
7/11/2000	14384	3,600	2	1800	2	4	0	3	1	0%	0
7/12/2000	14602	12,615	10	1,262	10	34	4	10	1	10%	1
7/13/2000	233	5,505	7	787	7	27	4	8	1	25%	2
7/14/2000	15834	3,705	11	337	11	66	4	0	0	0%	0

Table 1: Composite chart represents DTE's 5-day work effort on partial discharge testing.

KEMA:

KEMA utilizes a very low frequency partial discharge testing process. They performed test at 100% of the operating voltage level (8 KV) and at 150% of the operating voltage (12KV). Lightning arresters on the circuits became the limiting factor for the maximum 12KV. KEMA tests the system using two 5 kW diesel driven generators to operate the high voltage 0.1 Hz. Two KEMA engineers work with the test equipment within a test van at the job site. The KEMA system requires that a Pepco crew de-energize the circuit. Safety grounds must be connected during each test. A Pepco crew must connect the KEMA test apparatus to the phase that will be tested. A PD test at 100% of operating voltage is performed and if no PD levels of concern are found then the test is repeated at the next voltage level. The duration of each voltage application is typically 10 minutes.

The primary focus of KEMA cable diagnostics was directed at the testing of paper insulated lead cable in both point to point testing modes and also in their newly developed branch network mode. In earlier testing scenarios, KEMA was limited to 15,000 feet of cable per test. Remote terminals were utilized for point to point circuits, thus increasing their capability to 28,000 feet. They have the ability to test XLPE cable splices and terminations. KEMA believes that XLPE cable displaying partial discharges is already in a failure mode and not much benefit can be derived with further diagnostic cable testing.

KEMA added branched cable circuit testing to their diagnostic service in 2000. The new method utilizes very low frequency voltages, but not with reflected pulses. In a multi-terminal measuring system, only incoming pulses are mutually compared on a time-synchronized basis. Since branched cable circuits and long cables can not be accurately tested using reflectometry, KEMA developed this multi-ended GPS synchronized measuring system. It is used to diagnose cables up to 25,000 feet in length, and branched cable circuits containing PILC, extruded cables, or a combination of both. KEMA's very low frequency branched cable circuit diagnostic test is a non-destructive cable test. This test will detect defective cables having lead sheath punctures, electrical treeing between insulation layers, dried out paper insulation, and burned paper layers. KEMA also claims that their partial discharge testing can reveal voids, external cable insulation damage, electrical trees, and water trees in PE, XLPE, and EPR cables. This testing procedure is limited to cable voltages in the range of 10KV to 35 KV.

KEMA performed diagnostic cable testing on the Pepco system during May 2000 on Feeder 14381, out of Sub 56; Feeder 14749, out of Sligo Sub 9; Metro Feeder 14156; and Feeder 14602, out of Sub 117. (See table 2 for detail).

Test Date	Feeder(s)	Tot Cable (Feet) (A,B,&C) Phases	# of Sections Tested	Average Cable Section Length	Cable Sections Per Day	Total Number of Discharges Measured	Recommend # of Immediate Cable Section Replacement	Total # of Splices	Splices Per Section	% Splices With Discharge	Recommend # of Splices Replaced
5/8/2000	14381	6,600	6	1,100	6	5	3	6	1	16%	1
5/8/2000	14381	8,004	7	1,143	1	3	1	7	1	0%	0
5/10/2000	14749	8,592	3	2,864	3	5	2	3	1	33%	1
5/11/2000	14156	9,273	2	4,636	2	4	1	3	1.5	33%	1
5/24/2000	14602	4,380	4	1,095	4	4	0	4	1	0%	0
5/24/2000	14602	11,976	4	2,994	4	5	0	6	1.5	50%	3

Table 2: Summary of KEMA partial discharge testing on four feeders in May 2000.

Ultra Power Technologies:

Ultra Power utilizes a two step testing process based on time domain reflectometry (TDR). A voltage pulse is injected at one end of the cable. Low voltage TDR induces a variable pulse that determines the length, splice locations, and indicates neutral corrosion levels. Application of an increasing excitation voltage reveals the existence and location of PD signals. The voltage is gradually increased until a PD signal is detected or the maximum test voltage is reached (Ultra Power recommends 3 per unit). PD testing can damage cable, when the cable with PD inception voltage (PDIV) (the voltage at which PD starts) is less than or equal to the maximum test voltage. If PD is detected and the maximum test voltage equals PDIV then additional damages is negligible. It is when PD is not detected and the maximum test voltage is greater than PDIV that further damage is possible and test failure is eminent

Ultra Power's cable testing method utilizes the 60 Hz PD location process. The cable is isolated at both ends. The PD measurement device and the high voltage excitation source are connected at one end of the cable (the source). The voltage is gradually increased until a PD signal is detected or the maximum voltage roughly three times the service voltage is reached. If a defect exists in the cable, a PD signal is emitted from the location of the defect. This signal travels towards both ends of the cable. One signal (signal #1) reaches the cable end (the source) and it is recorded (recording #1). This signal reflects and travels towards the other end and is recorded after it makes the round trip back to the source (recording #3). The second signal (signal #2) travels from the defect in the cable to the far end and is reflected back to the source (recording #2). Location of the PD is achieved as a percent of total measured cable length by taking the ratio of the time separation between recorded signals. Approximate location is calculated on the basis of an average signal velocity over the cable.

Ultra Power provides the testing equipment and a testing crew. They also supply the testing service, data analysis, and a summary report. Pepco would have to provide a crew for connections and isolating the cable. The Ultra Power test can be applied to extruded dielectric cable, jacketed or unjacketed, direct buried or in conduit, and with live or dead front equipment. The test equipment accesses the cable at substations, cabinet to cabinet, or at the cable pole. For 15KV class cable the maximum testing length is 8,000 feet. Cables with 35KV elbows, T and Y connections, and overloaded conditions, create difficult, less reliable PD measurements. Ultra Power Technology becomes less efficient with cables in delta systems.

Ultra Power can test neutral cables using a combination of a neutral conductivity test (NCT) and a neutral corrosion location test (NCLT). The NCT measures the total conductivity of the neutral over the entire length of the cable. They compare this measurement with the ideal neutral cable conductivity. This comparison yields the percentage of existing "good" neutral cable. The NCLT identifies areas of neutral corrosion utilizing time domain reflectometry. Ultra Power performed diagnostic cable testing on 20 feeders. (Refer to table #3 for detail).

Table 3: Summary of Ultra Power Technologies partial discharge testing in 1999 and 2000.

Test Date	Feeder(s)	Tot Cable (Feet) (A,B,&C Phases)	# of Sections Tested	Average Cable Section Length	Cable Sections Per Day	Total Number of Discharges Measured	Recommend # of Immed Cable Section Replacement	Total # of Splices	Splices Per Section	% Splices With Discharge	Recommend # o Splices Replaced
7/6/1999	15295	12,106	24	504	2.3	34	9	39	1.6	15%	0
7/16/1999	15295,15294	24,502	51	480	10.2	109	5	123	2.4	40%	43
7/23/1999	15294,15295,	25,105	59	426	11.8	93	5	118	2	19%	22
	15875										
7/30/1999	15294, 15875,	43,094	63	684	12.6	82	2	110	1.7	17%	19
8/2/1999	15874,15875	29,640	57	520	11.4	70	0	69	1.2	9%	6
8/27/1999	14909,15874,	24,673	48	514	9.6	52	2	56	1.2	0%	0
9/2/1999	14909	11,736	19	618	4.8	29	8	59	3.1	5%	3
9/15/1999	15872	12,692	30	423	10	30	0	33	1.1	0%	0
9/24/1999	15872	20,420	36	567	9	53	0	30	0.8	0%	0
10/1/1999	15873	32,338	48	674	9.6	78	2	57	1.2	4%	2
10/14/1999	15873,15872	16,130	33	489	8.3	60	1	21	0.6	0%	0
10/22/1999	15122,15678,	66,045	8	8,256	2	9	1	78	9.8	9%	7
	14766,15678,										
	15679										
11/29/1999	14248	16,600	27	617	5.4	30	9	41	1.5	5%	2
12/10/1999	14381,14382,	54,472	21	2,594	5.3	49	0	89	4.2	0%	0
12/13/1999	14381,15676,1567	18,225	9	2,025	4.5	6	0	37	4.1	8%	3
12/17/1999	14381,14388	31,917	12	2,660	6	21	0	72	5	0%	0
12/27/1999	14389	456	9	152	3	5	0	0	0	0%	0
12/30/1999	14384,14387,	39,395	18	2,189	4.5	61	0	84	4.7	0%	0
	14388,14389,										

Baur: Cable Diagnostic Testing Equipment

Baur manufactures equipment to perform cable diagnostic testing. They can sell this equipment to Pepco or an outside contractor, who must supply the personnel to operate the device. The Baur very low frequency (VLF) cable test and diagnostic system is called PHG TD/PD and it includes the following:

1. PHG-VLF test generator.
2. TD – Dissipation Factor measurement (tan delta). Tan delta diagnostic test measures cable condition. The tan delta testing provides reliable results for PILC cable as well.
3. PD – Partial Discharge level measurement and source localization.

Baur uses 0.1 Hz sinusoidal voltage. The test with 0.1 Hz was especially developed for solid dielectric insulated cables. The Bauer equipment was utilized to test PILC cable on feeder 14381. The equipment was placed at the Montgomery Village Substation, Sub 56. The total feeder cable tested length was 2,100 feet.

Test Date	Feeder(s)	Tot Cable (Feet) (A,B,&C) Phases	# of Sections Tested	Average Cable Section Length	Cable Sections Per Day	Total Number of Discharges Measured	Recommend # of Immediate Cable Section Replacement	Total # of Splices	Splices Per Section	% Splices With Discharge	Recommend # of Splices Replaced
7/27/2000	14381	180	1	180	1	2	0	1	1	0%	0
7/27/2000	14381	500	1	500	1	42	1	1	1	0%	0
7/27/2000	14381	1,200	1	1,200	1	30	1	2	2	0%	0
7/27/2000	14381	200	1	200	1	4	0	1	1	0%	0

Table 4: Results from testing performed using the Baur Cable Diagnostic Equipment

Technologies – Advantages and Disadvantages

DTE:
Advantages – This technique can be performed in the field on energized cables without requiring any cable outage.

Disadvantages - Process requires a very large database generated through laboratory and field measurements to interpret results. This technique requires highly skilled personnel working with very specific and complex data information. Testing becomes necessary in each or every other manholes and hence may require excessive time for the testing. External noise signals can behave as PD pulses. DTE claims that their system detects PD in extreme noisy environments and distinguishes between PD generated in the cable under test and outside interference, generated from background RF noise and discharges generated in adjacent equipment.

Ultra Power Technologies:
Advantages - Ultra Power Technologies, Inc. evaluates the integrity of cable insulation and accessories. They also ensure the neutral integrity testing.

Disadvantages - To emphasize the presence of the PD inside of a PILC cable, the voltage is introduced and gradually increased until a PD signal is detected or the maximum test voltage is reached. Ultra Power recommends 3 per unit voltage. This magnitude of high voltage applied during the test may cause concern for many users because of the potential risk of initiating breakdown or creating new discharge sites, which may affect the future performance of the system. This technique requires additional Pepco labor to isolate all connected equipment.

KEMA:
Advantages - KEMA tests the system using a VLF HV testing source (0.1 Hz). It has been found that the PD inception is at a lower voltage level when using 0.1 Hz compared with power frequencies. A weak spot or an electrical tree in the insulation can be detected with a lower field stress when compared to higher frequency applications.

Disadvantages - KEMA does not provide any diagnostic tests for solid dielectric insulation. KEMA believes that XLPE cable displaying partial discharges is already in a failure mode and not much benefit can be derived with further diagnostic cable testing. This technique requires additional Pepco labor to isolate all connected equipment.

Baur:
Advantages – For the assessment of the condition of the insulating material in a single package, the Baur system is capable of performing two diagnostic tests (dissipation factor and partial discharge). The system is capable of producing an integral assessment of the condition of the insulation as well as detection and location of individual defects in the tested cable at a non-destructive test voltage level. Baur uses the dissipation factor for investigation of the insulating medium. The Baur's technique can be used for both PILC and solid dielectric insulation. The Baur's VLF range from 0.01Hz to 1 Hz covers the non-linearity of co-polymer dissipation factor characteristics (for solid dielectric insulation).

Disadvantages - Pepco must invest in $100,000 of equipment. Pepco must hire a contractor to operate equipment or train its staff for operation and diagnosis.

Comparing Methodologies and Equipment (Feeder 14381 Test Results)

Three contractors, Ultra Power, KEMA, and DTE were utilized to test Feeder 14381. In addition, the Baur cable diagnostic testing equipment was demonstrated on this circuit. The following table yields test conclusions.

#	Grid Locations	Cable Length	Contractor Testing Results (Measurements in table are 7kV level)****							
			DTE PD Levels	DTE Recommend	KEMA PD Levels	KEMA Recommend	Ultra Power PD Levels	Ultra Power Rcommend	BAUR PD Levels	BAUR Recommend
1	**Manhole 741486-8026**	*Splice*	level 3	Retest 1 yr	4,000 pC	**Repl Spli**	0-99 pC	Retest 1 yr	N/A	N/A
2	741486-8026 to 741486-9278	540 ft	level 3	Retest 1 yr	2,000 pC	Retest 1 yr	200 pC	Retest 1 yr	N/A	N/A
3	**Manhole 741486-9278**	*Splice*	level 4	**Repl Spli**	5,000 pC	**Repl Spli**	**> 1000 pC**	**Repl Spli**	N/A	N/A
4	741486-9278 to 741486-3894	560 ft	level 3	Retest 1 yr	2,000 pC	Retest 1 yr	**5000 pC**	**Repl Cab**	N/A	N/A
5	**Manhole 741486-3894**	*Splice*	level 1	Retest 1 yr	2,000 pC	Retest 1 yr	0-99 pC	Retest 1 yr	N/A	N/A
6	741486-3894 to 740487-8204	540 ft	level 3	Retest 1 yr	3,000 pC	Retest 1 yr	0-99 pC	Retest 1 yr	N/A	N/A
7	**Manhole 740478-8204**	*Splice*	level 1	Retest 1 yr	2,500 pC	Retest 1 yr	100 pC	Retest 1 yr	< 100 pC	Retest 1 yr
8	740478-8204 to 740487-7413	225 ft	level 4	**Repl Cab**	3,000 pC***	Retest 1 yr	0-99 pC	Retest 1 yr	< 100 pC	Retest 1 yr
9	**Manhole 740487-7413**	*Splice*	level 1	Retest 1 yr	2,500 pC	Retest 1 yr	0-99 pC	Retest 1 yr	< 100 pC	Retest 1 yr
10	740487-7413 to 740487-8775	640 ft	level 4	**Repl Cab**	2,500 pC**	**Repl Cab**	**> 1000 pC**	**Repl Cab**	1000pc*****	**Repl Cab**
11	**Manhole 740487-8775**	*Splice*	level 1	Retest 1 yr	2,000 pC	Retest 1 yr	0-99 pC	Retest 1 yr	< 500 pC	Retest 1 yr
12	740487-8775 to 740488-9228	350 ft	level 3	Retest 1 yr	1,500 pC*	**Repl Cab**	**1700 pC**	**Repl Cab**	750-1100pC	Retest 1 yr
13	**Manhole 740488-9228**	*Splice*	level 1	Retest 1 yr	1,500 pC*	**Repl Spli**	0-99 pC	Retest 1 yr	< 500 pC	Retest 1 yr
14	740488-9228 to 740488-9430	650 ft	level 3	Retest 1 yr	2,000pC	Retest 1 yr	**1100 pC**	**Repl Cab**	800-1000pC	**Repl Cab**
15	**Manhole 740488-9430**	*Splice*	level 1	Retest 1 yr	2,000 pC	Retest 1 yr	0-99 pC	Retest 1 yr	< 100 pC	Retest 1 yr
16	740488-9430 to Substation	275 ft	level 3	Retest 1 yr	2,000 pC	Retest 1 yr	0-99 pC	Retest 1 yr	< 100 pC	Retest 1 yr

* escalated to 19,000 pC when tested at 150% (12kV)

** escalated to 27,000 pC when tested at 150% (12kV)

*** did not escalate when tested at 150% (12kV)

**** Following 7kV measure, 12kV occurred - major escalation occurred

***** escalated to 6,000 pC when tested at 150% (12kV)

Table 5: Contractor results for cable testing on Feeder 14381 out of Montgomery Village Sub 56.

The results on feeder 14381 were very similar for all four testing scenarios regarding the cable located between manholes 7413 and 8775. The splice in manhole 9278 produced high partial discharge by all three contractors. Both KEMA and Ultra Power yielded similar analysis with minor variation. DTE captured the major locations of partial discharge but did not generate the same degree of concern for two other cable locations indicated by KEMA and Ultra Power. Additional testing is suggested after one year for the majority of feeder 14381 by all four testing cases.

Cost Analysis:

The average cost per day for services provided by each contractor ranged between $5,000 and $8,000. This alone does not demonstrate the cost associated directly with either cable repair or the proficiency of the testing process. See table #6 for detail information.

Table 6. Cost comparison related to cable type.

Contractor	13kv (PILC) Total Feet Tested	# Of Days	Feet per Day	Cost per Day	$ per Foot
DTE	9,730	2-2/3	3,648	$5,300	$1.45
KEMA	16,275	5	3,255	$8,000	$2.45
Ultra Power	159,849	79	2,023	$5,200	$2.57

Contractor	4kV Total Feet Tested	# Of Days	Feet per Day	Cost per Day	$ per Foot
DTE	3,435	2	1,718	$5,300	$2.06
KEMA	N/A	N/A	N/A	N/A	N/A
Ultra Power	N/A	N/A	N/A	N/A	N/A

Contractor	URD Total Feet Tested	# Of Days	Feet per Day	Cost per Day	$ per Foot
DTE	1,202	1/2	2,404	$5,300	$2.20
KEMA	N/A	N/A	N/A	N/A	N/A
Ultra Power	N/A	N/A	N/A	N/A	N/A

DTE and Ultra Power perform cable testing under de-energized conditions. Additional costs for Pepco manpower and equipment should be included in the daily expense. KEMA conducts testing with the cable energized, thus eliminating the need for Pepco switching. In most cases, KEMA requires flagging personnel to safeguard their multiple manhole access.

In comparison to contractor cable diagnostics, Bauer produces equipment for sale, which will be operated by the purchaser. The cost of this equipment is approximately $100,000. Based on an estimated $5,000 for other contractor daily use, this equipment cost would be realized in less than a two month period of comparable contractor costs.

Recommendations:

PD testing techniques are still evolving and their long-term benefits are yet to be determined. The results of the testing performed during the past two years suggest further study and analysis is necessary before implementing various replacement programs. The following is recommended:

- Develop a database to capture all test values and related information.
- Monitor performance of all tested cable.
- Remove and examine selected components showing excessive partial discharge. Record subsequent findings in database.
- Select five feeders utilizing the current criteria for selecting diagnostic cable testing and initiate PD testing using more than one contractor. Compare and contrast result of tests. Monitor feeder activities for two years.
- Maintain technological awareness of PD developments affecting the electric utility industry.

Conclusion:

Ensuring the reliability of underground cable system and striving to minimize the costs associated with outages have prompted interest in utilizing partial discharge technique. Although Pepco has tested a considerable amount of cable using several PD techniques, there remains an insufficient correlation between contractor test results and actual cable performance. Therefore, further study and analysis is necessary before developing a meaningful cost/benefit evaluation and implementing various replacement programs.