Assessment of the Underground Distribution System of the Potomac Electric Power Company

Final Report

December 7, 2001

Formal Case No. 991
Investigation into Explosions Occurring in or Around the Underground Distribution System of the Potomac Electric Power Company

Prepared by Stone & Webster Consultants
For the Public Service Commission of the District of Columbia

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1.0 EXECUTIVE SUMMARY

1.1 Project Objective and Scope

The objective of this assignment was to perform an independent assessment of Potomac Electric Power Company's (Pepco) underground electric distribution facilities in light of a series of manhole explosions and fires that have occurred in the District of Columbia (DC) over the past several years. In performing this assessment, Stone & Webster Consultants (Stone & Webster) was also required to review and evaluate the filings and studies submitted by all parties to Formal Case No. 991, opened by the Public Service Commission of the District of Columbia (DCPSC) on March 6, 2000, to investigate the causes and remedies for the manhole explosions and fires in Pepco's underground electric distribution system.

1.2 Assessment Approach

Stone & Webster conducted its assessment during the period of May 2001 through November 2001, which involved six consultants. In addition, the DCPSC Project Administrator attended several of Stone & Webster's team meetings with Pepco officials, and visited Stone & Webster's field investigation teams during inspections of Pepco's underground electric distribution facilities. More specifically, Stone & Webster's assessment included the following elements:

- field inspections of 41 manholes, 15 transformer vaults, 3 switch vaults, and 5 substations in Pepco's underground electric distribution system in DC,
- review and analysis of Formal Case 991 studies and filings submitted by Pepco and its consultants, ABB Power T&D, Inc. (ABB) and the Electric Power Research Institute (EPRI); the Office of the People's Counsel of the District of Columbia (OPC) and its consultant, Downes Associates; and all other parties to Formal Case No. 991,
- submission of data requests to Pepco and subsequent review and analysis of responses,
- review of Pepco's engineering design, construction, materials, operation, maintenance, and inspection practices,
- individual interviews and team interviews with members of Pepco's power delivery organization management and technical personnel,
- a team interview with representatives of ABB at their offices in Raleigh, NC to discuss the results of their studies performed for Pepco,
- attendance at EPRI's manhole event workshop held in DC, and discussion of their manhole tests performed for Pepco, and
- attendance at hearings held by the DCPSC, and review of hearing transcripts.

1.3 Summary of Findings and Recommendations

The following summarizes our major findings and recommendations:

- based on our review and examination of ABB's Georgetown area network system evaluation, and other elements of our assessment, it is our professional opinion that overloading is a primary factor in cable and splice failures, which may ultimately lead to manhole smoking, fires and explosions, and we recommend that Pepco's analytical electrical modeling of the network system to determine overloaded portions of the network be expedited from its four-year plan to a targeted completion date of the spring, 2003;
- based on our physical inspections and observations, we recommend that the networks serving the Adams Morgan area be given high priority in terms of the modeling effort because it shows significant overcrowding resulting from load growth;
- based on the high primary fault current levels on Pepco's system, and reported experience of Tampa Electric Company, we recommend Pepco perform a technical feasibility study of the application and installation of high speed, electronically controlled fuses and other current-limiting devices designed to limit fault currents by fast fault clearing; we believe such a study should be completed in nine to twelve months;
- Pepco should continue its trial installation of a remote monitoring system for network transformers and protectors, and we note that Consolidated Edison of NY employs real time remote monitoring on all 24,000 of its network transformers and protectors;
- evaluate the applicability of new technologies such as the above-ground meter and real-time fault location schemes that allow crews to quickly locate faulted cables under the street;
- consider alternate protection schemes for isolated spot networks;
- the Georgetown Project will separate primary from secondary cable circuits, reduce temperature buildup and improve heat dissipation, reduce the probability of a secondary cable failure propagating into a primary circuit failure (and vice versa), and make repairs easier; we recommend that Pepco capture all as-built Georgetown Project construction records in a form suitable for input into its GIS database;
- Pepco should perform network system modeling of the Georgetown Project design in order to evaluate the adequacy of the design before it is constructed;
- although our field inspections have noted good workmanship in manholes, primary splice failures have been involved in a number of manhole incidents, and we recommend a splicing /repair log be kept containing dates of installation, crew members performing the work, materials used, and other information deemed suitable for GIS database entry;
- based on the anticipated Georgetown construction activity, the manhole inspections and repairs program, our suggested expediting of the modeling of electrical networks, and the 30% decrease in underground and conduit staffing levels which occurred over the past decade, we recommend Pepco conduct a work force staffing analysis to assess the

adequacy of its work force to meet these demands; this should be completed within three to four months;

- based on our review and examination of EPRI's manhole cover test results and the performance of recently installed slotted manhole covers, we recommend that Pepco continue its ongoing installation and evaluation of slotted manhole covers;
- we recommend modifications to the manhole repair prioritization schedule to assure timely repairs, and additions to the information contained on the manhole inspection reports so as to develop a more comprehensive database. (A revised repair prioritization schedule has been adopted by Pepco and is included in Appendix A.5.)

1.4 Integrity of Pepco's Underground System

In addition to the recommendations for improvements summarized above, our review examined the overall integrity of Pepco's underground system. That review found the following:

- the integrity of major components of the underground system, namely distribution substations, network systems, the 13 kV and 4 kV radial systems are acceptable with the exception of sections of the Georgetown area which are characterized by overcrowded facilities due to load growth beyond the design criteria of the affected underground facilities, and overloading of circuits during both normal and single contingency (e.g., loss of one primary) conditions;
- the distribution substations employ designs, materials, and protection practices that are equal to or better than those of other metropolitan utilities;
- the distribution substations are designed to provide a high level of reliability and service continuity;
- the 47 low voltage network systems generally located in commercial areas are well designed, protected in accordance with or better than industry practice, use equipment and materials that are standard in the industry, and evidence good workmanship in manholes, transformer vaults, and bus holes;
- the 4 kV and 13 kV radial systems deployed mainly in residential areas are consistent with utility industry practices, and the 13 kV system uses the latest materials available in the industry.

However, our assessment does not include an examination of actual loading on facilities and equipment during normal and/or single contingency conditions because Pepco has not yet completed development of the load flow models needed to perform this analysis.

1.5 Analysis of Reports and Filings Prepared by Pepco and its Consultants

The following summarizes our review and comments (see Appendix A) regarding reports and filings by Pepco and its consultants.

- With regard to ABB's Georgetown Area Network System Evaluation (also referred to as the modeling study), the results of the load flow analysis show some Georgetown networks are not able to handle peak load conditions without overloading secondary cables, even with all primary feeders in service. Moreover, during a single contingency (e.g., loss of one primary feeder) many secondary cables are severely overloaded, as well as some network transformers, and in some cases the remaining primary feeders. This is the most significant finding of the ABB analysis because secondary cables have been implicated in a number of manhole incidents.

With regard to ABB's 4 kV system study, its results support Pepco's decision to convert the 4 kV radial distribution system in the residential area of Georgetown (adjacent to the network system) to a 13 kV loop system, so as to be able to carry higher loads and enable quicker service restoration. Overall, the study found:

- – The reliability indices (SAIDI, SAIFI) of the 4 kV radial distribution system in Georgetown reflect substandard performance. The 5-year record of outage statistics indicates significantly higher failure rates than experienced in new underground systems.
- – Overloaded 4 kV cables under peak system load conditions.
- – A primary feeder with a voltage drop in excess of 4%.

- With regard to ABB's Final Report on the Georgetown Area Low-Voltage Network (also referred to as the facilities study), the ABB report contained 14 recommendations for the low-voltage network systems. If Pepco follows these recommendations, the performance of the low-voltage network systems will be improved. Our review proposes three additional recommendations:
  - evaluate the applicability of high-voltage current-limiting devices such as used by Tampa Electric to reduce the probability of a fault in a primary splice causing a manhole explosion, and prevent the rupturing of transformer cable terminal and switch compartments;
  - evaluate the applicability of new technologies such as the above-ground meter and real-time fault location schemes that allow crews to quickly locate faulted cables under the street;
  - consider alternate protection schemes for isolated spot networks (e.g., the circular close characteristic of microprocessor relays).
- With regard to EPRI's Final Report on Manhole Event Tests, we find:
  - the study was carefully conducted using appropriate laboratory technique and instrumentation;
  - the study results are based on a reasonable reproduction of conditions observed in the field;
  - Pepco's decision to install non-tethered slotted manhole covers is appropriate, given that such equipment can reduce the severity of a manhole event.

It should be noted that a high current arc by itself can have sufficient energy to result in a manhole incident, that is, no combustible gases are necessary. As a result, mitigation methods may be different for primary versus secondary cable-caused incidents if for example primary cable splice failures result from arc energy while secondary cable faults result from combustion of liberated gases. We note to date, no slotted manhole covers have lifted due to a manhole incident.

- With regard to Pepco's response to Commission Order No. 12036, we find overall, Pepco is implementing the recommendations made by ABB in the modification of standards that will be used in rebuilding the Georgetown system. Specifically:
    - Pepco is revising the ratings assigned to primary circuit cables installed in ducts throughout DC, to take into account the heating effects of low-voltage cables in the same duct bank, which will result in a more appropriate conservative design;
    - Pepco will measure soil thermal resistivity which will be used for calculating cable ampacity ratings (i.e. the amount of current a cable can carry without overheating);
    - load flow models of the networks are being developed using the recently purchased EasyPower software;
    - Pepco's installation of slotted manhole covers, based on EPRI test results, appears to be a prudent approach to reducing manhole cover displacements;
    - the Georgetown modernization plan appears to be appropriately designed, will use EPR insulated cable (instead of PILC), and should improve reliability and allow for system capacity enhancements to accommodate future load growth.

1.6 Analysis of Reports and Filings Prepared by Other Parties

The following summarizes our review and comments (see Appendix B) regarding reports and filings by the OPC and its consultants, and other parties.

- With regard to the Downes Associates Report Dated October 31, 2000 and filed by the OPC on November 3, 2000, we find:
    - the report contains several appropriate recommendations that Pepco has acted upon (e.g., conduct failure analysis, carry out manhole inspections, and reliability inspection reporting);
    - however, we disagree with Downes' assertion that age is the primary causative factor and GIS the primary solution to failures in the underground system;
    - instead, we believe loading is the most significant factor, and the most immediate need is for electrical analytical modeling and load flow studies of the underground system, particularly the secondary networks.
- With regard to the OPC's Comments filed on July 24, 2001, in Response to Order No. 12036, we find that:
    - although Downes' discredits EPRI's manhole cover tests, we disagree since we believe that the tests were carefully conducted using appropriate laboratory technique and instrumentation, and that the installation of non-tethered slotted covers can reduce the severity of a manhole incident;
    - although Pepco is only installing slotted covers in sidewalks and crosswalks, the impact of exposure to street debris will require monitoring.

2.0 BACKGROUND

2.1 Introduction

On January 9, 2001, the Public Service Commission of the District of Columbia (DSPSC or Commission) issued a Request for Proposal (RFP) to perform an assessment of the underground distribution system of the Potomac Electric Power Company (Pepco). The assessment is part of Formal Case No. 991, opened by the DCPSC on March 6, 2000, dealing with the cause or causes of manhole explosions and fires in the District of Columbia. In its RFP the Commission requested

> "an independent and comprehensive review and evaluation of the scope, methodology, results, conclusions, and recommendations of the assessments and studies carried out by Pepco and its consultants, ABB Power T&D, Inc. (ABB) and the Electric Power Research Institute (EPRI), and a review of the filings of the Office of the People's Counsel of the District of Columbia (OPC) and any other parties to Formal Case 991, regarding the integrity of Pepco's underground electrical distribution system."

In addition, the Commission requested an independent assessment of Pepco's underground electrical facilities.

Stone & Webster Consultants (Stone & Webster) was selected to perform the Pepco assessment, and initiated the project in May 2001. A formal project kickoff meeting with the DCPSC and representatives of Pepco was held in the Commission's offices on May 31, at which time Pepco also provided information in response to Stone & Webster's initial request for data. Based on these sources of information as well as direction provided by the RFP, Stone & Webster developed a detailed project work plan and schedule which was submitted to the DCPSC. The work plan included monthly project status reports to the DCPSC (Appendix D included herein), periodic meetings with the DCPSC Project Administrator, scheduled meetings with the DCPSC Commissioners and staff, participation in formal hearings held by the Commission, and a final report documenting Stone & Webster's findings, recommendations, and reviews of the filings and studies by parties to Formal Case 991.

2.2 Approach

Stone & Webster conducted its assessment during the period May 2001 through November 2001, with on-site field work and interviews completed by October 2001. A total of six consultants were involved in the assessment. In addition, the DCPSC Project Administrator attended several of Stone & Webster's team meetings with Pepco officials, and visited Stone & Webster's field investigation teams during their inspections of Pepco's underground electric distribution facilities. More specifically, Stone & Webster's assessment included the following elements:

- Individual interviews and team interviews with members of Pepco's power delivery organization management including the
  - Senior Vice President, Power Delivery,
  - General Manager, Asset Management,

  - Manager, Distribution and Transmission Engineering,
  - Manager, Georgetown Project,
  - Manager, Reliability Services,
  - Manager, Electric System Planning,
  - Manager, System Protection Planning and Analysis,
  - Manager, Benning Service Center,
  - Manager, Distribution Support Services,
  - Manager, Business Performance,
  - Engineering Consultant, and
  - Supervisor, Manhole Inspection Program.

- Review and analysis of Formal Case 991 studies and filings submitted by:
  - Pepco, ABB, EPRI (Appendix A),
  - OPC, Downes Associates (Appendix B).
- Submission of eight multiple data requests to Pepco (Appendix C) and subsequent review and examination of responses.
- Team interview with representatives of ABB at their offices in Raleigh, NC to discuss the results of their studies performed for Pepco.
- Attendance at EPRI's manhole event workshop held in DC, and discussion of their manhole tests performed for Pepco.
- Field inspections of Pepco's underground electric distribution system facilities located in DC including:
  - 41 manholes,
  - 15 transformer vaults,
  - 3 switch vaults, and
  - 5 substations.

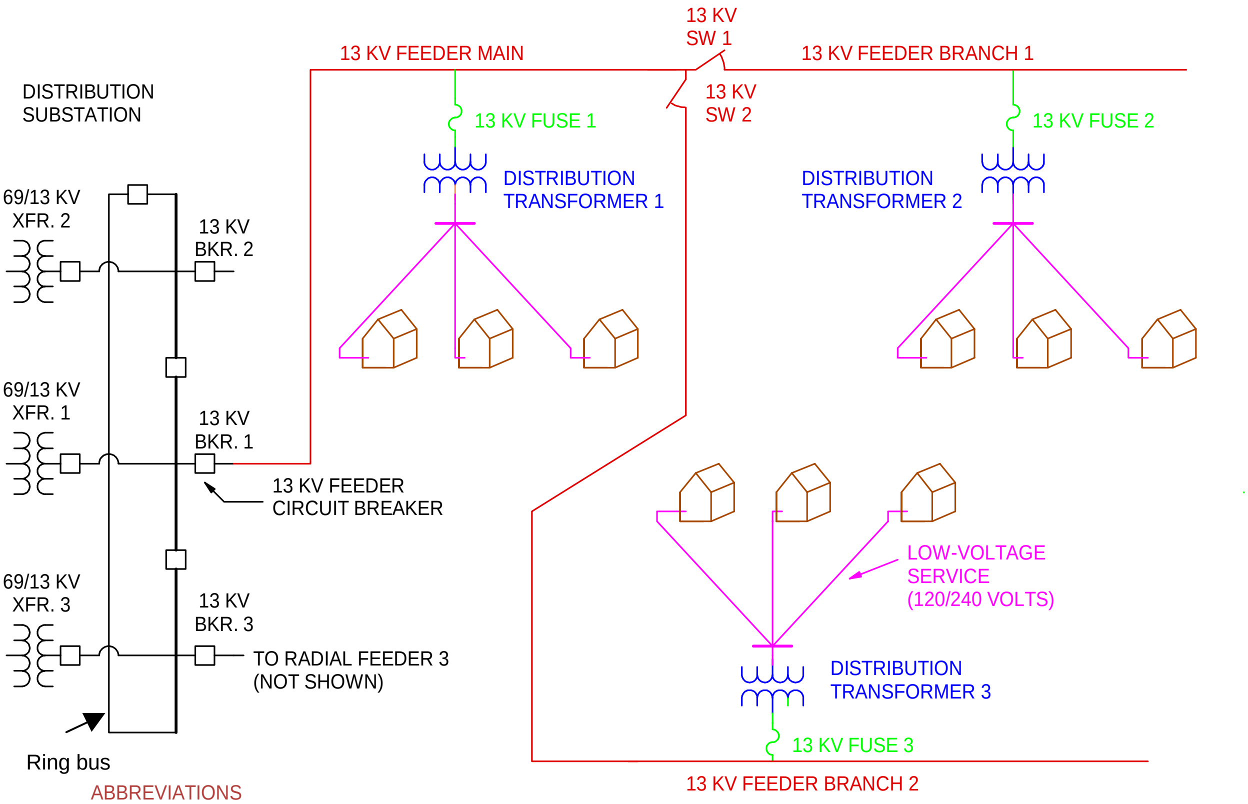
After all assessment elements were completed, Stone & Webster developed a draft final report and submitted it to the DCPSC for review and comment. This was followed by an oral presentation of the report to the Commission. In addition, Stone & Webster attended formal hearings on Formal Case 991 held November 5-7, 2001, and reviewed the hearing transcripts.

2.3 Radial and Network Underground Electrical Systems

Pepco operates both radial distribution systems and low-voltage network systems in the DC area. Low-voltage network systems are used mainly in commercial areas such as the business district of Georgetown, and other areas where it is desired to supply the highest level of reliability possible with conventional types of power systems. Radial systems have a simpler configuration and lower cost than low-voltage network systems, and they are generally found in residential areas.

2.3.1 Radial Systems

Figure 1 shows a simplified radial primary distribution system with 13 kV high voltage feeders.



ABBREVIATIONS

BKR.	CIRCUIT BREAKER
XFR	TRANSFORMER
13 KV SW	13,000 VOLT SECTIONALIZING SWITCH

Note: Emergency tie circuits to other 13 kV radial circuits are not shown.

Figure 1 Simplified Radial Primary Distribution System

The radial distribution system originates in the distribution substation. The main components of the radial system are the 13 kV feeder circuit breakers located in the distribution substation, the

13 kV feeders, the distribution transformers, and the low-voltage services to the customers. Other important components are the 13 kV switches located in the 13 kV feeders and the 13 kV fuses on the input side of each distribution transformer.

The voltage level of the high-voltage feeders in the Pepco system usually is either 4 kV or 13 kV. As most customer load will not operate at these high voltage levels, distribution transformers are connected to the high-voltage feeders to step the voltage down to the utilization level, for example the 120/240 volts found in residences. Low-voltage secondary circuits carry the power from the distribution transformer to the customer's premises.

In the simplified system of Figure 1, only one radial 13 kV feeder is shown emanating from the distribution substation. In an actual system, there would be many such feeders emanating from the substation, going in different directions to supply the loads.

Under normal (unfaulted) conditions in the radial system of Figure 1, the power flow in each component is always away from the distribution substation towards the customer. The topology of the system is similar to that of a tree. The 13 kV feeder main corresponds to the tree's trunk; the 13 kV feeder branches correspond to the tree's branches connected to the tree's trunk; the distribution transformers correspond to second-level branches of the tree; and the low-voltage services correspond to third-level branches of the tree. As long as there are no interruptions in any of the paths of the radial distribution system, power will flow from the distribution substation to all customers fed from the system. This is analogous to nutrients flowing from the earth to the tree's leaves as long as the trunk and none of the branches are completely severed.

Should a short circuit (fault) occur on the 13 kV feeder main or one of the 13 kV feeder branches, all customers will be out of service until the fault can be located. After the fault is located, all or a portion of the customers will still be without service until the fault can be repaired and the feeder re-energized. If the fault were on the 13 kV main feeder, all customers are without service until the fault is located and repaired. If there are emergency tie circuits to other 13 kV feeders, then service can be restored to some of the customers before the fault is repaired.

If the fault were on 13 kV feeder branch 1 in Figure 1, all customers are without service until the fault is located. After the fault is located, 13 kV switch 1 can be opened to isolate the faulted section of the feeder. Then the 13 kV circuit breaker at the substation is closed to energize the 13 kV main feeder and 13 kV feeder branch 2. This restores electric service to all customers supplied from the transformers connected to these portions of the radial circuit. After the fault is repaired, service can be restored to the customers supplied from 13 kV feeder branch 1 by the closing of 13 kV switch 1.

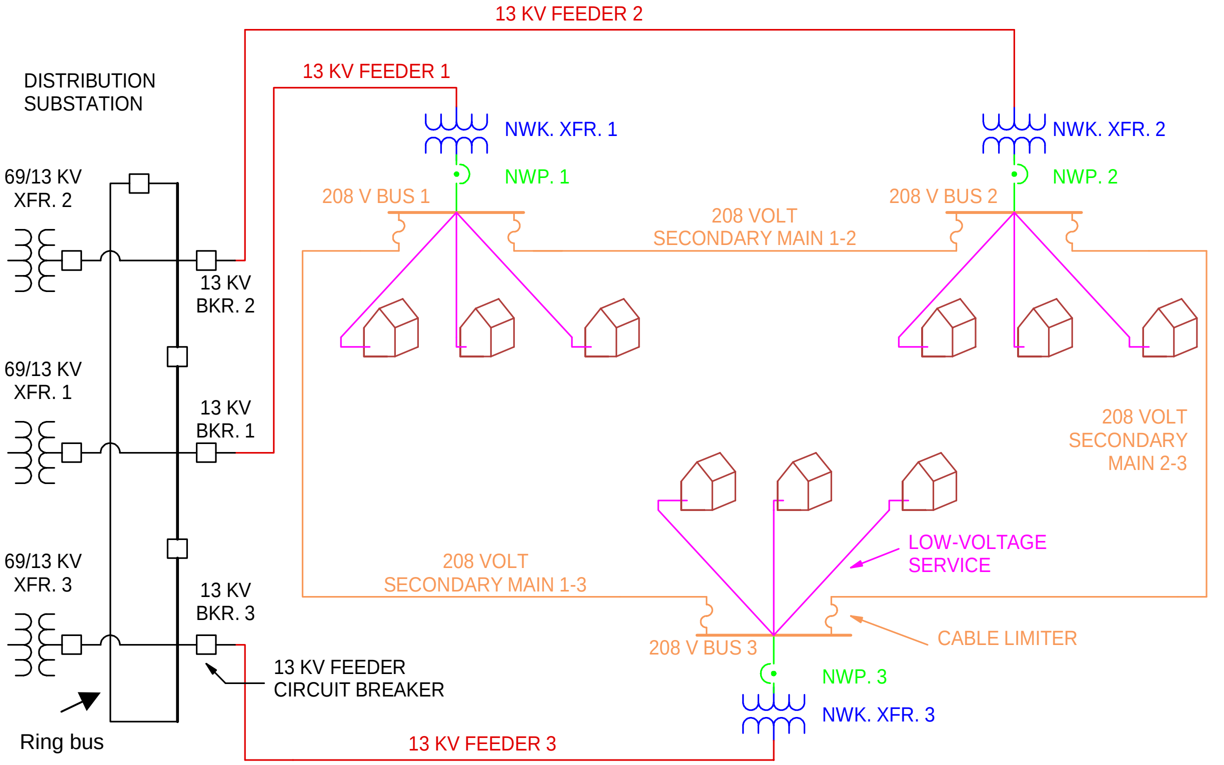
If a short circuit occurs in any one distribution transformer, the 13 kV fuse feeding the transformer blows, and only those customers served from the faulted transformer experience a power outage.

When faults occur in radial systems a large number of customers can be affected, and the length of the power outage can be quite long to all or a portion of the customers fed from the primary feeder. This is especially true in radial distribution systems that are located below ground, because it may be difficult and time consuming to locate the fault. However, Pepco installs branch fuses in 13 kV radial circuits to lower the number of customers experiencing a power outage from faults, and faulted circuit indicators to reduce the time required to locate faults.

Further, Pepco's 13 kV radial circuits also have a loop configuration, which allows service restoration, in many cases, without need to repair the fault.

2.3.2 Low-Voltage Network Secondary Systems:

Low-voltage secondary network systems were developed in the 1920's to provide highly reliable service to commercial areas of cities and towns.



ABBREVIATIONS

BKR.	CIRCUIT BREAKER
NWK. XFR.	NETWORK TRANSFORMER
NWP.	NETWORK PROTECTOR

Note: Only three 13 kV feeders are shown in this simplified low-voltage network system.
Each PEPCO low-voltage network is supplied from six 13 kV feeders, with a multiplicity of nwk. xfrs. on each feeder.

Figure 2 Simplified Low-Voltage Secondary Network System

Figure 2 shows a simplified low-voltage secondary network system serving the same loads as the radial system in Figure 1. In a network system a short circuit on a 13 kV feeder circuit, in a network transformer, and in a low-voltage secondary main does not cause a loss of power to customers. The reason for this is that there is a multiplicity of paths from the distribution substation to the customers. When any one path is opened, there still are other paths for delivering power from the substation to the customers.

The low-voltage network system originates at the distribution substation in Figure 2. The main components of the low-voltage network system are the 13 kV feeder circuit breakers located at the Distribution Substation, the 13 kV feeders, and the network units (consisting of a network transformer and a network protector). Each network unit feeds a 208 volt (or 480 volt) secondary bus adjacent to each network unit. Low-voltage 208-volt secondary mains connect the 208 volt buses at different locations in the load area. Low-voltage services to the customers are fed from the 208 (or 480 volt) volt buses. Sometimes, customers are fed directly from taps to the secondary mains.

In the simplified system of Figure 2, there are three (3) 13 kV feeders with just one network unit fed from each 13 kV feeder. Each of Pepco's 47 networks has six (6) 13 kV feeders supplying it, with a multiplicity of network units fed from each 13 kV feeder

Under normal conditions in the low-voltage network system, the power flow in each 13 kV feeder is from the distribution substation to the network unit (network transformer and protector). In each network unit the power flow is from the network unit to the secondary buses, and along the secondary mains. There is more than one path for the power to flow from the distribution substation to any one customer. The system is protected such that if a short circuit (fault) occurs in any one path, the short circuit is automatically isolated without causing an interruption to the customers served from the network. The system is designed so that with any one 13 kV feeder and its associated network transformers removed from service, the remaining parts of the system can carry the peak load. This is referred to as single-contingency design.

Pepco also designs its low-voltage network systems such that if a short circuit occurs on any one bus section in the distribution substation, no customer will experience an outage. Similarly, if there is a failure of any one main power transformer, there will be no customer outages.

If a short circuit occurs on a secondary main, it will either burn clear or be isolated by the cable limiters at each end of the secondary mains. This also will not result in an outage to any customers served from the secondary buses. However, if there are customers tapped directly from the secondary main which has the short circuit, the customers on the shorted secondary main will lose power until repairs can be made.

It is clear that most short circuits in the system do not cause power outages to the customers supplied from the network. The main reason for this is that there is a multiplicity of paths from the substation to the customer loads, and the short circuits are automatically isolated. This is why the low-voltage network system offers the highest levels of reliability possible with conventional power systems, and is used extensively in many metropolitan areas.

2.4 Causes of Manhole Incidents

Pursuant to DCPSC Order No. 11716 dated June 16, 2000, Pepco was directed to file annual reports detailing all manhole incidents for the previous calendar year. Per this Order, manhole incidents are characterized as follows:

- Smoking manhole: Smoke, but no visible flame is escaping from holes in the manhole cover or around the cover's edge.
- Manhole fire: Flame is visible at holes in the manhole's cover or around the cover's edge and the cover remains seated in the frame.

- Manhole explosion: A release of energy from the manhole occurs, and one or more manhole covers are dislodged from their respective frames, or other debris, such as cement or dirt is projected into the air.

The underground electrical distribution systems illustrated in Figure 1 and Figure 2 require a large number of connections to be made to the various primary and secondary cables. These connections are made in underground concrete vaults, to allow access for construction and maintenance. These vaults are called manholes, except for the smallest, which are called handholes because they are too small to allow a person to enter. Manholes have openings on the top for access. These openings are covered with steel covers (manhole covers) which are removed when necessary to allow entrance to the manhole.

Overhead electrical systems rely on air as the primary insulating medium, except for the support insulators at structures. Splices and connections are relatively simple and are in the open air. Underground electrical systems rely on insulating material along the entire length of a cable to provide the necessary insulation. This insulating material may be either fluid impregnated paper-insulated lead-covered cable (PILC), or solid dielectric such as ethylene propylene rubber (EPR) or cross-linked polyethylene (XLPE). Splices and connections are much more complicated than with overhead construction because of the need to maintain insulation integrity. Underground systems are very unforgiving compared to overhead systems in that any failure of the insulation does significant damage resulting in significant repair time.

Electrical short circuits (faults) result in the release of large amounts of energy. This is why residential circuits are protected with fuses or circuit breakers. A short circuit that is not quickly disconnected would result in overheating of wiring and a fire. A fault in electrical facilities (e.g., cable, splices, taps, transformers and switches) in a manhole results in significant energy release in the manhole.

Another source of energy release in a manhole comes from the combustion of flammable gas produced by decomposition of overheated cable insulation. Overloaded cables (whether from load current or fault current) produce quantities of combustible gases. If ignited, burning of these gases releases significant energy in the manhole.

Overheated cables and accessories (splices, etc.) can produce smoke and result in smoking manholes. If ignited, a manhole fire results. Under the right conditions, ignition can result in an explosion. The explosion causes a rapid air pressure rise in the manhole. If the pressure rise is sufficient, the manhole cover can lift to relieve the pressure. Under more severe conditions, the roof of the manhole may lift. Sufficient pressure may be generated by the arc energy itself to cause a pressure rise sufficient to lift a manhole cover.

Another concern is for faults in oil-filled equipment such as switches, cable terminal compartments, and transformers. Such faults can rupture the enclosure and result in fire if filled with oil. As this equipment is frequently in underground vaults with venting, fire and smoke emanate from the vault. The EEI AC Network Operations Reports, which were last published for the years 1959-1961, document that faults have been occurring in network transformers and the oil-filled switches on the primary side of the network transformers for decades. Faults in compartments typically result in tremendous amounts of energy delivered to the arc, producing pressures that rupture the compartment. These incidents have occurred around the country in the network systems operated by many utilities, and are an industry problem.

2.5 History of Manhole Incidents

Manhole incidents are not unique to the District of Columbia, but have occurred around the United States in a number of cities for many years. For example, the Miami, Florida secondary network was about the third ac network installed in this country, constructed in 1923-1925.[1] Isolated manhole incidents started in the 1940's. One manhole event in Miami in 1969 involved a sustained fire in two manholes. The network was de-energized for 23 minutes to cut cables in three manholes and to open a protector before service could be restored.

The South Bend, Indiana system was converted from 27 kV to 34.5 kV in the 1980's.[2] Failures started soon after the conversion. The failures multiplied during single phase fault conditions that resulted in overvoltages and additional cable faults. Recent interruptions occurred in April and December 2000 and January, February, and March 2001. Major reconstruction of the system is in progress as a result of these failures.

Other utilities and cities in which manhole incidents have occurred are:

- Los Angeles Department of Water and Power on both 4.8 kV and 138 kV systems. One explosion at 4.8 kV lifted the 4 foot square concrete cover of the manhole.
- Tampa Electric (Tampa, Florida), which has investigated a technique for reduction of energy release during faults and mitigation of manhole incidents.[3]
- Pittsburgh, where a female was killed by a flying manhole cover on August 1, 1991.[4]
- New York City has had numerous incidents.[5]
- Pacific Gas and Electric (San Francisco), where one event resulted in a manhole cover resting on the roof of a Honda automobile.

Consolidated Edison (New York), Hawaiian Electric (Honolulu), and Duquesne Lighting Company (Pittsburgh) have installed ventilating or tethered manhole covers as a result of manhole incidents.[6]

Table 1 summarizes experience with manhole incidents at a number of US utilities, as provided by the DCPSC. The data in Table 1 must be treated with caution due to possible differences among utilities regarding what constitutes an incident, and also due to possible differences in the number of years' experience used to generate the statistics. Variations in numbers of incidents may occur from year to year, so the experience in Table 1 may have little statistical significance

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[1] William Thue, "Miami Heat" presented at the EPRI Manhole/Vault Event Summit Workshop, Washington, D.C., August 30-31, 2001.

[2] Roy Middleton, "Underground Events and Mitigation at AEP," presented at the EPRI Manhole/Vault Event Summit Workshop, Washington, D.C., August 30-31, 2001.

[3] David Denison, "Electronic Fuses Protect Cable, Network Transformers," *Electrical World*, Jan 1994.

[4] Joe Koepfinger presentation at IEEE Insulated Conductors Committee meeting in Toronto Apr 8, 1998.

[5] *Daily News*, January 31, 1997

[6] Ralph Bernstein, "Underground Events and Explosion Mitigation Research and Experience," presented at the EPRI Manhole/Vault Event Summit Workshop, Washington, D.C., August 30-31, 2001.

other than to indicate that manhole incidents occur in a number of cities in the US. This lack of statistical significance is especially true where only 1 or 2 incidents per year are recorded. Discounting detailed numerical comparisons, Table 1 indicates that manhole problems are not unique to Washington, D.C. Subject to the statistical limitations discussed above, Table 1 indicates Pepco's experience is in the lower end of the range of utilities surveyed.

Table 1 Manhole Incidents Experience in Other Jurisdictions

Utility	Number of Network Manholes	Number of Manhole Incidents per Year	Manhole Incidents per 1000 Manholes per Year
Alabama Power	250	5	20
Florida Power and Light	220	3	14
Texas Utilities	3500	24	7
GPU Energy (PA)	286	2	7
Boston Edison	3000	12	4
ConEdison	275,000	1219	4
NYSEG	250	1	4
Tampa Electric	500	1	2
Jacksonville Electric Authority	1400	2	1.5
Pepco	**57,000**	**38**	**0.7**
Duquesne Light	1800	1	0.6
Virginia Power	2400	1	0.4
Southern Company	2937	1	0.3

In response to DCPSC Order No. 11716, issued June 16, 2000, Pepco filed a "Report of the Potomac Electric Power Company on Manhole Events in the District of Columbia During 2000." The filing date was February 1, 2001. There were 48 reportable manhole incidents in year 2000, 28 involving primary feeders and 15 involving secondary cables. The incidents included:

- 22 manhole explosions
- 17 smoking manholes
- 5 manhole fires
- 4 other incidents

The total of 48 reportable manhole incidents in year 2000 corresponds to 0.8 manhole incidents per thousand manholes per year. The total of 22 manhole explosions in year 2000 corresponds to 0.4 manhole explosions per thousand manholes per year.

Pepco's experience with manhole incidents in the first seven months of year 2001, as provided by Pepco, is summarized in Table 2.

Table 2 Pepco Manhole Incidents - First 7 Months of 2001

	Total Reported Manhole Incidents		Explosions	
Implicated Equipment	In Georgetown	Outside Georgetown	In Georgetown	Outside Georgetown
Secondary Cable	6	18	1	1
Primary Cable	1	3	0	1
Secondary Cable Splice	1	2	0	0
Primary Cable Splice	1	8	1	8
Other	1	5	0	2
TOTALS	**10**	**36**	**2**	**12**

The “Other” category includes:

- Gas company failure (one of the explosions)
- Oil switch manufacturing defect (one of the explosions)
- Failure in network transformer network termination box
- Network protector failure external damage (roof slab dropped on it in past)
- Fuse box failure

The 46 total reported manhole incidents, when ratioed by 12/7 to estimate a full year, corresponds to 1.4 manhole incidents per thousand manholes per year. The 14 total reported manhole explosions correspond to 0.4 manhole explosions per thousand manholes per year. As a result, it appears that the frequency of manhole incidents on Pepco's underground system is increasing. However, the overall conclusion of this comparison is that Pepco’s experience with manhole incidents is not unique in the electric utility industry.

2.6 Other Studies Relating to Manhole Incidents

The cables in the 208 volt secondary networks that were originally installed in the 20’s and early 30’s did not have cable limiters (special fuses for secondary cables) as they were designed with the belief that cable faults in a duct would burn clear.

As experience was gained with secondary networks in the 20’s and early 30’s, it was found that some faults persisted and did burn clear. Cables at that time had copper conductors with different types of insulation (paper or rubber) and a lead sheath. If a fault did not burn clear, current would feed into the fault from one or both directions. With the melting temperature of the copper being 1083 degrees C, the insulation remote from the fault could be damaged, allowing the fault to spread. If the fault spread back to a manhole at either end of the duct, the fault could propagate to other cables in the manhole, and there could be a massive event.

In the 1930’s, Consolidated Edison, working with the Burndy Corporation, developed the cable limiter. It is basically a fuse that is installed at either end of each cable. The intent was that if a fault did not burn clear, the cable limiters at either end would melt and interrupt the fault current before the temperature of the cable insulation, remote from the fault, would reach a point that would damage the insulation. Tests were also run on cables in ducts to establish the "insulation damage curve" for the cable insulation. For very low currents, the limiter may not protect the cable insulation for intermittent arcing faults. This is why today there are still cable fires in systems that have limiters.

Questions continued, and in 1957 the AIEE Insulated Conductors Committee formed a Task Group to "Develop a device to reduce manhole fires and explosions," chaired by an engineer from Boston Edison. This group produced a 1963 technical paper "Faster Acting Limiters for Secondary Network Systems."

Research on ways to reduce manhole fires and explosions continues to the present day. Within the past ten years, research has intensified. In addition to the tests performed for Pepco, the Electric Power Research Institute (EPRI) Lenox laboratory has performed tests for Consolidated Edison, Duquesne Light, and other clients.[7] The Hydro Quebec Institute of Research (IREQ) has conducted tests in conjunction with the Los Angeles Department of Water and Power.[8] At the same time, analytical research on developing analytical simulations of manhole explosions is being conducted at Georgia Institute of Technology.[9] Manhole incidents are the subject of planned additional research at the present time.[10] The fact that Dr. Black of Georgia Tech has two technical papers submitted for review and publication at the present time and a third in preparation indicates manhole incidents remain a current research topic, not one that was solved years ago.

2.7 PILC Splice Failure Modes

In any cable system the splices and terminations are the weak links. At these locations the factory-manufactured cable will be interrupted, and field handling of the insulation will be performed in a manhole, trench, or substation. If the cable system fails, it is most likely that the failure will be associated with a section of cable that has been exposed to field handling, such as the splice or termination locations.

The PILC splice has several failure modes:

- Degradation of the insulation due to contamination during installation
- Mechanical deterioration of the lead sheath
- Thermal overload of the insulation

The order listed does not imply any ranking of probability of occurrence of the failure modes.

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[7] Doug Howes, "Overview of the Test Facility & Tests at Lenox," presented at the EPRI Manhole/Vault Event Summit Workshop, August 30-31, 2001.

[8] "138-kV Maintenance Hole Restraining System Testing," EPRI and LADWP report TR-113556, 1999.

[9] William Z. Black, "Underground Explosion Software," presented at the EPRI Manhole/Vault Event Summit Workshop, August 30-31, 2001.

[10] Frank Goodman, "EPRI Manhole/Vault Event Workshop Issues, Needs, Solutions," presented at the EPRI Manhole/Vault Event Summit Workshop, August 30-31, 2001.

2.7.1 Contamination During Installation

Several possible scenarios exist for splice contamination during installation. The field conditions for splicing the cables are often not perfect, so the splicing craftsmen must be very careful and particular during the preparation and splicing operation.

Some of the potential areas for contamination entering the splice during the splicing operation include:

- Moisture getting into the paper tapes
- Manhole debris being inadvertently included during the taping operation of the splice
- The splice not being completely filled with compound, resulting in an imploded splice

Over time, contamination introduced during installation can result in electrical failure.

2.7.2 Mechanical Deterioration of Lead Sheath

The lead sheath of a PILC splice creates a hermetic seal that prevents water and other contaminants from entering the insulation. Cracks can form over time that will allow moisture to enter the paper insulation and lead to an electrical failure. Therefore, locating leaking cables and repairing lead sheaths should result in fewer PILC cable/splice failures within manholes.

The normal daily load cycle on a cable causes the cable materials to expand and contract as its temperature changes. The thermal expansion of 500 feet of a copper conductor will be about 6.5 inches when going from an ambient temperature of 20^o C (68^o F) to the maximum conductor operating temperature of 85^o C (185^o F). Most of this expansion results in cable bending, which starts where the cable already has a bend, such as at the splice location within a manhole. Repeated cable expansion and contraction may mechanically fatigue the lead sheath and eventually cracks develop. Also, the lead sheath can deteriorate at the duct mouth in the manhole and at support brackets if the porcelain insulator is missing.

2.7.3 Thermal Overload of Insulation

The paper insulation of PILC deteriorates when exposed for extended periods to temperatures exceeding 105^o C (221^o F), which is the emergency operating temperature. The electrical properties of the paper insulation deteriorates and leads to a thermal runaway type electrical failure. Also, paper insulation that is degraded from severe overloading, may withstand normal operating voltage, but fail to withstand temporary overvoltages.

When PILC cable operates at high temperatures over a long period of time, the insulating paper becomes brittle with a degradation of mechanical strength. If fault current passes through the cable, the mechanical forces and movement can further damage the insulation and result in an electrical failure.

2.7.4 Findings During Manhole Inspections

Stone & Webster's physical inspections of PILC primary cable in Pepco's underground system found instances of fluid leaks at or near primary cable splices, and imploded splices.

3.0 FINDINGS AND RECOMMENDATIONS

3.1 Network System Modeling

3.1.1 Expedite The Analytical Modeling

We recommend that Pepco expedite the analytical modeling of its 47 networks from the current four-year plan to a targeted completion date of the spring of 2003. Additionally, the highest priority should be given to the poorest performing networks.

- The intention of Pepco's design criteria for its network systems is to be able to operate at system peak without overloading secondary cables, even with one feeder and its associated network transformers and protectors (single contingency design) out of service. From the results of the ABB load flow analysis, the Georgetown networks are not able to handle peak load conditions without overloading some secondary cables, even with all primary feeders in service. During a single contingency, many secondary cables are severely overloaded as well as some network transformers and primary cables. This is the most significant result of the ABB analysis, because secondary cables have been implicated in a number of manhole incidents. This finding raises concerns about the performance of the remaining network systems in DC, and emphasizes the need to expedite the underground network modeling. As noted earlier, our assessment did not include an examination of the actual loading on facilities and equipment during normal and/or single contingency conditions because Pepco has not completed development of the load flow models needed to perform this analysis.
- Based on the predominant types of equipment failures involved in manhole incidents and the findings of the ABB Georgetown modeling study, it is our professional opinion that overloading is a primary factor in cable and splice failures, which in turn can create manhole incidents. While the Downes Report as submitted by the OPC suggests that age is a primary factor in manhole incidents, we find no definitive support for such opinion. In fact, we believe that PILC cable has an indeterminately long life if never overloaded or exposed to harsh physical and environmental stresses. As a result, we believe that analytical electrical modeling of the 47 networks is a higher priority than the implementation of a fully developed GIS system as recommended by the OPC.
- Analytical electrical modeling of the existing underground network systems, excluding those in Georgetown, has not been performed in sufficient detail to determine whether cables are being overloaded under normal or single contingency situations during peak loading. Additionally, Pepco has not satisfactorily answered requests for a description of the procedures, methodologies, or calculations presently employed when designing or evaluating secondary network systems. Pepco's response referred to its design standards, which contained nothing about planning or analysis tools, methods, or procedures. However, during a team interview session held with Pepco at its Benning Service Center, Pepco stated that the Company uses a program that is only capable of analyzing about a three-block area.

- While time-consuming, the technology and software to model the secondary networks has been used by other utilities for many years. As discussed in detail in our Power Flow Modeling section, digital computer-based power flow programs became available in the 1960's and were used to model the secondary networks for the City of Richmond, Indiana, and also for Niagara Mohawk Power and others. During the 1970's and 1980's, Alabama Power, Northern States Power, Portland General Electric, and others modeled their secondary networks using the next generation of power flow programs. Pepco purchased a power flow program in 1977 for studies related to its transmission system, but evidently did not use it to model the secondary networks of its distribution system.
- Pepco has responded to its manhole incidents by retaining ABB and EPRI as consultants, performing ongoing manhole inspections and repairs, installing slotted manhole covers in sidewalks and pedestrian crosswalks, formulating the Georgetown Project, and initiating modeling and load-flow analysis. Pepco has purchased the EasyPower load-flow program, and is preparing interfaces with existing data bases to facilitate electronic transfer of information. However, there is need to expedite modeling of the network systems.
- An analytical model, once developed and implemented, is a powerful tool for predicting the impact of load growth on the network and for developing long-range system enhancement and strategic plans.

3.1.2 Adams Morgan

In particular, we recommend the networks serving Adams Morgan be given high priority in terms of the modeling effort.

- Based on our inspection and observations of the manholes in the Adams Morgan area, we find less crowded manholes than in Georgetown but more crowded than elsewhere in DC. However, without modeling of the networks in this area, it is not possible to estimate if or when load growth or other variables may cause overloads within the Adams Morgan secondary networks.

3.2 Technology Enhancements

3.2.1 Current-Limiting Devices

We recommend that Pepco perform a technical feasibility study of the applicability of high speed, electronically controlled fuses and other current-limiting devices designed to limit fault currents by fast fault clearing. This study should be completed by October 1, 2002.

- Pepco has not thoroughly investigated the applicability of these devices that protect network transformers, primary feeder cables, primary cable splices, and other equipment in the primary system from extremely high currents which can result in equipment damage and manhole incidents. Tampa Electric Company has successfully installed such devices on its underground network and has indicated that they are effective in preventing manhole cover displacement, and the rupture of terminal and switch compartments on network transformers, similar to the occurrence at 29th and O Street in Georgetown on May 2, 2001.

- Data received from Pepco shows that the available fault currents on its 13.8 kV buses that supply its network feeders is very high. If current-limiting devices could be installed in the network primary feeders at the substations, they would result in a significant reduction of energy into faults in the splices of PILC cables. This in turn reduces the likelihood of a displaced manhole cover from the pressures generated by high current arcing in the splice. Additionally, there would be a significant reduction in energy into faults in the terminal compartment and high voltage switch compartment of network transformers. This reduces the likelihood of rupturing the compartment and creating an oil fire, as occurred in Georgetown at 29th and O Streets on May 2, 2001.

3.2.2 Monitor Technology Developments

We recommend that Pepco continue to monitor technology developments and evaluate their applicability to its underground electric distribution system.

- Pepco is installing, on a trial basis, a remote monitoring system for network transformers and protectors. Such systems provide real time data intended to improve reliability and optimize maintenance. Con Edison of New York employs real time monitoring on all of its 24,000 network transformers and protectors.
- Additionally, Con Edison is employing the above ground meter, a new technology which allows rapid fault location on primary feeders without the need to open and enter manholes.

3.3 Georgetown Project

3.3.1 Construction Records

We recommend that Pepco capture all as-built Georgetown Project construction records in a form suitable for input into its GIS database. These construction records should include, but not be limited to, the following categories of data:

- Manhole type, layout, and dimensions
- Duct type, layout, and dimensions
- Cable type, size, date of installation, and rating (ampacity)
- Location of cables in ducts, including number of cables per duct
- Cable limiters
- Date of Pepco standards used

3.3.1.1 Existing Georgetown System

Based on our examination of information provided by Pepco, our visual observations, and our inspections of Pepco's existing underground facilities and substations, we find the following:

- The predominant equipment failures related to manhole incidents are secondary cables and primary splice failures. In Georgetown, crowded manholes and ducts create additional heat thereby increasing temperatures and the possibility of failures. Crowded manholes may also compound failures by propagating them between secondary and primary cables, and increasing the difficulty of making repairs.

- Materials and workmanship are at or above industry standards. However, we found the Georgetown area manholes to be overcrowded due to load growth beyond the design criteria of the affected manholes. Overcrowding affects the Georgetown system from a physical standpoint as well as electrical and thermal standpoints in terms of cable thermal ratings and the ability of the duct banks to dissipate heat.

3.3.1.2 Pepco Construction Standards

Based on information provided by Pepco, we find the Georgetown Project will utilize the latest Pepco standards, for example:

- Manhole size
- Separation of primary and secondary systems
- Newer materials (e.g., EPR cable systems, PVC ducts, and URD technologies)
- Improved cable ratings

Pepco maintains and updates design and construction standards for its system as overall documents, rather than for each individual project. Construction records should identify the date of the standards applied during construction.

3.3.1.3 Benefits of Georgetown Project

Based on information provided by Pepco, we believe the Georgetown Project will:

- eliminate the crowded manholes,
- separate primary from secondary cable circuits, reducing the probability of a secondary cable failure propagating into a primary circuit failure, and vice versa,
- reduce temperature buildup and improve heat dissipation, and
- make repairs easier in the event of future failures.

3.3.2 Analytical Electrical Modeling

We recommend that prior to construction, Pepco should model its planned Georgetown primary and secondary systems using the EasyPower load flow program to evaluate the adequacy of the design before it is constructed. The modeling will ensure:

- adequate number and size of cables,
- optimum layout (topology) of cables,
- sufficient number of ducts, and
- adequate capacity for future load growth.

3.4 Quality Assurance Measures

3.4.1 Splicing and Repair Log

We recommend a splicing and repair log be kept containing dates of installation, crew members performing the work, materials used, and other information deemed suitable for GIS databases.

- Although primary splice failures have been involved in a number of manhole incidents, our field inspections have noted good workmanship in the manholes.
- Pepco formed a joint union/management committee that conducted a training needs analysis of underground workers and initiated a comprehensive refresher training program. The program does not require re-certification of splicing skills for cable splicers.

3.5 Staffing and Support Needs

3.5.1 Workforce Staffing Analysis

We recommend a workforce staffing analysis be undertaken to address possible staffing needs in light of increasing workloads. This study should be completed by April 1, 2002.

- Pepco’s underground and conduit staffing levels have decreased by 30 percent over the past decade. During the same period, underground construction expenditures have decreased by nearly 50 percent while Pepco’s system reliability indices from 1996-2000 have improved. However, additional manpower may be required to meet the needs of underground system modernization plans and ongoing manhole inspection and maintenance projects and programs. Additional manpower may also be required to meet the expedited schedule for the network modeling effort as proposed above.
- Pepco’s capital and O&M budgeting and variance reporting processes are well defined and suitable to the needs of the Company. The business performance department compiles and reports multiple years’ analysis of power distribution and customer care budgets and spending. These are circulated to appropriate members of management, and facilitate both trend and variance analyses.

3.6 Manhole Inspections, Repairs, and Reporting Program

3.6.1 Slotted Manhole Covers

We recommend that Pepco continue its ongoing installation and evaluation of slotted manhole covers.

- Based on our review and examination of EPRI's manhole cover tests, we found that the studies used appropriate laboratory technique and instrumentation. The test results give reasonable guidance concerning the effects of slotted covers on mitigating displacements.
- Pepco's experience to date indicates that no slotted manhole covers have been displaced due to a manhole explosion.
- We agree with Pepco's decision to install slotted covers in sidewalks and crosswalks, and note the need to monitor the affected manholes for accumulation of debris.

3.6.2 Manhole Repair Prioritization Schedule

We recommend changes be made to Pepco's manhole repair prioritization schedule.

- Pepco's comprehensive manhole inspection program is an important element of ongoing underground maintenance plans and actions. However, the repair prioritization schedule does not reflect the need to make certain repairs immediately. Also, we believe all electrical repairs should be completed within 12 months, rather than 18 months. The current and recommended revised prioritization schedules are shown in Appendix A.5.

3.6.3 Manhole Inspection Reports

We recommend changes be made to Pepco's manhole inspection reports.

- Pepco prepares quarterly manhole inspection reports listing the actions to be taken based on the manhole inspection findings. The report lists the number of manholes inspected and the items to be corrected including a time schedule for the repairs. The value of this report could be enhanced if the following additional data were incorporated: a) the priority code for repairs, b) date and type of repairs performed in the past 12 months, and c) all outstanding corrective actions to be completed within the prioritization schedule.

4.0 FACILITIES INSPECTION

4.1 Introduction

Stone and Webster inspected Pepco underground distribution system facilities in the District of Columbia on three separate occasions between June and August 2001. Inspections were conducted in the District as illustrated on the map shown in Figure 3, and detailed in Table 3. Included in the inspection program were:

- 41 manholes
- 15 transformer vaults
- 3 switch vaults
- 5 substations

From visual observations and inspections of Pepco's existing underground facilities and substations, Stone and Webster finds that materials and workmanship are at or above industry standards. However, the Georgetown area manholes are overcrowded due to load growth beyond the design criteria of the affected manholes. Manholes in the Adams Morgan area are less crowded than in Georgetown, but are more crowded than elsewhere in DC.

4.2 Manhole Inspection Criteria

The following information was given to Pepco as the criteria for the manhole and transformer vault inspections:

Cable Manholes within Georgetown:

- Manholes where explosions occurred
- Manholes where secondary and primary cables are in the same duct bank
- Manholes that have been inspected and where repairs were made
- Manholes that have been inspected where no repairs were required
- Manholes that have not been inspected
- Manholes with different designs from the ones that have failed
- Manhole where failure occurred in 1999 on O Street between 35th and 34th Street
- Manhole where failure occurred in 1999 on R Street between 29th and 28th Street

Cable Manholes outside of Georgetown:

- Manholes installed during the reconstruction when the subway system was constructed
- Manholes in areas of the subway but not changed during the subway construction
- Manholes with different system designs within the subway reconstruction program
- Manhole where failure occurred in 1999 east and north of Thomas Circle
- Manholes where primary cables initiated failures during 1999, 2000, and 2001
- Manholes where secondary cables initiated failures during 1999, 2000, and 2001
- Manholes in other areas within Pepco's underground distribution system within Washington DC.

Substations:

- Cables and cable connections, 13 kV units
- Cables and cable connections, 4 kV units

Handholes:

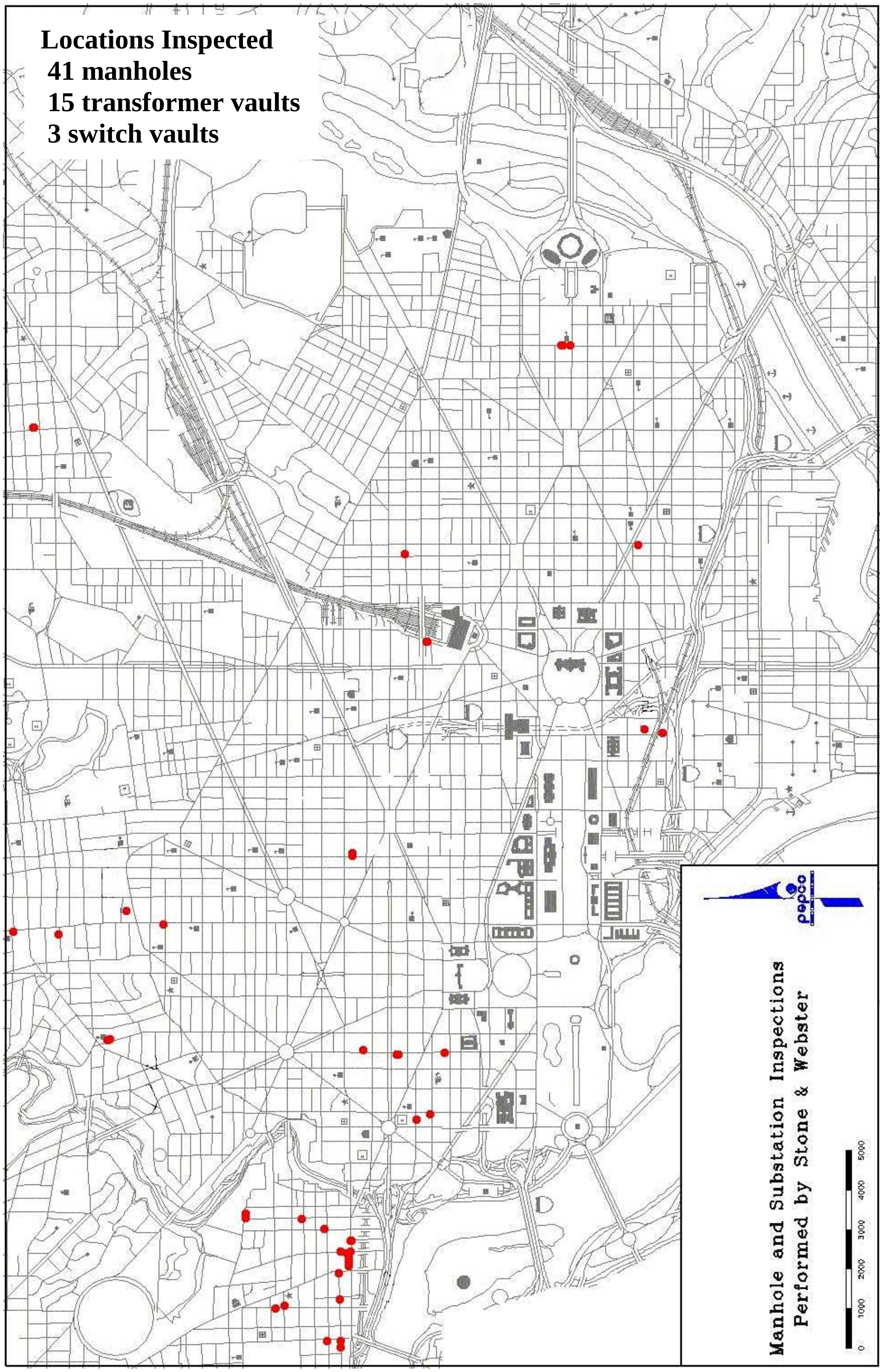
- Handholes involved with manhole incidents
- Handholes with network and/or distribution equipment

Transformer Vaults within Georgetown:

- Vaults where manhole incidents from primary cable failures occurred, or in close proximity to these types of manhole incidents during 1999, 2000, and 2001
- Vaults where manhole incidents from secondary cable failures occurred, or in close proximity to these types of manhole incidents during 1999, 2000, and 2001

Transformer Vaults outside Georgetown:

- Vaults where manhole incidents from primary cable failures occurred, or in close proximity to these types of manhole incidents
- Vaults where manhole incidents from secondary cable failures occurred, or in close proximity to these types of manhole incidents



Locations Inspected
41 manholes
15 transformer vaults
3 switch vaults

Figure 3 Stone & Webster Inspection Locations of Pepco's Underground Distribution System within Washington DC

Table 3 Locations of Underground Site Inspections

Type of location	Site Location	Grid Number
	Locations within Georgetown:	
Transformer vault	Prospect & Potomac St	782390-391576
13 kV, secondary cables with limiters	Prospect & Potomac St	782390-313588
13 kV, secondary cables with limiters	Prospect & Potomac St	782390-381588
4 & 13 kV	Prospect & 35th St	780390-261551
Secondary cables	1562 33rd St	781392-080187
Transformer vault	SE side of 33rd & Volta Place	781391-138966
3 Phase Transformer Vault 120/208 Network	31st St in front of Post Office	782390-178340
Manhole next to vault	31st St in front of Post Office	782300-154340
Manhole	31st St & M St, NW	782390-511293
Manhole with primary & secondary cables	31 St & M St	782390-470345
3 Phase Transformer Vault 120/208 Network	29th St & "O" St, NW	783391-328528
3 Phase Transformer Vault 120/208 Network	South side Prospect St West of Wisconsin Ave.	781390-974591
Single Phase Transformer Vault	29th St & "R" St NW	783392-365960
Handhole	2810 & 2812 R St.	783392-365965
Manhole	2804 & 2808 R St.	783392-546963
Single Phase Transformer Vault	30th St & "N" St NW	783390-096975
Manhole	1200 36th St NW	779390-890667
Manhole	3500 Prospect St NW	780390-261551
Manhole	35th St & "N" St N.W	780390-246901
Handhole – 120/208 volt	M Street near 31st St.	782390-438343
Handhole – 120/208 volt	M Street near 31st St.	782390-395342
Handhole – 120/208 volt	M Street near 31st St.	782390-326342
Handhole – 120/208 volt	M Street near 31st St.	782390-309342
Handhole – 120/208 volt	M Street near 31st St.	782390-289342
Handhole – 120/208 volt	M Street near 31st St.	782390-270342
4 and 13 kV, 120 V	M Street near 31st St.	782390-226341
13 kV and secondary bus	M Street near 31st St.	782390-193340
Transformer Vault	NW Corner M & 31 Streets	782390-470345
Manhole next to Transformer Vault	NW Corner M & 31 Streets	782390-475387

Type of location	**Site Location**	**Grid Number**
	Locations outside Georgetown:	
13 kV PILC, Joint had been replaced	NW corner of 22nd & G St	785388-991287
13 kV PILC, imploded splice Limiters on secondary cables	I St between 22nd & 23rd Streets	785388-835642
Metro construction, 13 kV EPR cables	14th St, between O & M	790398-595818
Metro construction, 13 kV & secondary	14th St & Girard	790397-528692
Secondary hole, Cable limiters installed	14th St, Columbia & Irving	790398-594832
3 Phase Transformer Vault 277/480 Network	1900 "K" St, NW Eastside	787389-502127
Bus Hole 277/480	1900 "K" St, NW Eastside	787389-479089
Primary cable manhole	1900 “K” St, NW	787389-502115
3 Phase Transformer Vault 277/480 Network	1111 19th St NW	787389-604979
4 Transformer Vaults 120/208 Network	2500 Virginia Ave. SW	784387-536936
Bus manhole	2500 Virginia Ave. SW	784387-552988
Manhole	400 “D” St SW	794382-964115
Manhole	6th & Pennsylvania Ave. SE	800383-378029
Manhole	500 “I” St NE, North Side	800388-144928
Manhole	Manhole in front of substation gate	795382-624425
Manhole	Manhole in road near substation	795382-586425
Manhole	Manhole 15 ft. north of gate	795382-586411
Switch Hole	17 St NE and East Capitol St SE	803398-430930
Transformer Vault	17 St NE and East Capitol St SE	805384-430971
Bus Hole	2705 13 St & Evarts St NE	803398-348307
Transformer Vault	First St NE near Union Station	797388-949379
Secondary Bus Hole	1100 Block of 10 Street NW	792390-570264
Primary manhole	1100 Block of 10 Street NW	792390-590264
Feeder holes, several transformer vaults	Eastern Sr. HS, 17th & East Capital	805384-430307
Transformer Vaults	13th St & Evarts St	803398-348324
Transformer Vaults, Bus hole	777 North Capital	797388-949379 797388-961418
Transformer Vaults, Bus hole	810 North Capital	797388-029687 797388-023662
Transformer Vaults, Bus hole, Primary hole	1100 block 10th St	792390-570264 792390-590264 792390-530252 792390-632264

4.3 Review of Manholes within Georgetown

In general, manholes in Georgetown were smaller, more crowded, and were found to contain older style equipment than those outside of Georgetown. This evidence of crowded underground facilities is primarily a result of load growth beyond the originally intended design criteria of the manholes. An example of crowding in Georgetown is the manhole at Thomas Jefferson and M Streets which contains 4 kV primary, 13 kV primary, 208 volt network secondary, 120/240 volt single phase secondary, as well as a 4 kV switch and a 4 kV transformer. Street lighting, traffic signals, and communications cables can also be found in the same Georgetown manholes as primary and secondary cables.

While it is recognized that these inspections were performed on hot days, it is noteworthy that the highest manhole temperatures seemed to be in the smaller more crowded holes. Air temperatures of 95-98 degrees F were observed.

Georgetown manholes contain more cables of larger wire size than was originally considered in their design. This presents several kinds of problems. While more cables by themselves lead to more difficult working conditions in small holes, larger diameter cables are more difficult to work than the smaller wire sizes considered in the original designs. In spite of the crowding, a generally high quality of workmanship was observed.

Figure 4 shows an example of a crowded manhole in Georgetown. Primary cables, secondary cables, ground (neutral) cables, and either street light or traffic signal wires all come together in one place.

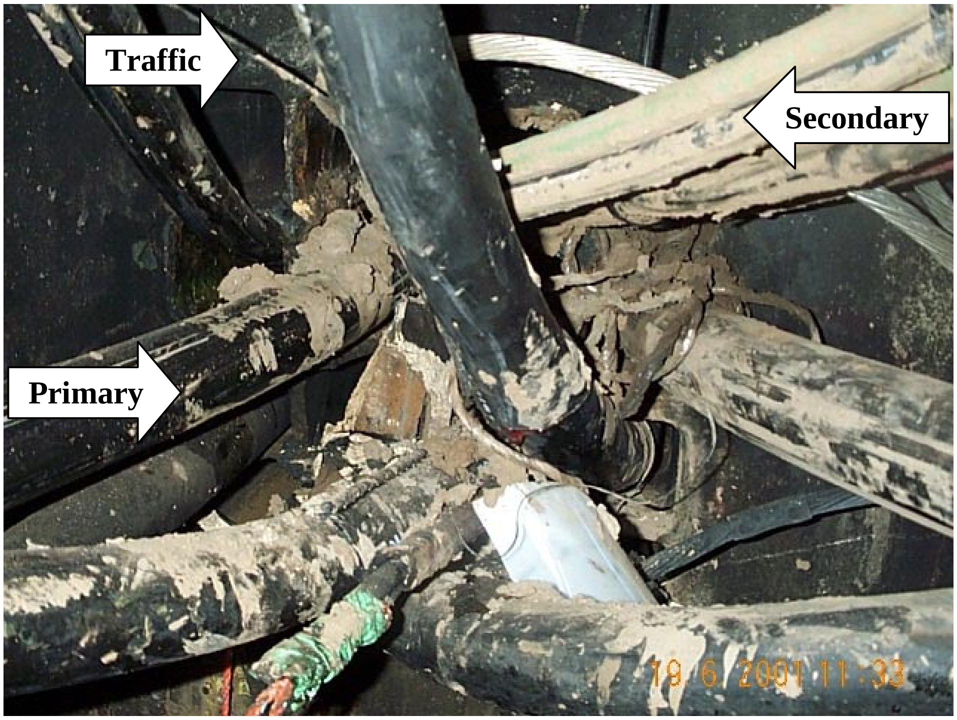


Figure 4 Crowded Manhole within Georgetown with Primary Cables, Secondary Cables, and Traffic Signal or Street Light Cable

Figure 5 shows an example of a crowded hand hole in a sidewalk of Georgetown. Working in a hole like this can be quite difficult because of the lack of space.

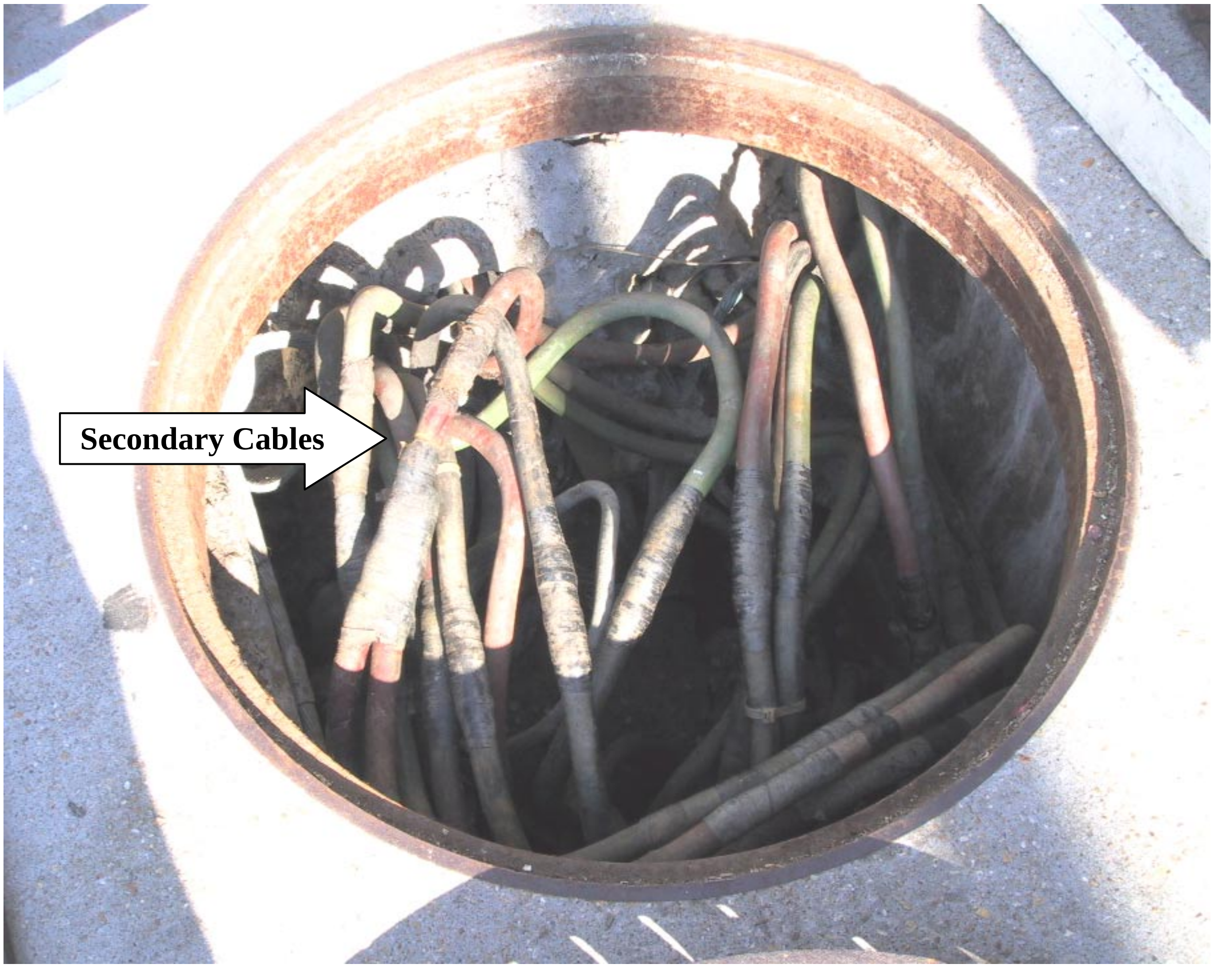


Figure 5 Manhole (Handhole) in Georgetown Crowded with Secondary Cables

Many manholes in Georgetown contain both primary and secondary cables, with close spacing between primary and secondary cables as illustrated in Figure 6. At this location secondary cables are adjacent to primary cable splices. Should the primary cable splice fail, it is likely to affect the secondary cables.

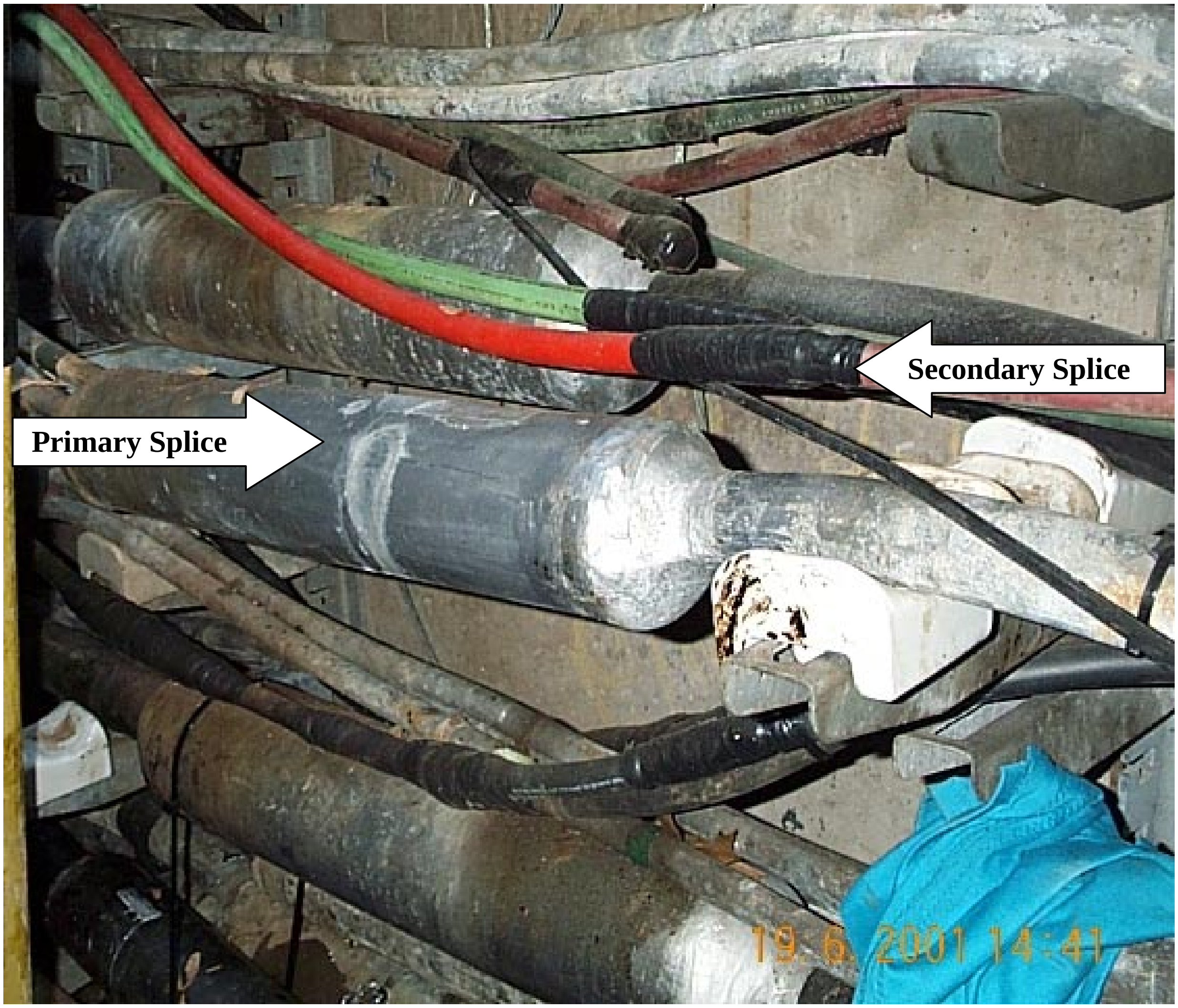


Figure 6 Crowded Manhole in Georgetown with Primary and Secondary Cables in Very Close Proximity

Due to lack of physical space in Georgetown manholes, the primary was not always below the secondary cables, nor were the secondary cables on an opposite wall from the primary cables. Separation between primary and secondary cables is desirable to reduce the probability of a fault originating in a secondary cable from affecting a primary cable (and vice versa), as happened in Georgetown in the June 13-16, 2001 event.

A hot (290° F versus the design maximum of 167° F) 208-volt splice was found at the corner of N and 35th Streets in the Georgetown secondary network system (Figure 7). Bubbling and blistering of the insulation are visible in the picture. The hot splice was called in and repaired by a responding crew. During the repair, the crew found and replaced another splice with deteriorating insulation. This small, crowded manhole contained both 4kV primary and 208-volt secondary cables, and is an example of a situation where a primary fault could propagate into a secondary fault and vice versa.

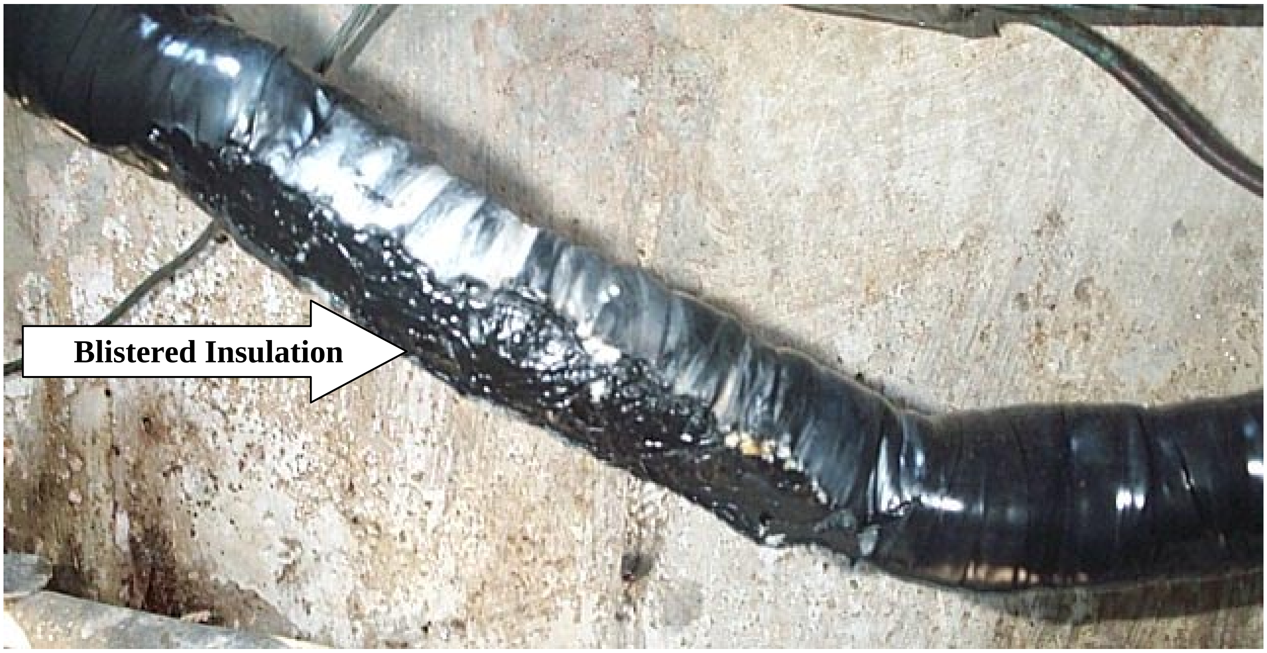


Figure 7 Hot (290^o F) Secondary Splice Located During Field Inspection

Figure 8 shows a section of secondary cable removed during repair of failures in Georgetown. The sample was selected from a large bin of failed cable stored in a warehouse at the Benning Service Center. Visual inspection of the cable's insulation reveals overheating. However, since there is no indication of fire damage, the insulation was most likely overheated due to excessive electric current.

Figure 8 Overheated Secondary Cable Removed from Georgetown after a Manhole Incident

An example of the use of old-style material in Georgetown manholes is terracotta ductwork, shown in Figure 9. In this example, the terracotta tiles form four square duct holes arranged in an overall square. Different numbers of ducts of different cross-section areas are found in different manholes. Although terracotta is a durable material, it is brittle and the joints between tiles can separate, effectively blocking the duct.

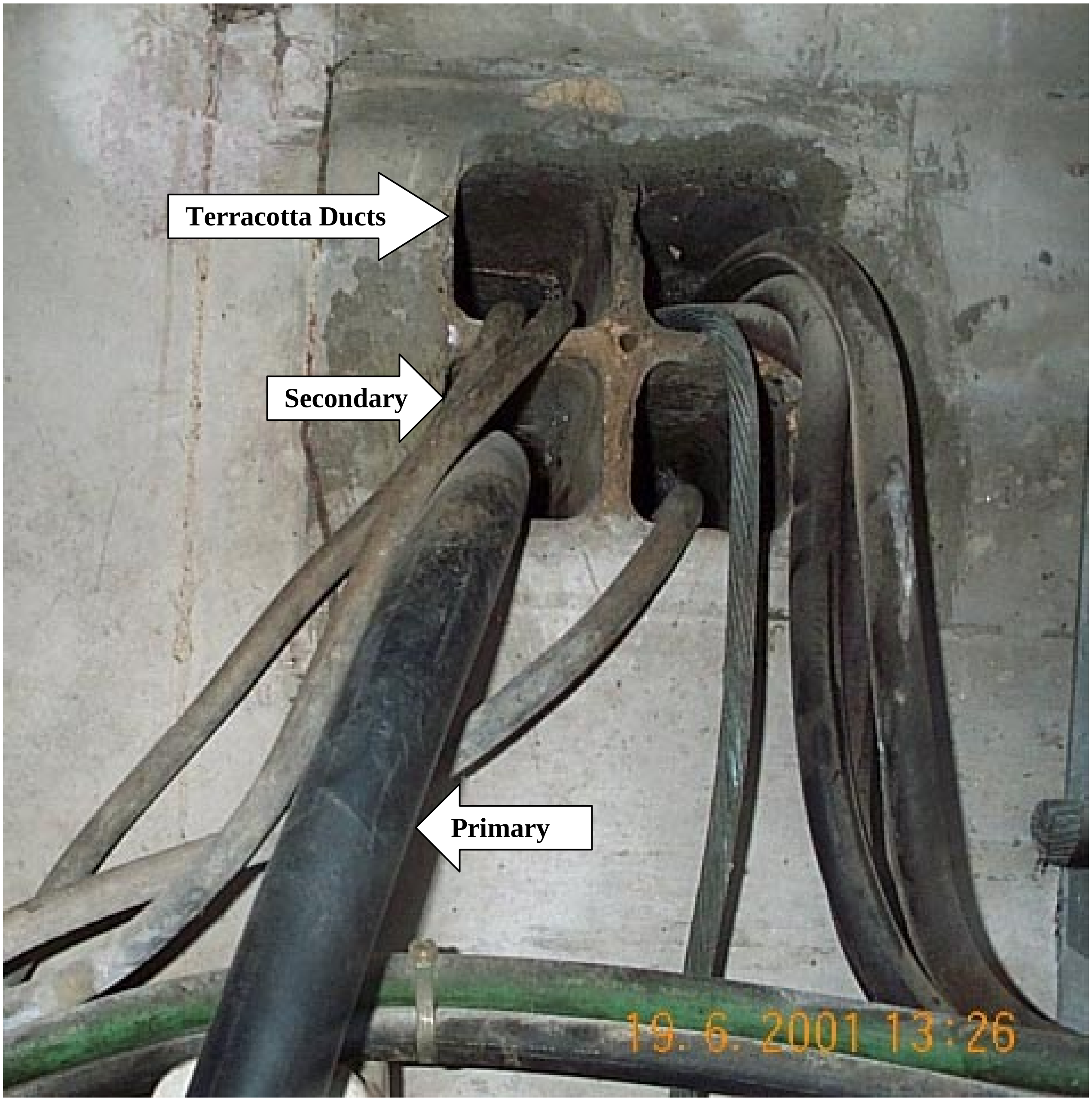


Figure 9 Terracotta Ducts with Primary and Secondary Cables within a Duct Bank

Newer installations use PVC duct, as shown in Figure 10. Newer ducts also generally have a larger cross section area than older ducts and have more spacing between them. Larger spacing between ducts allows better heat transfer away from the cables than when the ducts are close together. The spacing also reduces the chance of a fault propagating from one duct to another. Figure 10 also shows a double set of secondary cables in a single duct. Doubling up of cables in a duct reduces the ampacity of the cables due to the increased heat generated by the extra cables vis-à-vis the limited heat dissipation capability of a single duct.

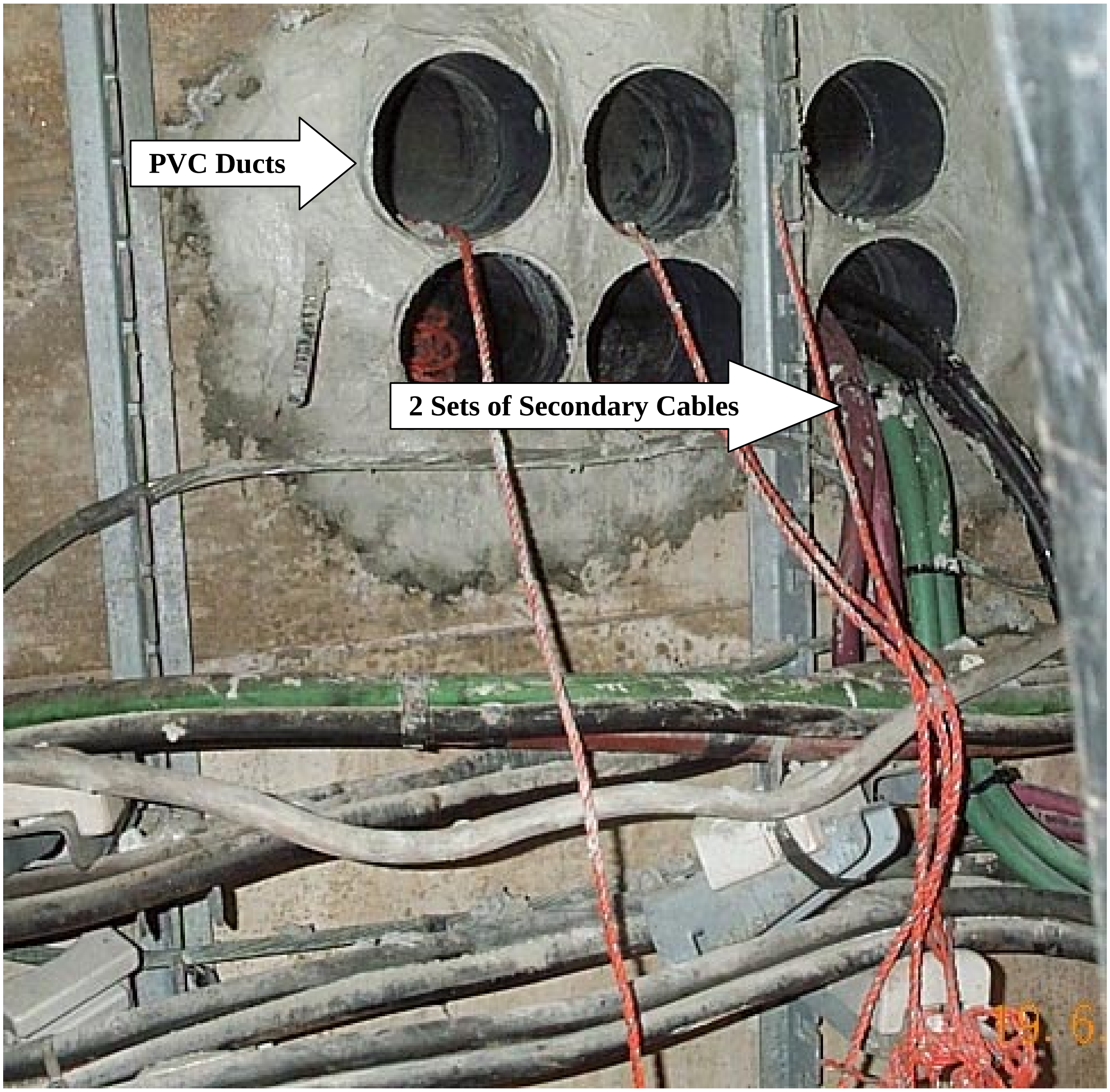


Figure 10 Ductbank with PVC Ducts and Two Sets of Secondary Cables in One Duct

Concern has been expressed about the accumulation of debris in manholes with slotted covers. This concern is justified, as debris was found on the floors of some manholes with slotted covers. Figure 11 shows an example of debris accumulation on the manhole floor. Another example of debris accumulation was observed in a manhole on 33rd Street near Q Street, which had a layer of leaves on the manhole floor.

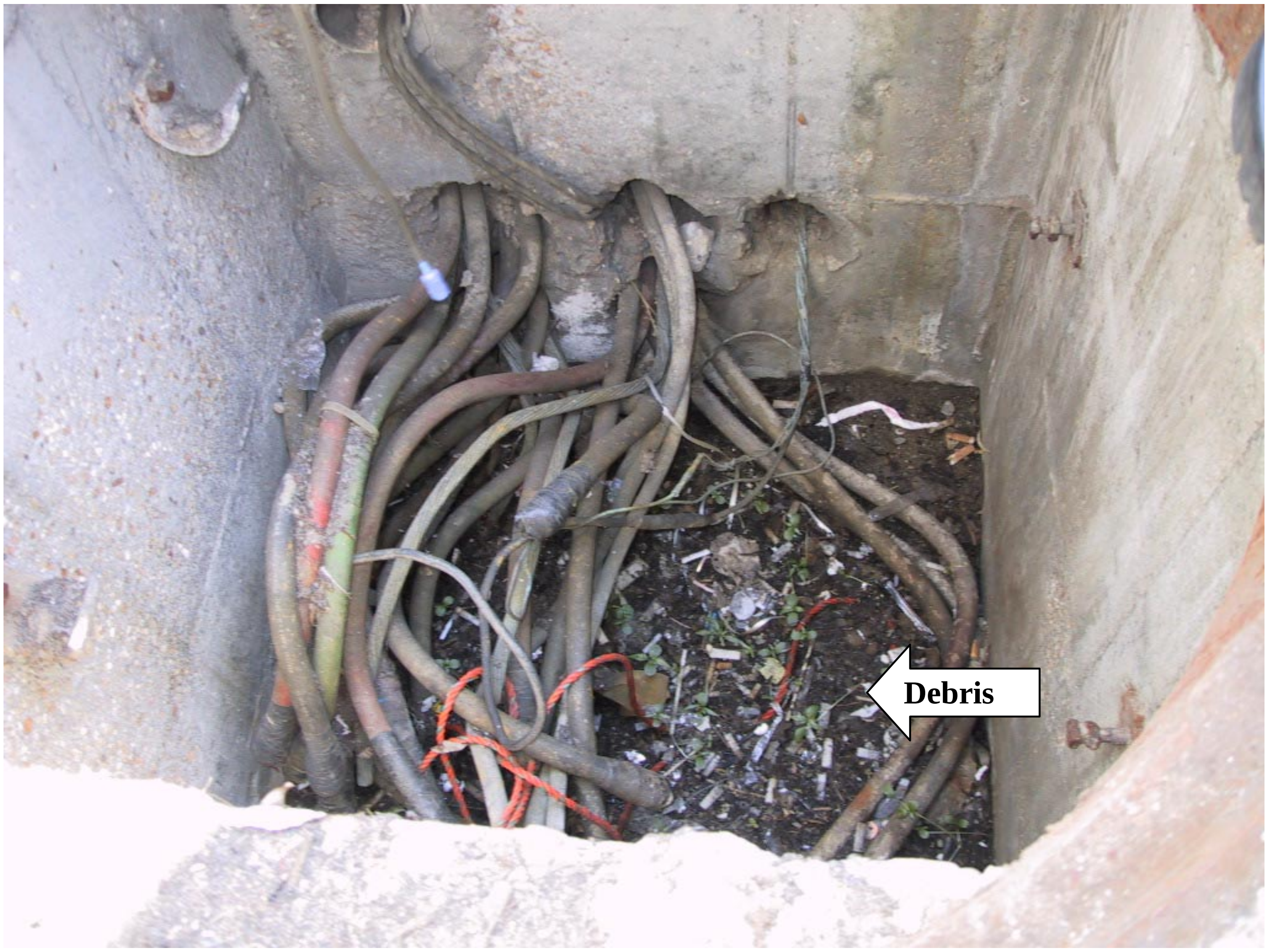


Figure 11 Debris Inside a Manhole With a Slotted Cover

4.4 Review of Manholes Outside Georgetown

In contrast to conditions observed in Georgetown, manholes outside of Georgetown exhibited mostly larger sizes, newer materials and newer methods. An example of newer materials and methods is the use of elbow connectors to make connections to the cables. Figure 12 shows a sidewalk tap hole using load break elbow connectors. Elbow connectors can be connected and disconnected without the labor-intensive lead work required on the older PILC wiped joints. The connectors can be operated from the sidewalk level above the hole. This construction allows rapid reconfiguration of the primary cable system for maintenance, repair, or restoration of service. Fault indicators are applied on all outgoing cables from the hole, facilitating identification of faulted cables. The layout of the tap hole, together with data on the underside of the lid is arranged to facilitate rapid operation.

Elbow connectors are an example of methods originally developed for underground residential distribution (URD) that are now finding their way into urban systems. The loop system to be installed in the Georgetown residential neighborhood to replace the existing 4 kV radial and secondary network systems is planned to be constructed using these methods. URD derived methods offer simplicity and faster restorations following failures.

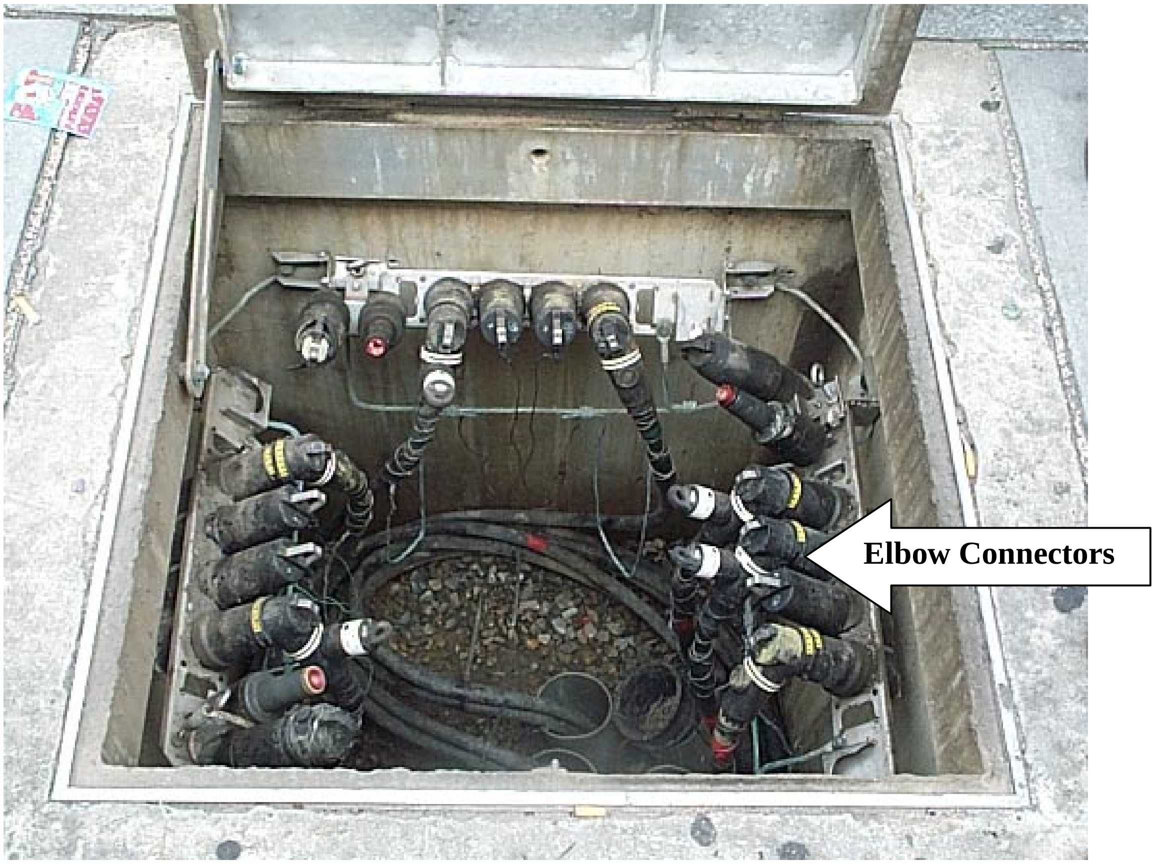


Figure 12 Tap Hole Showing Load Break Elbow Connectors

As in Georgetown, a generally high quality of workmanship was observed. Figure 13 shows an example of high quality workmanship in a secondary bus hole. Note the cable limiters installed on the secondary cables and empty ducts available for future expansion.

Most of the manholes outside of Georgetown are of ample size, with ample separation between primary and secondary cables when it is necessary to place both in the same hole. In such a case, the best approach is to place primary and secondary cables on opposite walls of the manhole, which is done in the Pepco system when possible. One exception to the ample size of manholes was found in the Adams Morgan area. Some of the manholes in the Adams Morgan area are small, and with the area changing from residential to small commercial these manholes may become crowded as load increases. In an Adams Morgan-area manhole that had recently experienced an event, Stone and Webster observed Pepco repair crews installing additional secondary cable to eliminate overload conditions.

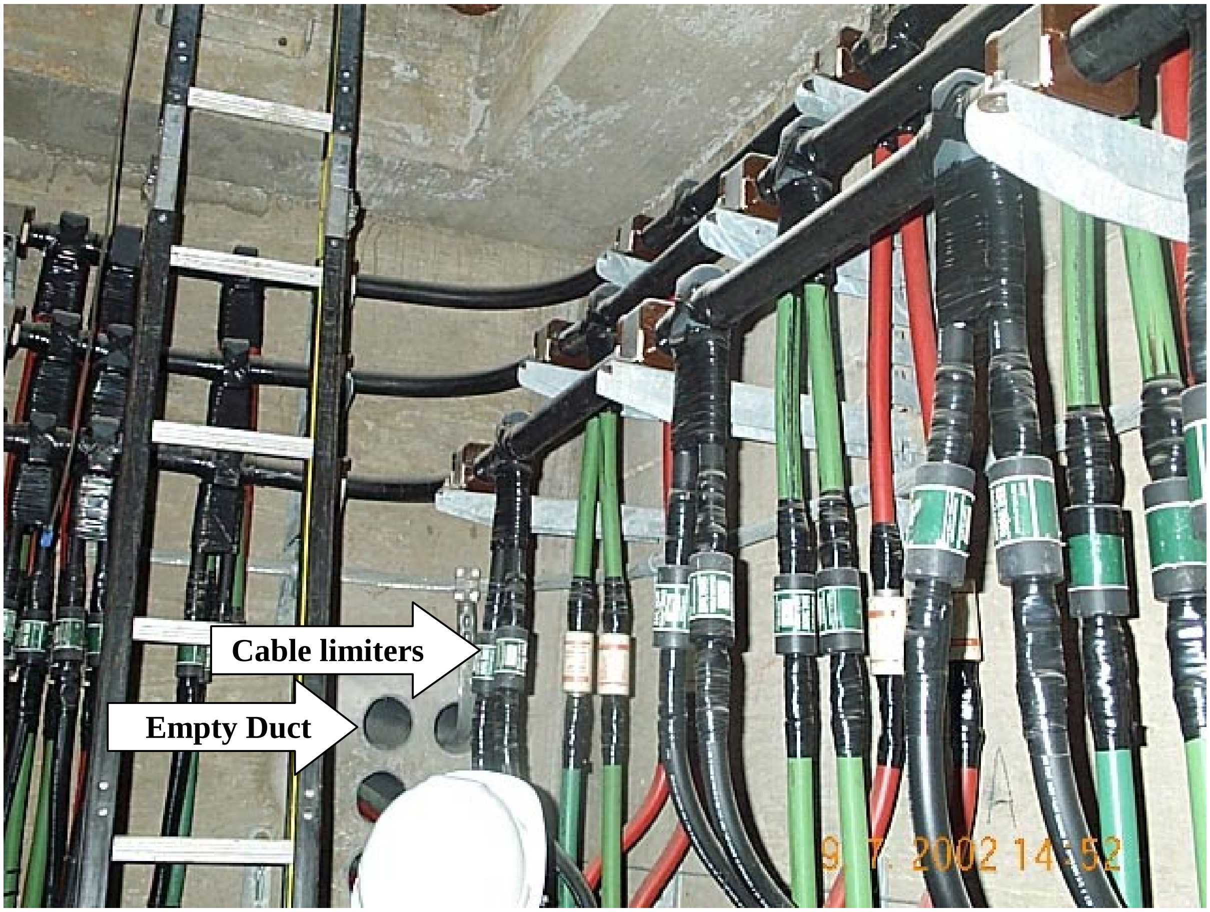


Figure 13 Secondary Bus Hole Showing Quality Workmanship

Figure 14 shows an Adams Morgan manhole while the work was in progress. The present need for additional cables further raises a concern regarding the future capacity of the underground system in Adams Morgan. This needs to be resolved by network modeling and analytical prediction of cable loading for present and future years.

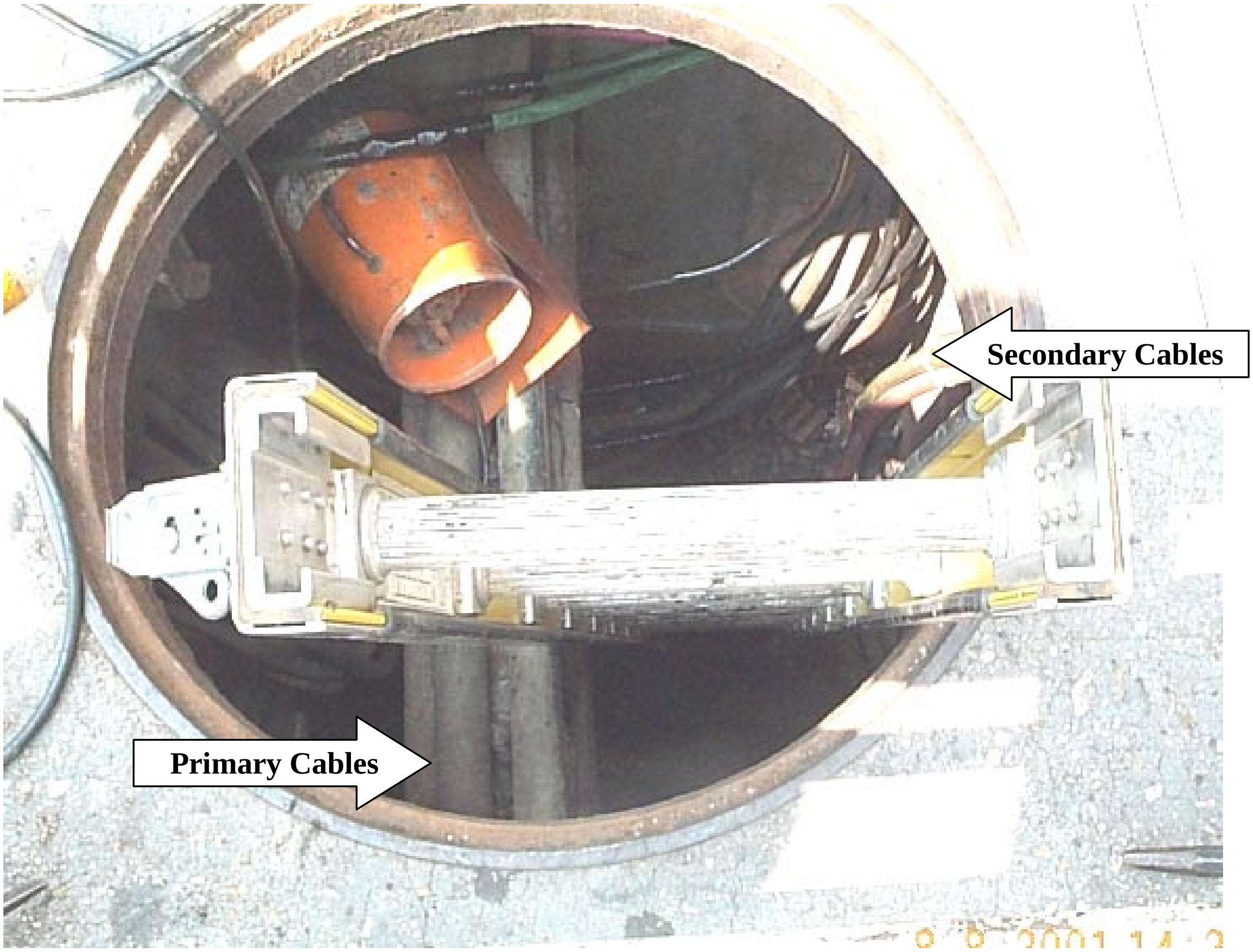


Figure 14 Crowded Adams Morgan Manhole

Evidence of good up to date engineering design and workmanship was found in manholes outside of Georgetown. For example, bus in busholes is double insulated, consisting of the insulation on 1000 and 1500 kcmil bus cable plus porcelain insulators. Pepco's use of a new staggered bus design (used since about 1987) maintains higher phase spacing than the old design. Figure 15 shows the newer staggered secondary bus design.

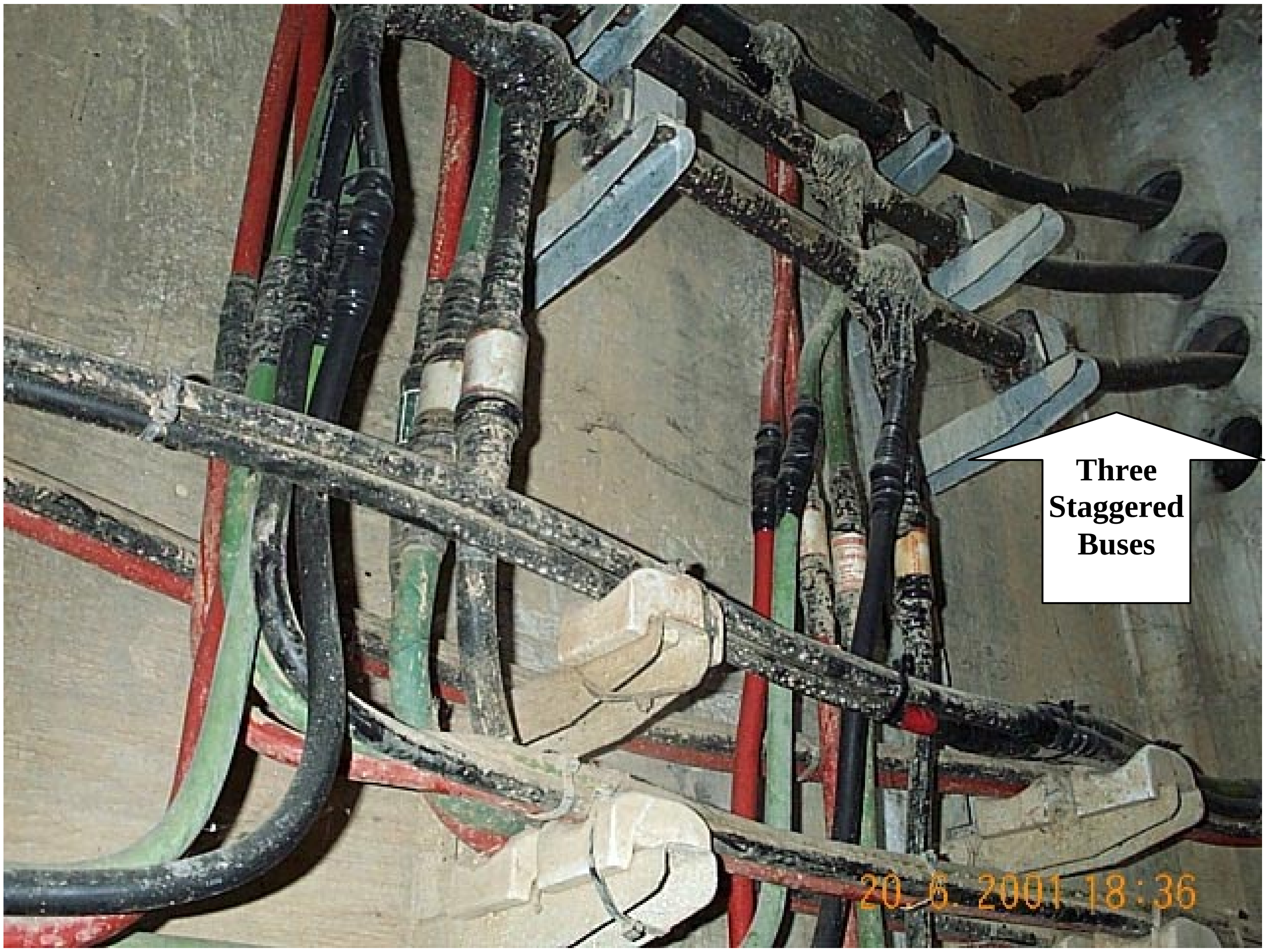


Figure 15 Staggered Secondary Bus Design

Deficiencies were observed in some of the manholes. For example, two slightly imploded primary cable lead splices were found. When a lead cable is spliced, the splice is filled with a tar-like compound. If insufficiently filled, the lead will partially collapse over time. Figure 16 shows an imploded splice. The lead covering the splice should be cylindrical. In this case, the upper surface of the outside lead is indented, appearing like a groove on the top of the splice. While not an immediate concern for failure, imploded splices should be replaced to prevent premature failure. This is an example of the kind of condition the Pepco manhole inspection program is designed to detect and repair.

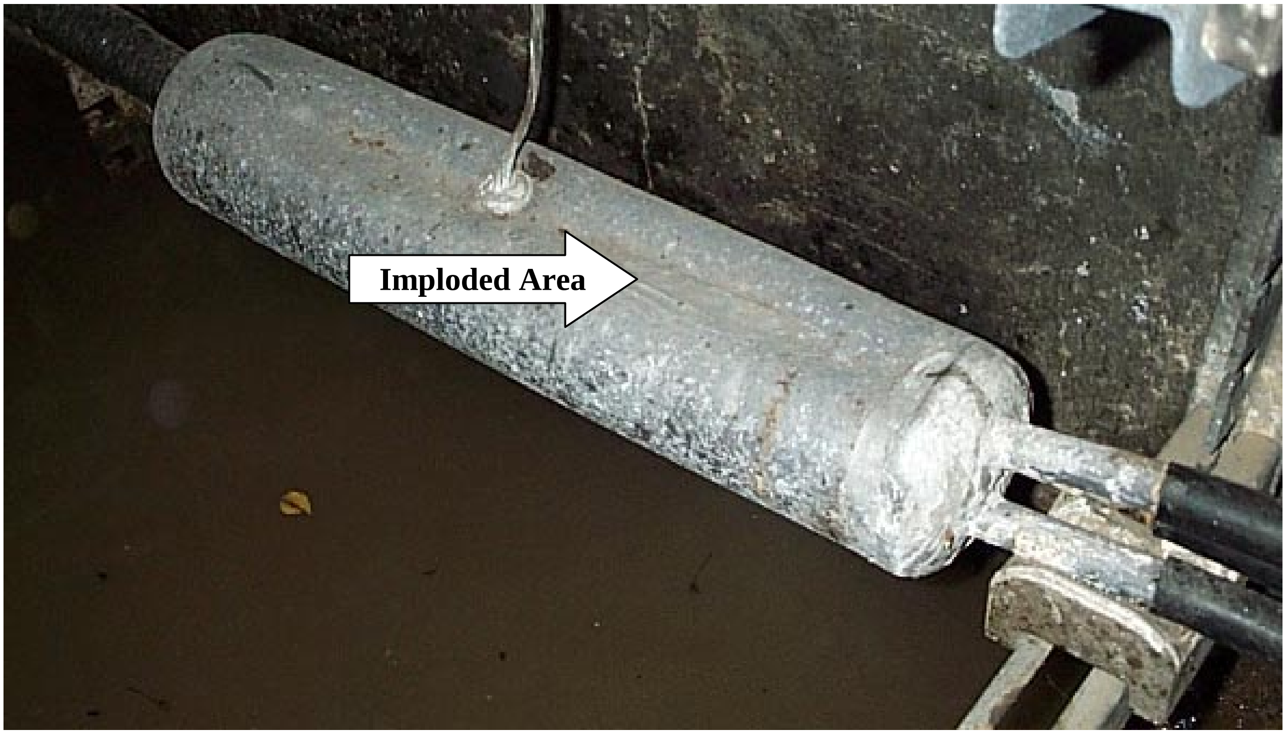


Figure 16 Imploded Primary PILC Y-Splice

While workmanship is generally very good, problems do exist in manholes anywhere. For example, Figure 17 shows some additional problems observed in a manhole. The primary cable has a small tight bending radius that can lead to problems as the cable heats and cools over its load cycle. Also, the porcelain saddle the cable should rest on is missing. Sliding of the cable over the metal bracket can result in wear on the jacket and possible ingress of moisture and subsequent failure.

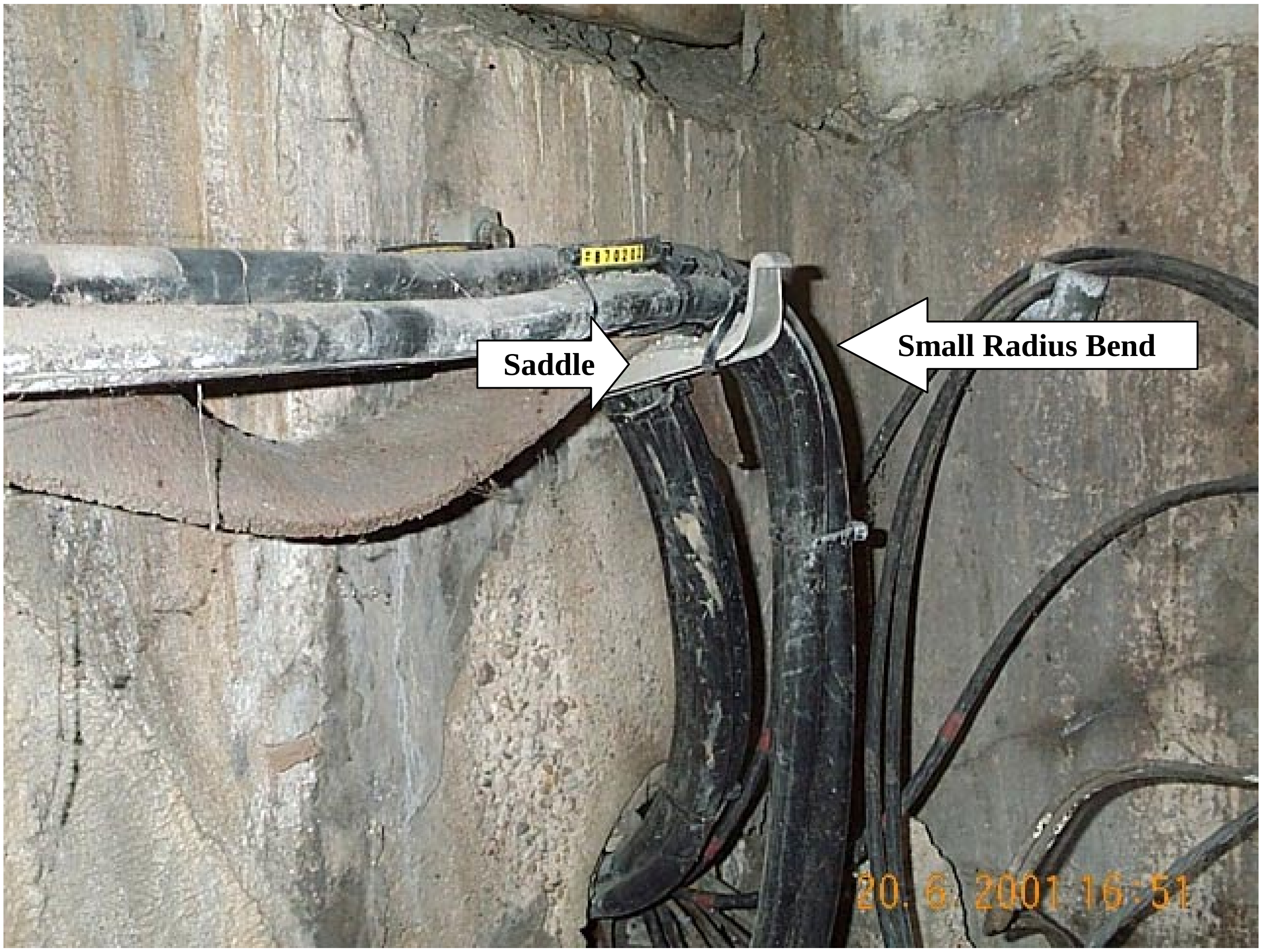


Figure 17 Primary Cables with Small Radius Bend and Missing Porcelain in the Saddle

4.5 Review of Transformer and Switch Vaults

Stone and Webster found workmanship in all underground vaults to be good. Especially good is Pepco's present design practice to use a separate vault for each network unit (i.e., network transformer and its protector), with only one primary feeder into each vault. Use of a separate vault for each network unit is preferable to multiple transformers in the same vault, because separate vaults minimize the chance of a fault in an oil-filled transformer propagating to a second transformer or protector. A separate vault is also used for the secondary bus connections, thus separating primary and secondary facilities as much as possible to contain the consequences of any faults that may occur. In some cases separate manholes are also used for primary switches and primary connections. An example of this was at 17th Street NE and East Capitol Street SE by Eastern Senior High School. Each hole in that location is of adequate size and the entire installation is laid out to limit collateral damage from a failure.

Newer transformer vaults use elbow connectors to the transformers. Figure 18 shows an elbow connector at the top left of the tank of a single-phase transformer. Use of elbow connectors allows simplified connection/disconnection in much the same manner as obtained in the tap hole shown in Figure 12.

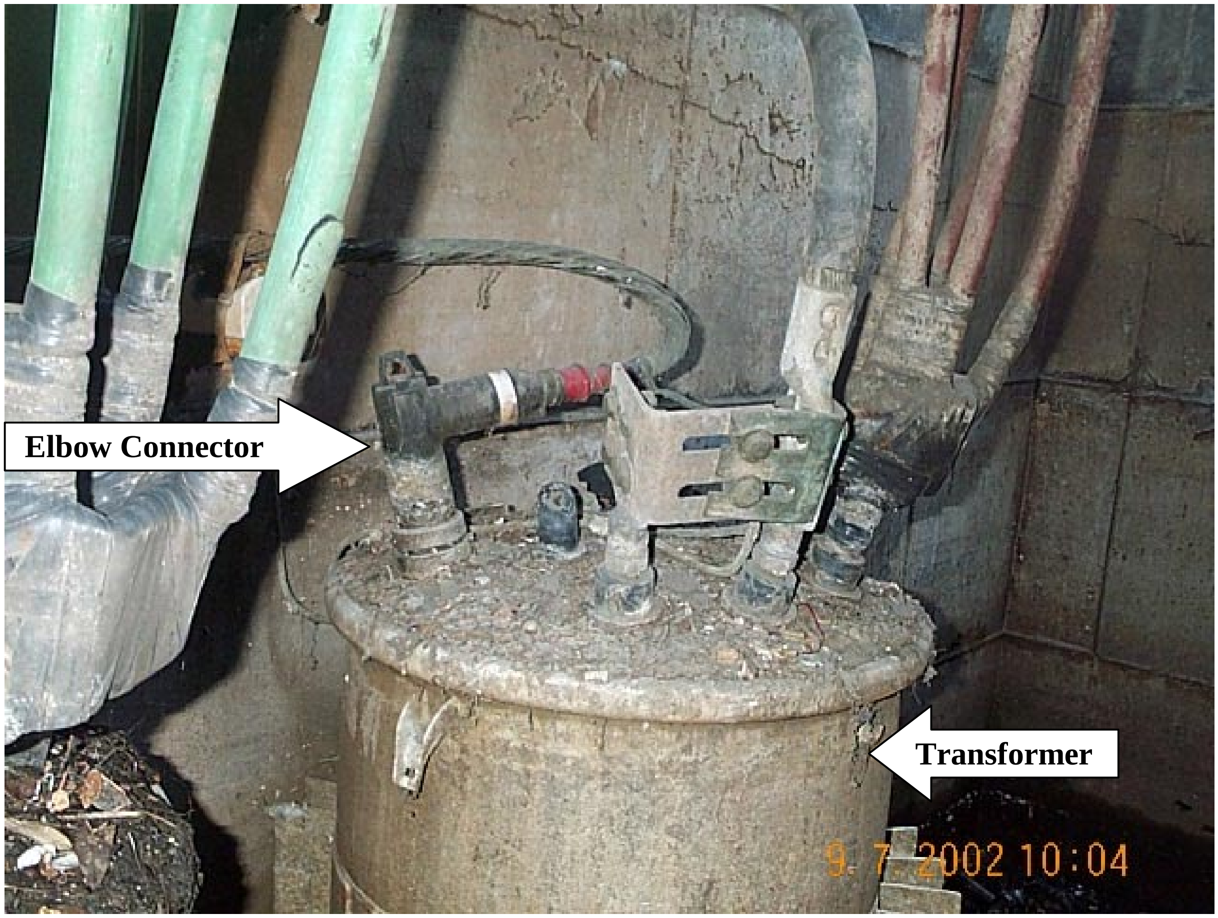


Figure 18 Single Phase Transformer Using Elbow Primary Connector

An example of a well-designed new transformer vault is given in Figure 19. Note the ample space and clean layout.

Figure 19 New Transformer Vault with Neatly Arranged Secondary Cables

Transformer vaults are covered with a grating for ventilation. These gratings allow entrance of water and debris (leaves, etc.) as shown in Figure 20, which shows a flooded transformer vault with a layer of leaves on top of the installed equipment. Water is almost up to the top of the protector. Flooded transformer vaults result in rusting of the transformer tank. Some transformers at the Benning Service Center that had been removed from service showed severe rusting on the lower part of their tanks due to water immersion.

It was observed in the Georgetown residential areas that dual primary voltage transformers capable of operation at either 4 kV or 13 kV are being installed when transformer replacements are necessary in the Georgetown radial systems. This is being done to prepare for the planned conversion from 4 kV to 13.8 kV. This reduces the number of transformers that will need to be changed when conversion is made from 4 to 13.8 kV as part of the Georgetown plan.

Figure 20 Flooded Transformer Vault with Debris

4.6 Review of Substations

The focus of the Stone and Webster investigation was on primary and secondary cables and associated manholes. Substations were not the main focus, except as they relate to the cables which enter and exit the substations. During the course of the site visits, Stone and Webster visited five substations, including Substation 12, which supplies Georgetown. The substations were generally found clean and in good order. However, during one substation visit, an odor similar to burning insulation was detected at the substation. This odor was called in, and was quickly responded to by a Pepco crew.

At one substation it was noted that a 69 kV transmission cable termination was leaking dielectric fluid. Figure 21 shows dielectric fluid being collected by an absorbent material. It should be noted that, based on Pepco's design criteria, the failure of a single transmission feeder will not result in customer outages.

Figure 21 69 kV Transmission Cable Leaking Dielectric Fluid

The primary feeders at the substations generally show good workmanship (Figure 22). However, problems do occur, such as the leaking primary feeder splice shown in Figure 23, as noted by fluid spots on the lower cables and floor.

Figure 22 Primary Feeders in Substation Showing Good Workmanship

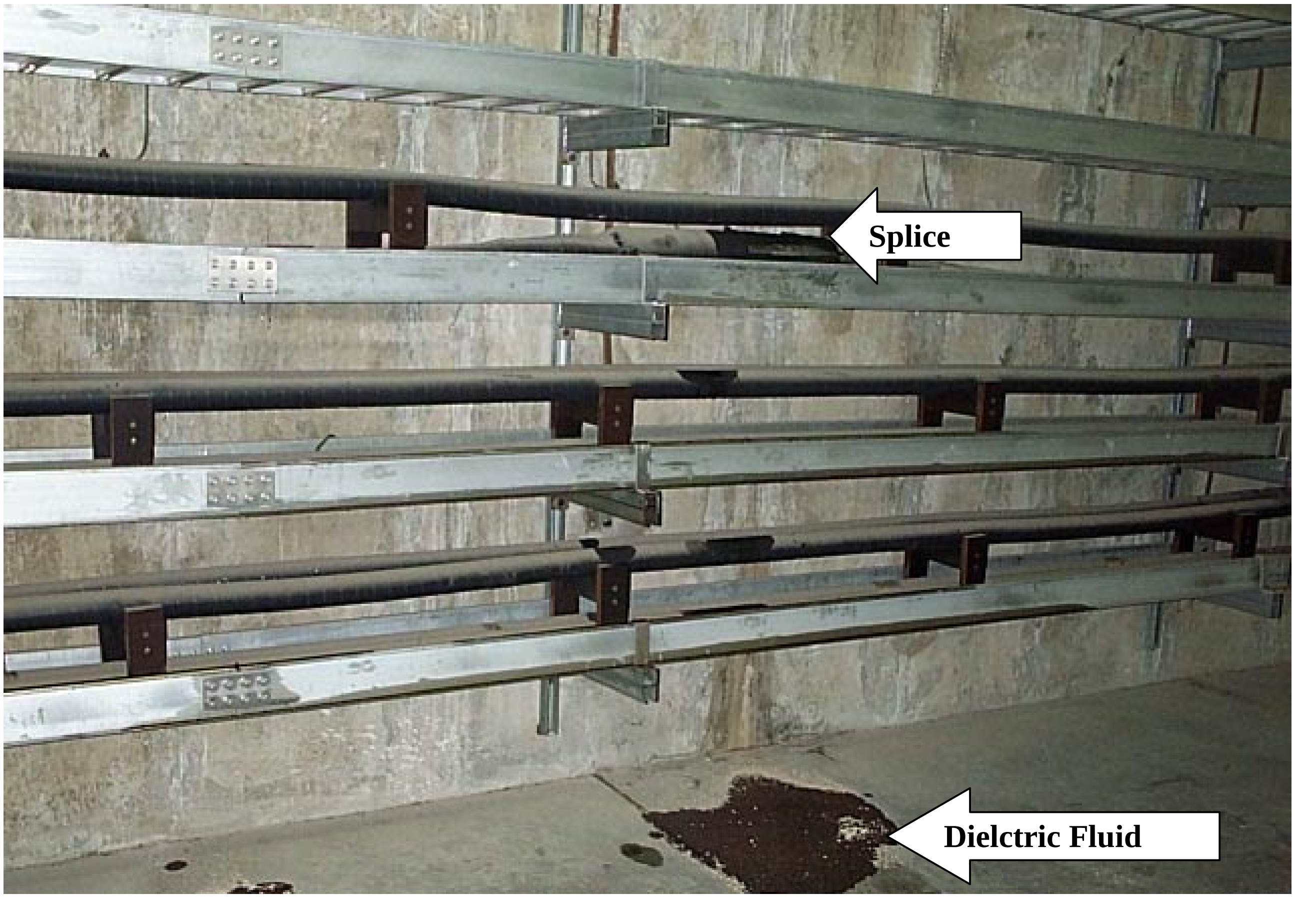


Figure 23 Primary Feeders in Substation with Leaking Splice

5.0 INTEGRITY OF PEPCO'S UNDERGROUND DISTRIBUTION SYSTEM

5.1 Introduction

Our assessment is primarily based upon an examination of selected Pepco documents, interviews with Pepco staff, physical inspection of equipment at over 60 locations (i.e., manholes, substations, transformer vaults, and switch vaults), and a review of consultants' reports, and Commission filings. This assessment reflects our professional judgment and generally considers the engineering design, construction, materials, operation, maintenance and inspection practices used by Pepco. However, it does not include an assessment of actual loading on facilities and equipment during normal and/or single contingency conditions (e.g., loss of one feeder) because Pepco has not yet completed the development of the computerized load flow models of its low-voltage network systems needed to perform this analysis. It is noteworthy that the results of such analysis of the Georgetown network performed by ABB identified components that are significantly overloaded during peak conditions and single contingency conditions.

The main focus of our assessment has been the distribution equipment under the streets and sidewalks of DC. Pepco has two types of underground distribution systems: low-voltage network and radial systems. Low-voltage network refers to systems of low voltage secondary cables that are interconnected in a grid, fed from a multiplicity of network transformers that are fed from multiple 13 kV primary feeder cables. Radial system refers to where the low voltage secondary cables are not interconnected and use a single 4 kV or 13 kV primary cable. Pepco's underground distribution system starts in above-ground substations, and a reliable distribution system is dependent on appropriate substations. Therefore, we have included distribution substations as part of this assessment.

5.2 Summary

In general, we find the integrity of major components of Pepco's underground distribution system to be acceptable with the exception of sections of the Georgetown area which are characterized by overcrowded manhole facilities and overloading of circuits during both normal and single contingency (e.g., loss of one primary) conditions. The overcrowding and overloading are due to load growth beyond the design criteria of the affected manholes. However, Pepco's major modernization plans will correct this condition.

We also find that Pepco has not performed load flow modeling of its low-voltage secondary network system outside of Georgetown, and therefore it is not possible to determine whether those circuits are overloaded during normal or single contingency conditions.

5.2.1 Summary of Distribution Substations

Pepco's distribution substations in the District of Columbia employ designs, materials, and protection practices that are equal to or better than those of other metropolitan utilities. Pepco designs, constructs, and operates its distribution substations to provide a high level of reliability and service continuity.

5.2.2 Summary of Low-voltage Network Systems

Pepco operates 47 separate low-voltage network systems in the District, generally in commercial areas. The network systems provide the highest level of reliability and service continuity possible with conventional types of power systems. Pepco’s network systems appear to have the right balance between size, contingency capability, and utilization of equipment capacity. Pepco’s low-voltage network systems are well designed, protected in accordance with or better than industry practice, employ equipment and materials that are standard in the industry, and show good workmanship in transformer vaults, manholes, and bus holes.

The one area where an assessment can not be made is with regard to the actual loading on equipment, especially the low-voltage secondary mains, during normal and single-contingency conditions. Visual observation of every vault, manhole, or handhole in the system will not reveal the loading on the components during peak conditions, or under contingencies. It is for this reason that Pepco is strongly encouraged to construct load flow computer models of all of its network systems. ABB also made this recommendation. These models should be used to evaluate loading of components under both normal and contingency conditions. Prevention of overloads may be key to reducing the number of cable faults, and consequently the number of manhole incidents.

5.2.3 Summary of Radial Systems

Pepco also operates radial distribution systems, generally in residential areas, with 4 kV and 13 kV primaries. The 4 kV and 13 kV underground systems are installed in ducts, vaults, and manholes, similar to those used for the network systems. The practices are consistent with those used by other utilities. Pepco recognizes the limits of its 4 kV systems with regard to power delivery capability, splicing issues, and outage restoration issues. The 13 kV systems can handle significantly higher power loads, utilize newer EPR cable technology that is much easier and faster to splice together, and the loop system design results in faster customer service restoration. Therefore, Pepco is converting the 4 kV systems to 13 kV as load demand increases. When Pepco replaces a distribution transformer in a 4 kV system, a dual primary voltage (4 kV & 13 kV) unit is employed to allow convenient and cost-effective conversion to 13 kV operation at a later date.

Pepco’s 13 kV radial systems use the latest materials (e.g., primary cables, elbow connectors, splices, fuses, switches, and distribution transformers) available in the industry. The materials have a proven track record in suburban URD (underground residential distribution) systems.

5.3 Details of the Assessment

The following sections of this report contain a more detailed discussion of the assessment of the integrity of Pepco's underground distribution system.

5.3.1 Distribution Substations

Pepco's distribution substations supplying loads in the District of Columbia are designed to provide a high level of reliability and service continuity. The stations will carry the peak load connected to the station under any single contingency, that is when:

- there is the outage of any one transmission line into the station
- there is an outage of any one main power transformer in the station
- there is a fault on any one bus section in the station

Pepco has multiple transmission feeds to each distribution substation, multiple power transformers within the station, and ring-buses that feed the 13 kV primary feeders. A substation can have primary feeders for the low-voltage networks, primary feeders for the radial distribution systems, primary feeders that supply government installations and high-voltage customers, and feeders for the METRO system.

5.3.1.1 Ring Bus Design

With the ring bus design, a fault on a section of the 13 kV bus does not cause outages to any customer served from the low-voltage network, any METRO installation, and most government sites as they frequently employ spot networks or other redundant-type systems within their facilities. In comparison, some utilities may have to drop an entire low-voltage network system for a fault on a bus section in the station, as they do not employ a ring bus configuration. Furthermore, Pepco operates the 13 kV ring bus with all tie breakers closed. This minimizes circulating currents in the low-voltage network, thereby providing for the optimum operation of the network protectors, and very efficient utilization of the network transformer capacity.

5.3.1.2 Metal-Clad Switchgear

Most of Pepco's distribution substations use metal-clad switchgear, consisting of the 13 kV ring bus, main transformer breakers, feeder breakers, and relays and control equipment. This highly reliable, factory assembled and tested equipment allows for compact indoor installations, located in buildings that blend in with the surrounding architecture. Older switchgear designs employed air-magnetic circuit breakers and electromechanical relays, but in new stations and station upgrades the new-technology vacuum circuit breakers and microprocessor relays are employed.

5.3.1.3 Relays

Pepco uses extremely sensitive settings for the instantaneous ground current relays for primary feeders that supply low-voltage networks. Their settings for the network primary feeders are two or more times lower than those used by most other utilities. This means that short circuits in primary feeder cables, feeder splices, and the network transformer are cleared in the fastest time possible with conventional circuit breakers. In the event that a primary feeder breaker would fail to open for a fault on the feeder, backup protection is provided.

5.3.1.4 Loading Issues

Stone & Webster has not obtained peak loading data on each of the existing distribution substations, and has not evaluated and quantified their ability to handle additional load. However, our meeting with the Pepco planning manager revealed that the loading issues are continually being addressed, with capacity additions or load transfers between substations planned, as needed, to allow single contingency operation.

5.3.1.5 Summary

Pepco's distribution substations in the DC area employ designs, materials, and protection practices that are equal to or better than those of other metropolitan utilities.

5.3.2 Low-voltage Network Systems

Pepco, as many other utilities supplying metropolitan areas, selected the low-voltage network system for the commercial and other areas of the city. These systems provide the highest level of reliability and service continuity possible with conventional types of power systems.

Pepco operates 47 separate low-voltage network systems in the Washington DC area. Each low-voltage network is supplied from six 13 kV primary feeder circuits, and serves a peak load that will not exceed about 45,000 kVA (1 kVA is equivalent to a mechanical power of about 1 horsepower). Each six-feeder network is designed to carry the peak load with any one primary feeder out of service. This single-contingency design practice is used by all utilities for the design of their low-voltage networks, with the exception of one. That is, Consolidated Edison of New York designs systems that will not overload when any two primary feeders are out of service during peak loading (double contingency design). This is possible because their low-voltage networks are much large than 45,000 kVA, and because they have a much larger number of primary feeders supplying each network. The downside of that approach is that, should a major catastrophe develop, the amount of load dropped may be more than 200,000 kVA, and network restoration is more difficult with the larger networks. In comparison, in Pepco's system a major catastrophe will not drop more the 45,000 kVA of load.

Pepco's low-voltage network systems appear to have the right balance between size, contingency capability, and utilization of equipment capacity.

5.3.2.1 Paper Insulated Lead Covered Cables

The primary feeders of Pepco's low-voltage networks use paper insulated lead covered (PILC) cables. Recently, they have changed to EPR insulated cables for the exits from the substations, as this type of cable results in a simpler and reliable termination of the cable to the switchgear buses in the distribution substation. Similarly, they have changed from PILC cables to EPR cables and elbow connectors for making connections to the high-voltage terminals of the network transformers. This eliminates the lead-wiped terminations that are expensive to make and require skilled workers. This allows for greater operating flexibility, should a network transformer need to be changed. Pepco, like some other utilities, is evaluating the use of EPR cables for all applications in the primary feeders of their networks, with ongoing work to develop suitable means for making transition "Y" splices between EPR and PILC cables.

5.3.2.2 Manhole Conditions

Ideally, a manhole should have just one 13 kV primary feeder and no secondary cables in the same manhole as a primary feeder. No utility has this luxury. Thus multiple primary feeders in a manhole plus secondary cables is typical. For these manhole conditions, Pepco tries to separate the primary and secondary circuits such that an arc in the secondary does not burn into a primary cable. When this is not possible, the secondary cable is located above the primary cables in order to minimize the probability of a secondary failure propagating into the primary cables. Very small and crowded manholes can be found in old parts of the Pepco system, as observed in Georgetown. However, manholes constructed to newer standards are much larger, simplifying the installation and splicing of cables.

5.3.2.3 Transformer Vaults

Pepco places just one network transformer/protector in an underground vault, the preferred practice, as a failure will not propagate to other portions of the system. In contrast, some utilities place multiple transformers/protectors in the same vault, an arrangement that can result in double contingencies during faults, and loss of the entire network. Furthermore, in Pepco’s system, the paralleling bus for multiple transformers is in a separate vault, referred to as a bus hole. In comparison, some utilities will place the paralleling bus in the same vault that has the transformers/protectors, clearly a less reliable design. The use of a separate bus hole for the paralleling bus is preferred, offering higher reliability.

Our inspection of transformer vaults and bus holes in the Pepco system revealed good workmanship in the installation of low-voltage secondary cables. The neatness of the work shows good craftsmanship and pride on the part of the workers installing the system. The staggered arrangement of the phases in the paralleling bus in the bus holes produces a bus with high reliability, as the insulated conductors of different phases are separated with air.

5.3.2.4 Cable Limiters

Pepco's design practice is to install cable limiters on most sets of low-voltage cables, but not on 250 kcmil secondary cables unless the available current into the fault from both sides is less than 3200 amperes. In contrast, some utilities install limiters on all secondary cables, and there are utilities that do not install any limiters on the secondary cables. Pepco is encouraged to re-evaluate its design standards with regards to the application of cable limiters on single sets of 250 kcmil secondary cable mains, for future additions to its system.

5.3.2.5 Materials

The basic materials that Pepco purchases for their low-voltage network system are in accordance with industry standards such as the American National Standards Institute (ANSI) and with those used by other utilities. Included are the metal-clad switchgear for the distribution substations, the primary and secondary cables, and the network transformers and network protectors. Pepco is one of the few utilities that purchase color-coded low-voltage cables, which aids in installing and trouble shooting the secondary systems. Although terra cotta ducts are found in old portions of the system, more modern materials have been used for duct bank construction in recent years.

The old braided low-voltage cables have shown deterioration and are replaced by Pepco when found.

5.3.2.6 Monitoring Systems

Several utilities have installed systems for monitoring the loading on network transformers and the status of the network protectors. Such systems provide real time data, valuable for both engineering purposes and operating purposes. For example, Con Edison of New York has real time monitoring of all 24,000 network transformers and protectors in its network systems, using an old power line carrier technology to communicate from the network transformers and protectors to the distribution substation. Pepco is presently installing, on a trial basis, a remote monitoring system using enhanced technology incorporating microprocessor relays located in the network protectors. Although such monitoring systems do not provide loading on secondary cables in the network, the transformer load data, in conjunction with metered load data, could provide insight into the loading on secondary mains.

5.3.2.7 Summary

Pepco's low-voltage network systems are well designed, protected in accordance with or better than industry practice, employ equipment and materials that are standard in the industry, and show good workmanship in transformer vaults and bus holes.

The one area where an assessment can not be made is with regards to the actual loading on equipment during normal and single-contingency conditions. Visual observation of every vault, manhole, or handhole in the system will not reveal the loading on the components during peak conditions, or under contingencies. It is for this reason that Pepco is strongly encouraged to construct the load flow computer models of all of its network systems. ABB also made this recommendation. These models should be used to evaluate loading of components under both normal and contingency conditions. Prevention of overloads may be key to reducing the number of cable faults, and consequently the number of manhole incidents. When overload conditions are identified, the model can be used to confirm that reinforcement measures will eliminate the overloads. ABB studies of the old system in Georgetown showed the validity of this approach for identifying components that are significantly overloaded during contingencies.

5.3.3 Radial Systems

The primary voltage level of Pepco's non-network underground distribution systems in Washington DC are either 4160 volts (4 kV) or 13800 volts (13 kV). The first radial systems operated at 4 kV, primarily because equipment was not available for the higher voltage levels, and because the load levels were such that power delivery capability of a 4 kV radial circuit was adequate. The maximum load that can be supplied from the 4 kV radial feeder is about 2000 kVA. With the increasing loads in urban areas during and following WWII, and the development of higher-voltage distribution transformers, utilities selected primary voltages above 4 kV for their underground radial systems. By going to a higher primary voltage, such as 13 kV, a larger amount of power can be transmitted through a given duct in the underground system. Pepco's 13 kV radial underground systems were designed to operate in an open-loop configuration, so that service could be rapidly restored following a fault on a 13 kV cable.

Pepco's 4 kV systems operate in a radial fashion, use lead sheath primary cables and lead sheath secondary cables in some instances, oil fused cutouts on the 4 kV circuits for protection, and single-phase distribution transformers. To connect the cables of the 4 kV system to oil fused cutouts (immersed in oil) and to distribution transformers requires making of wiped leaded connections, an expensive and time consuming process requiring a skilled worker. The same is true when splicing 4 kV lead-sheath cables. These characteristics of Pepco's 4 kV underground systems are consistent with most other 4 kV underground systems in the country, because the newer materials used in the 13 kV systems were not available when the 4 kV systems were engineered. As the 4 kV systems operate in a radial fashion, a fault on the 4 kV primary feeders can result in long duration outages for many customers. This is due to the time required to locate the faults and perform the repairs that are necessary before service can be restored.

In contrast, Pepco's 13 kV distribution systems employ an open loop design, where in effect two radial feeders are connected by a normally open switch or connection. This normally open switch or connection allows the 13 kV systems to operate in a radial fashion, just as the 4 kV systems. However, should a fault occur on a feeder, the supply can be reconfigured, usually allowing service to be restored to all customers in a much shorter time. This is because the open-loop design permits service restoration without need to repair the faulted 13 kV primary cable. Rapid restoration of service to all customers is achieved by isolating the fault and closing the "open loop" connection. This is made possible by using non-lead sheath construction for cables, and by making connections to distribution transformers, switch cabinets, and fuse cabinets with elbow connectors (separable connectors). With these types of connectors, 13 kV cable connections can be easily made and broken, similar to plugging and unplugging extension cords used in residences. Elbow connectors are mature products developed initially for use in underground distribution systems in suburban areas.

In Pepco's 13 kV system, a cable fault is found much faster than in its present 4 kV system, because permanently installed fault indicators are used with the non-leaded 13 kV cables. The technology of the fault indicators is not applicable to systems using lead sheath cables and consequently the fault indicators cannot be applied in the 4 kV systems. Once the fault is located, the cables on either side of the fault are opened with the elbow connectors, or switches if installed. Then the system on either side of the fault can be re-energized without need for an immediate repair of the fault. This is possible because of the open loop design used for 13 kV primary circuits described above. Furthermore, within the 13 kV system are oil switches that are installed to allow reconfiguration of the system. In addition, Pepco's 13 kV system utilizes fuses in submersible enclosures to allow isolating only the faulted section of the primary feeder, without opening the entire feeder at the substation. The overall advantage derived from Pepco's 13 kV design practices (e.g., non-leaded cables, elbows or separable connectors, fault indicators, switches, and fuse cabinets), is that the reliability of the 13 kV systems is higher than that of the 4 kV systems.

Pepco's 13 kV open-loop system design reflects industry recognized concepts that provide for fast fault location, isolation, and restoration of service.

The 4 kV and 13 kV systems are installed in ducts, vaults, and manholes, similar to those used for the network systems. The practices are consistent with those used by other utilities. Pepco recognizes the limits of its 4 kV systems, and when a distribution transformer is replaced in these systems, a dual primary voltage unit (4 kV/13 kV) is employed to allow convenient and cost-effective conversion at a later date to 13 kV operation when required by loading levels.

Pepco’s 13 kV radial systems use the latest materials (primary cables, elbow connectors, splices, fuses, switches, distribution transformers) available in the industry. The materials have a proven track record in suburban URD (underground residential distribution) systems. Furthermore, determining loading of equipment in the radial distribution systems is a relatively simple matter. The load at any point is found by the addition of the diversified demands of each customer beyond the point of interest. In comparison, in the low-voltage network systems, loading can be found only by developing models of the network suitable for use in the load flow program.

6.0 POWER FLOW MODELING

6.1 Introduction

The electric power transmission system consists of a complex network of lines containing many parallel paths. A similar situation occurs in a low voltage network distribution system where there are multiple secondary cable paths between two points on the system. The complexity of the secondary network is shown in the diagram of the Georgetown East Network in Figure 24 below. Also shown are multiple parallel paths to the loads, as illustrated by the multiple squares.

When there are parallel paths, the power flow divides among them according to the relative electrical impedances of the paths. The flow in one line or cable can be affected by flows in the rest of the system. From a calculation standpoint, the situation gets more complicated when there are voltage regulators or transformer tap changers. The consequence of this is that it is impossible to guess how the power divides among the different cables, and some form of analysis is necessary. This is called the "load flow" problem and has been the subject of development and study for decades.

At the distribution level, the main parameters are the electrical resistance and reactance of each line or cable. These are mathematical parameters derived from calculation or measurement. Because of the sheer number of lines/cables and buses, the problem quickly becomes beyond the ability of calculation by hand, even without the nonlinearities caused by voltage regulators and tap changers.

6.2 Development of Analytical Modeling

The first attempt to solve the calculation problem was the "dc calculating board." In this device the resistance of lines was neglected and only the reactances were modeled. The limitations of this method led to the development of the "ac calculating board," also called the "ac network analyzer." This was a large analog computer, which contained units representing lines, loads, transformers, and generators. Connections were made with plug boards resembling old fashioned telephone switchboards. A large room full of equipment was required to model 100 buses, and a significant amount of time was required to set up a base case for a study. The ac network analyzer reached the highest state of development in the 1950's. Network analyzers were installed at manufacturers such as General Electric and Westinghouse, and at universities. For example, Niagara Mohawk Power Corporation and New York State Electric and Gas combined to install a network analyzer at Syracuse University.

Development of digital computers soon rendered the ac network analyzer obsolete, and by the end of the 1960's it was little used. Early computer load flow programs were developed by General Electric, Westinghouse, and Philadelphia Electric. The 1960's versions ran on batch computers and required input on punch cards and paper output. The development of time sharing and mini computers (in a 6 foot rack at the time) allowed development of load flow programs that did not require a mainframe computer. Power Technologies, Inc., (PTI) of Schenectady developed the Power System Simulator program PSS/2 for use on Hewlett Packard mini computers about 1970, and the later PSS/E for time sharing and later personal computer (PC) use about 1975. The capabilities and ease of use have increased with each update. Other load flow programs have become available in recent years, for example the EasyPower program purchased by Pepco.

6.3 Analytical Modeling of Secondary Networks

Three digital computer programs were available in the 1960's: GE, Westinghouse, and Philadelphia Electric. During the 1960s Dave Smith of the Stone & Webster team modeled the secondary networks for the City of Richmond, Indiana electric utility using the Westinghouse load flow program. Niagara Mohawk Power first modeled its network systems in the early 1960s using a technology with very limited node capacity. During the late 1960s, Niagara Mohawk used the Philadelphia Electric program.

During the 1970s, PTI developed and made commercially available its Power System Simulator/Engineering (PSS/E) program, which has been used to model secondary networks by Alabama Power, Northern States Power, Portland General Electric, Niagara Mohawk Power and others. Much of this work started in the 1980s.

Pepco purchased the PSS/E program in November 1977 for studies related to its transmission system, but evidently did not use it to model its secondary networks. The EasyPower program, which Pepco recently purchased and has begun to use, was made commercially available in the early 1990s. Virginia Power began using EasyPower during the early 1990s. Previously, Virginia Power had used the Philadelphia Electric program.

6.4 Pepco Secondary Network Analytical Modeling

Because Stone & Webster had been informed that Pepco had not modeled its secondary networks, the 5th Stone & Webster data request asked:

> "Provide a narrative or a description of the procedures, methodologies, or calculations that are presently employed by Pepco when designing a secondary network system, and when evaluating the performance of an existing secondary network system to determine if the components of the system will be loaded above their rating under both normal conditions and single contingency conditions."

Pepco's response referred to its design standards, which contained nothing about planning or analysis tools, methods, or procedures. However, during a team interview session held with Pepco at its Benning Service Center, Pepco stated that the Company uses a program that is only capable of analyzing about a three-block area.

In order to address this need, Pepco contracted with ABB to develop analytical models of the Georgetown secondary network systems and 4 kV radial distribution system. ABB developed the models using their own load flow program, performed an analysis of the Georgetown systems, and produced the following two final reports:

- "Georgetown Area Network System Evaluation," ABB Final Report May 21, 2001
- "4 kV System Load Flow and Reliability Analysis," Final Report March 9, 2001

Figure 24 was taken from the “Georgetown Area Network System Evaluation” report.

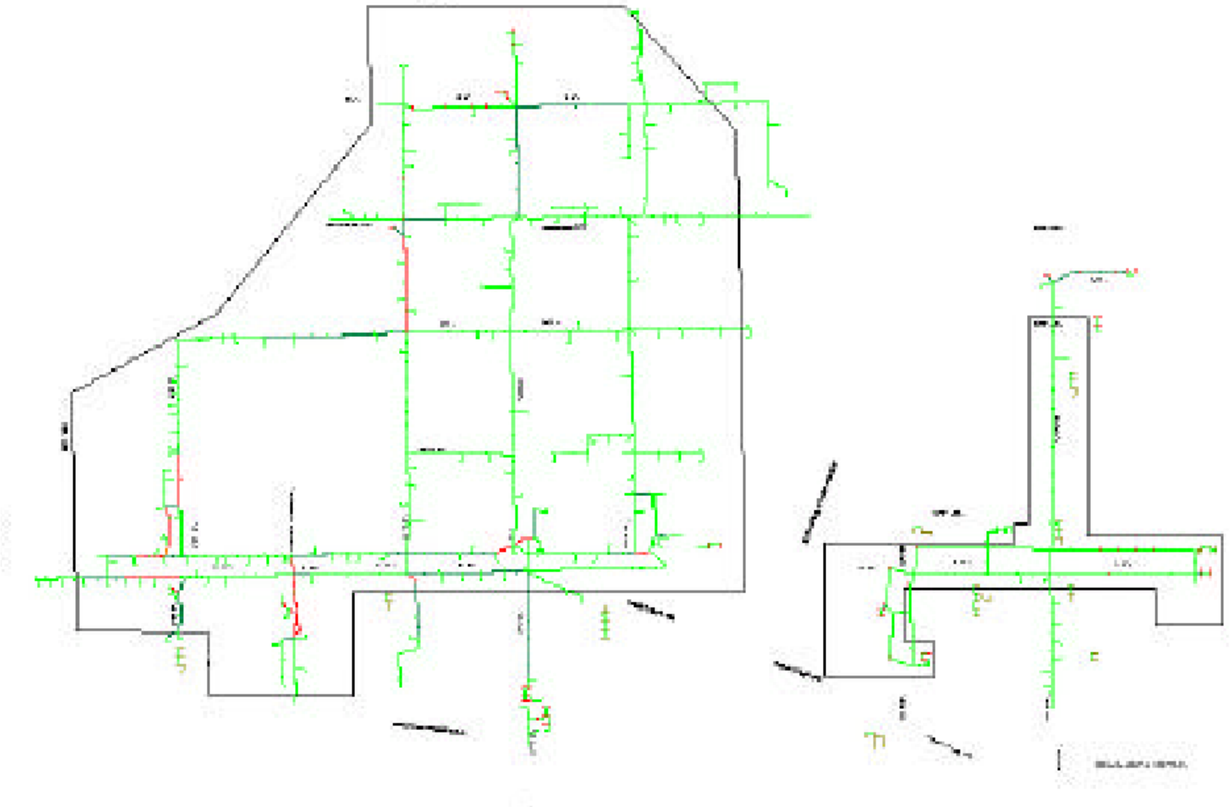


Figure 24 Georgetown East Network Load Flow Results from ABB Report

The intention of Pepco's design criteria for its network systems is to be able to operate at system peak without overloading secondary cables, even with one feeder out of service. From the results of the ABB secondary network load flow analysis, the Georgetown East and North networks are not able to handle peak load conditions without overloading some secondary cables, even with all primary feeders in service. The red line in Figure 24 is a section of secondary cable in the Georgetown East Network that is overloaded as a result of a single contingency (single primary feeder out of service). This is a result that is available because of analytical network simulation and is not intuitively evident or amenable to hand calculation.

During other contingencies many secondary cables can be severely overloaded as well as some network transformers. This is the most significant result of the ABB analysis, because secondary cables have been implicated in a number of manhole incidents. This finding also raises concerns about the performance of the remaining network systems in DC, which emphasizes the need to expedite the underground network modeling.

ABB analyzed the performance of the Georgetown 4 kV system based on reliability indices and load flow analysis. The study supports Pepco’s decision to convert the 4 kV radial distribution system in the residential area of Georgetown to a 13 kV loop system. Overall, the study found:

- The reliability indices (SAIDI, SAIFI) of the 4 kV radial distribution system in Georgetown reflect substandard performance. The 5-year record of outage statistics indicates significantly higher failure rates than experienced in new underground systems.

- Overloaded 4 kV cables under peak system load conditions.
- A primary feeder with a voltage drop in excess of 4%.

The results of the ABB load flow analyses in Georgetown show the need for Pepco to develop an analytical model of all their secondary networks as quickly as possible. These models are needed both to identify possible overloads in the existing system and to properly plan for expansion. Once developed and implemented, an analytical model is a powerful tool for predicting the impact of load growth on the network and for developing long-range system enhancement and strategic plans.

7.0 RECENT TECHNOLOGIES

7.1 Fault Current-Limiting Devices

Data from Pepco and other utilities surveyed by ABB in its study for Pepco show that more faults occur on the primary feeders of secondary networks than in the low-voltage cables. Further, faults in primary cable splices have resulted in ejection of manhole covers.

Researchers suggest that the high pressures that eject manhole covers may be caused by two separate mechanisms for faults in the splices of PILC cables. One is the ignition of gases generated when the splice insulating materials become decomposed from heating due to tracking. The other is from the heating of air and volatilization of conductor material during the ensuing high-current arc.

The first mechanism, involving a partial breakdown of the splice insulation, is insufficient by itself to result in a power arc and consequent circuit breaker operation. This mechanism is called “tracking,” and is characterized by lines engraved in the splice insulation. The electrical discharge that causes insulation tracking creates heat. The heat and electrical discharge generate combustible gases from decomposition of the insulation. If these gases are ignited, they may result in an explosion of a magnitude sufficient to lift a manhole cover. In this case, the manhole explosion is a consequence of a chemical gas explosion, and the use of current-limiting devices probably would not be effective in preventing manhole cover ejections from faults in cable splices.

In the second mechanism, the manhole cover lifts as a result of gas pressure created from energy contained in the fault arc. In this case, current-limiting devices may possibly prevent manhole cover ejections by reducing the amount of energy liberated in the manhole by the arc itself.

When a fault path develops in a splice of a high-voltage cable, the resulting power arc has very high currents that flow from the substation to the fault until the circuit breaker at the substation opens. Even after the station circuit breaker opens, fault currents may continue to flow in the fault until all backfeeding network protectors open. Any changes in system design or protection that reduce the magnitude of the available fault current, and any changes that reduce the time that the current flows will reduce the energy into the fault, and the pressures generated in the manhole.

Figure 25 shows the current flow from the substation to a fault in a splice when current-limiting devices are not installed (heavy curve), assuming a 5 cycle clearing time typical of the Pepco system. The lighter curve in Figure 25 is representative of the current that flows in the faulted phase from the substation to the fault when current-limiting devices are installed in the feeder at the substation. The current-limiting device limits not only the duration of the current flow in the faulted phase, but also the peak magnitude of the current flow when the available fault currents are high. Reduced fault current magnitude and duration mean the current-limiting device can result in a significant reduction in energy input to the fault.

Unfortunately, there appears to be no formal research on the relationship between pressures generated in the manhole for primary cable faults and the electrical energy input to the fault arc from the high-current arc. Reducing energy input will reduce pressures, but studies have not been conducted to quantify the relationship. This is one area that EPRI or other industry groups should consider investigating if indeed a significant percentage of the manhole lid ejections are due to the energy from the effects of the high-current fault arcs in primary cable splices.

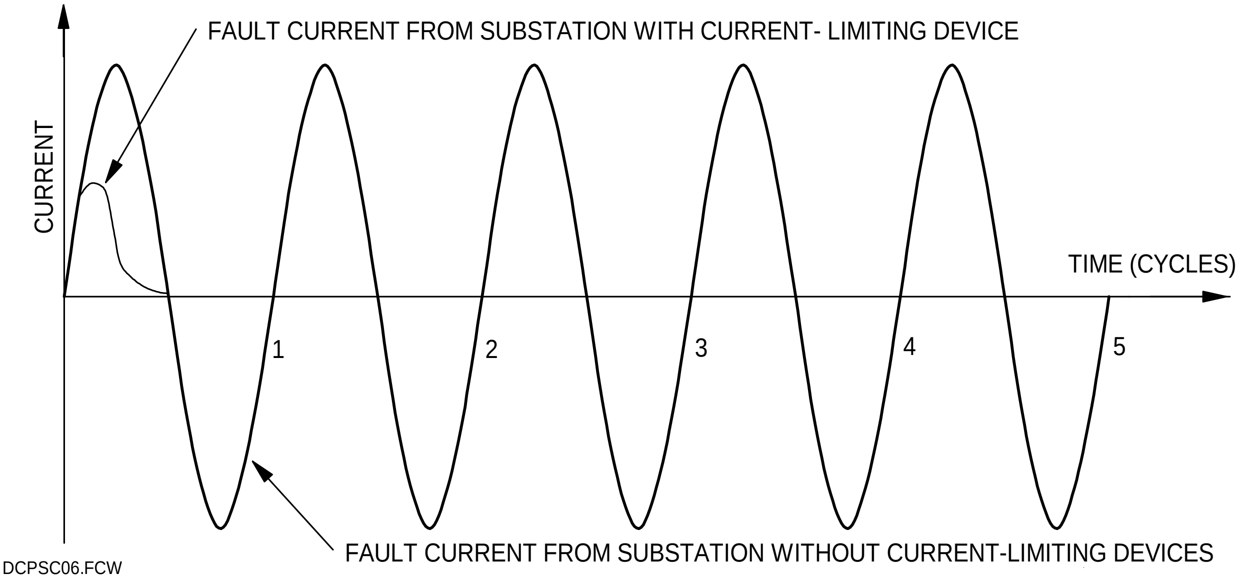


Figure 25 Comparison of Waveform of Fault Current from Substation with and without a Current-Limiting Device at the Station

However, one utility in this country, Tampa Electric, has reported that for their system, a commercially available device, the S&C Fault Fiter, has been effective in minimizing the chance of a manhole lid ejection for faults in primary cable splices located in manholes filled with water. This device was described in an article by David Denison, “Electronic Fuses Protect Cable, Network Transformers,” in the January 1994 issue of *Electrical World*.

These devices are installed in each primary feeder at the substation. In effect, they replace the phase instantaneous current relays for the primary feeder as currently used by Pepco. The device limits the flow of the current from the substation, in the faulted phases, to less than one cycle. Furthermore, the device may limit the peak current flow in the first cycle to a value less than the available peak current. When the single-phase current-limiting devices are installed, relaying and control must be incorporated that will trip the circuit breaker for the feeder after the single-phase device operates in the faulted phase.

In comparison, conventional circuit breakers do not limit the magnitude of the fault current, but the current flow in all three phases is interrupted when the breaker opens. The current flow from the station to the fault may last for 5 or 6 cycles, as shown in Figure 25, with a conventional circuit breaker having phase instantaneous current relays.

Tampa Electric's experience has shown that the Fault Fiter devices also significantly reduce the probability of an explosion of the terminal or switch compartment of network transformers for faults within these compartments. These compartments are filled with insulating oil or other insulating compounds. Such a fault did occur in the terminal compartment of a 500 kVA transformer in the Pepco Georgetown network, located at 29th and O Street. The fault ruptured the terminal compartment, resulting in a small oil fire. Furthermore, it is recognized that should a fault occur within the switch compartment or the terminal compartment of a network transformer, it is quite likely that the cover plate will be partially or completely blown off when the fault is cleared with a conventional circuit breaker at the substation.

Pepco should determine whether commercially available current-limiting devices, like the S&C Fault Fiter, the G&W CliP, or similar devices are applicable to the primary feeders of its network systems. In evaluating the installation of current-limiting devices in network primary feeders at the substation, the following additional areas need to be considered.

- Application when capacitor banks are located in the substation
- Impact on grounding network primary feeders in the substation using a grounding and test device in metal-clad switchgear located at the substation
- Impact on phase and ground relaying for the network primary feeders, and relaying needed to prevent single phasing of the circuit when the current-limiting device operates
- Impact on network protector relaying for faults on the primary feeders
- Effect on reliability (false operation)
- Space requirements and availability in existing substations

7.2 Advantages of Fault-Limiting Devices in Pepco's System

Pepco supplied data for three-phase and single line-to-ground fault currents on the 13.8 kV buses that supply the network feeders in the Pepco system. The data shows that the available fault currents on the buses are very high. Pepco does not install phase reactors at the substation in primary feeders for secondary networks. This means that currents for feeder faults close to the substation are the same as for a fault on the substation bus.

As a result, if current-limiting devices were installed in the network primary feeders at the substation, such as the S&C Fault Fiter or the G&W CLiP, they would result in a significant reduction in energy into faults in the splices of PILC cables. This in turn reduces the likelihood of a displaced manhole cover from the pressures generated by high-current arcing in the splice.

Further, current-limiting devices would result in a significant reduction in energy into faults in the terminal compartment and high-voltage switch compartment of network transformers. This reduces the likelihood of rupturing the compartment and creating an oil fire, as occurred in Georgetown at 29th and O Streets on May 02, 2001. If the available fault currents were low, the application of the current-limiting device would not result in as large a reduction in energy.

The ground relay settings used by Pepco on its dedicated network feeders for low-voltage networks are extremely sensitive, allowing for sensitive detection of ground faults in the primary windings of network transformers, and the shortest possible clearing time from the substation when conventional circuit breakers are used. The phase instantaneous current relay settings for Pepco's dedicated network feeders are in a range which suggests that current-limiting devices, such as the S&C Fault Fiter, or the G&W Clip could be applied, so long as other application constraints are not present.

These fault current values, in conjunction with the relay settings used by Pepco, further substantiate the recommendation that Pepco should evaluate the applicability of the current-limiting devices to their system.

7.3 Fault Location Time in Network Systems

Each of Pepco's low-voltage networks has six 13,800 volt primary feeder circuits. When a fault occurs on any one primary feeder circuit, it is automatically isolated, and the remaining five primary feeders carry the load of the network. When this happens, the load on the remaining five feeders will increase about 20 % or more, depending on the interlacing of the feeders and the load distribution. The corresponding resistive losses and heating on some primary feeder cables will go up by as much as 44 %. Furthermore, in the 208-volt grid network the loading on secondary cables will increase.

Operating at higher loading levels increases the likelihood of a failure occurring in a second component of the system, and in turn causing a manhole event or an outage.

It is therefore important that faults on network high-voltage primary feeders are rapidly located and repaired, and the high-voltage primary feeder placed back into service as soon as possible. At present, Pepco uses sheath coils to pre-locate faults on primary feeders, and picks to pinpoint the fault location on feeders with PILC cable. This can be a time consuming process, as it requires opening manholes so that personnel can enter to make measurements. If a manhole is flooded, additional delays are incurred until the water is removed.

Some newer technologies and equipment have recently been developed for locating faults on network primary feeder circuits for Con Edison, the operator of the largest low-voltage network systems in the world. The particular device that Con Edison is presently using is the "above ground" meter, which allows pre-location of the fault without the need to open and enter manholes. The device was originally developed by AT&T Bell Laboratories, and is now available in commercial form from the Technology Enhancement Corporation. The operator of the above ground meter need only travel the route of the primary feeder to locate the fault, without need to enter manholes.

In addition, real-time fault location schemes are also being developed for Con Edison. With these schemes, the objective is to have a system that will tell system operators, almost instantaneously after feeder breaker opening, the distance of the fault from the substation or some other reference point.

7.4 Isolated Spot Networks

Pepco operates isolated spot networks in the DC area. An isolated spot network consists of two or more network units installed at the same location. A network unit consists of a network transformer and a network protector. The load terminals of the network protectors are connected to the paralleling bus located in the bus hole, adjacent to the vaults with the network units. Customer loads are fed from service cables connected to the paralleling bus in the bus hole. In the isolated spot network system, there are no ties to the low-voltage secondary mains located in the streets. Multiple sources provide the reliability expected of a network system.

In order for the spot network to provide the highest level of reliability, all network protectors should be closed whenever the associated high-voltage (HV) primary feeder is energized. That way, the disturbance to the load supplied from the spot network, if any, will be minimized for a fault on one of the HV primary feeders of the spot network. Whenever a high-voltage feeder is taken out of service for maintenance or system modifications, the network protectors associated with that feeder open. This creates the condition where not all network protectors in the spot network are closed. Whenever the feeder is subsequently re-energized, it is desired that the open protectors automatically close under the proper conditions that will not result in an ensuing reverse power and another tripping of the protector.

Relays control the automatic reclosing of network protectors. Prior to the development of microprocessor relays for network protectors, automatic reclosing was controlled with two separate electro-mechanical relays. These relays had “straight-line close characteristics,” which set the conditions under which the relay operated. With the most recent microprocessor relays for network protectors, the user can select the type of close characteristic that the relay will exhibit, either straight line or “circular.” The circular close characteristic allows the protector to close at a lower load on the network, thereby helping to keep all network protectors closed regardless of the load on the spot network. This in turn enhances the reliability of the network system. The circular close characteristic is recommended for use in network protectors for isolated spot networks

7.5 Recommendations on New Technologies

7.5.1 Recommendation No. 1

Pepco should evaluate the effectiveness of high-voltage current-limiting devices installed in each primary feeder at the substation as a means of reducing the probability of a fault in a primary cable splice causing a manhole explosion (manhole lid displacement).

Tampa Electric has installed these devices and has found them to be very effective for this purpose in their low-voltage network systems. Tampa Electric has also determined that these devices are effective in preventing the rupture of cable terminal compartments and switch compartments on the high-voltage side of network transformers, events which can result in oil fires in transformer vaults.

7.5.2 Recommendation No. 2

Pepco should evaluate the applicability of new technologies for locating faults on the high-voltage feeder cables of the low-voltage network systems. The faster a fault on a high-voltage feeder cable can be located and repaired, the shorter the duration of the higher loading placed on the other components of the low-voltage network system. This reduces the likelihood that a fault on one high-voltage feeder circuit will cause a second fault in another cable due to overloading. Pepco’s low-voltage network systems, like those of most other utilities, may overload when two high-voltage primary feeders are out of service.

Specifically, Pepco should evaluate some of the newer technologies and equipment recently developed for locating faults on network primary feeder circuits developed for Con Edison, the operator of the largest low-voltage network systems in the world. The particular device that Con Edison is presently using is the “above ground” meter, which allows pre-location of the fault without the need to open and enter manholes. The device was originally developed by AT&T Bell Laboratories, and is now available in commercial form from the Technology Enhancement Corporation. The operator of the above ground meter need only travel the route of the primary feeder to locate the fault, without need to enter manholes.

In addition, Pepco is encouraged to monitor the progress being made on real-time fault location schemes being developed for Con Edison. With these schemes, the objective is to have a system that will tell system operators, almost instantaneously after feeder breaker opening, the distance of the fault from the substation or some other reference point. When such devices or systems become available, Pepco is encouraged to evaluate their applicability to the Pepco low-voltage network systems.

7.5.3 Recommendation No. 3

Pepco is installing newer microprocessor relays in the isolated spot networks. By programming these relays, Pepco can select either a circular close characteristic or a conventional straight-line close characteristic. Pepco is encouraged to consider the application of the circular close characteristics in each spot network whenever the microprocessor relays are incorporated into all protectors in the spot network to increase circuit reliability.

APPENDIX A

ANALYSIS OF REPORTS & FILINGS PREPARED BY PEPCO & ITS CONSULTANTS

Contents

Appendix A.1

REVIEW OF

Final Report on Manhole Event Tests for Pepco at Lenox

EPRI Final Report WO-049296

Prepared by Stone & Webster Consultants

For the Public Service Commission of the District of Columbia

Submitted September 13, 2001

A.1.1 Purpose of This Document

At the request of the Public Service Commission of the District of Columbia, Stone & Webster reviewed the document “Final Report on Manhole Event Tests for Pepco at Lenox,” EPRI Final Report WO-049296, October 2000, and the two earlier EPRI reports cited as References 1 and 2 in EPRI report WO-049296. A Stone & Webster consultant also attended the “Manhole/Vault Event Summit Workshop,” sponsored by EPRI held August 30-31, 2001 in Washington, D.C.

A.1.2 Purpose of the EPRI Study

The following two statements are from the introduction to the EPRI report:

> “The (manhole) events are related to the ignition of gases in manholes and cable joint failures. In order to mitigate the damage from such events in the future, Pepco has designed new manhole covers with about 47% and 28% open area for venting the accumulated gases and for pressure relief during the event."
>
> "The objective of the tests were to confirm the venting effectiveness of and explosion pressure reduction by manhole covers with 47% and 28% opening by area, and also the effectiveness of manhole tethers.”

Thus, the purpose of this study was to evaluate a design proposed by Pepco in terms of its effectiveness in controlling movement of manhole covers. It is assumed that a failure in the underground electrical system has occurred, and some method will be applied to mitigate the impact of this failure. Thus this report is not concerned with elimination of the ultimate cause of manhole events, which is some form of cable or splice failure, but with the release of the explosive pressure in such a way as to reduce or eliminate manhole cover displacement.

A.1.3 Background to the EPRI Study

The EPRI study does not exist in isolation. Manhole events do not exist only on the Pepco system, but occur in other cities with underground electrical systems.[11] In addition to the tests performed for Pepco, the EPRI Lenox laboratory has performed tests for Con Edison, Duquesne, and other clients.[12] At the same time, analytical research on developing analytical simulations of manhole explosions is being conducted at Georgia Institute of Technology.[13] Manhole events are the subject of planned additional research at the present time.[14] The fact that Dr. Black of Georgia Tech has two technical papers submitted for review and publication at the present time and a third in preparation indicates manhole events are a current research topic, not one that was completed years ago.

It is a characteristic of all engineering that decisions must be made concerning design and application with less than complete data. For this reason engineering is part art as well as part science. It is only now that manhole events are receiving the research attention they deserve, but actions to reduce or mitigate manhole events can not await conclusion of all proposed research. Thus, it is important to place the EPRI report into the context of other research and present needs.

The EPRI Lenox report for Pepco is itself built on data from previous work. References 1 and 2 of the October 2000 EPRI report cite two earlier related EPRI projects, as discussed below.

A.1.3.1 Evaluation of Gases Generated by Heating and Burning of Cables[15]

The UL study focused on the underground secondary network system, and characterized the mechanism by which two distinct mechanisms (overheating caused by overload currents and low voltage arcing) can result in manhole events. The study considered:

- Conditions necessary for low voltage arcing and thermal decomposition of cable insulation.
- Kind and quantity of flammable gases generated from decomposition of cable insulation.
- Propagation of gases through underground facilities as related to airflow in ducts and manholes.
- Flammability limits of gases as they collect in manholes.
- Explosive force and consequences for manhole covers.

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[11] Roy Middleton, “Underground Events and Mitigation at SEP, presented at the EPRI Manhole/Vault Event Summit Workshop, August 30-31, 2001.

[12] Doug Howes, “Overview of the Test Facility & Tests at Lenox,” presented at the EPRI Manhole/Vault Event Summit Workshop, August 30-31, 2001.

[13] William Z. Black, “Underground Explosion Software,” presented at the EPRI Manhole/Vault Event Summit Workshop, August 30-31, 2001.

[14] Frank Goodman, “EPRI Manhole/Vault Event Workshop Issues, Needs, Solutions,” presented at the EPRI Manhole/Vault Event Summit Workshop, August 30-31, 2001.

[15] Reference 1, “Evaluation of Gases Generated by Heating and Burning of Cables,” EPRI Final Report TR-106394 4142-01, August 1996, prepared by Underwriters Laboratories, Northbrook IL.

The UL study demonstrated that cable insulation degradation could result in production of flammable gases that can then be ignited with a consequent explosion. A mixture of flammable gases identified in the UL study was used for the EPRI Pepco study.

In a sense these are not new results. It has been known for many years that degradation of insulation in transformers results in production of flammable gases, with different types of insulation problems resulting in different gases. Gas in oil analysis is a well-established diagnostic technique for oil filled transformers. Large power transformers are commonly tested at intervals for gas to check for incipient failures. What is new is the extension of this knowledge to the secondary network system.

A.1.3.2 Manhole and Service Box – Explosion Suppression and Mitigation[16]

The 1998 EPRI report focused on the explosion mechanism within manholes and consequences of the resulting blasts. A large variety of explosions is possible depending on details of fuel, oxidizer, geometry of the manhole installation, cover, and other parameters. For example, once a solid manhole cover is gone, air from the outside can enter the manhole and result in a secondary explosion that can be as violent as the original explosion. The major conclusion to be drawn from this study is to not be over simplistic in thinking all manhole events are the same.

The power transformer analogy is again helpful. Explosions in transformers can result in deformation of the transformer tank, with a large variety of observed damage relating to the details of the failure.

A.1.4 Assumptions in the EPRI Study

No study can cover all possible variables. It is necessary to choose representative conditions and then draw the appropriate conclusions. Thus, 2 manholes, 1 vault, 3 service boxes, and various types of conduit were utilized. The fundamental underlying assumption (evaluated below) is that manhole events are the result of ignition of combustible gases liberated from degradation of cable insulation. Further, these gases were restricted to hydrogen and a “UL mixture” taken from the results of the UL study.

A.1.5 Summary of Results

The “UL mixture” results in a more intense explosion than hydrogen. Tests with mixed gases result in a hotter, louder explosion with higher cover lift. However, tests using the UL mixture are not very repeatable. Because of the combination of different gases, explosions under supposedly identical conditions gave different resulting pressures and temperatures. Efforts were made to improve repeatability, including warming the gas and mixing with a fan, but tests with the UL mixture were never as repeatable as with hydrogen. Hydrogen explosions are easier to control and more repeatable. This led the investigators to favor hydrogen for comparison between vented and unvented covers, even though the explosions were not as intense.

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[16] Reference 2, “Manhole and Service Box – Explosion Suppression and Mitigation, ” EPRI Final Report TR-109741, January 1998.

Vented covers allow dispersal of combustible gases in the manhole, reducing the gas concentration or possibly eliminating the explosion. This dispersal of gas is illustrated by the observation by the Lenox researchers that with hydrogen gas and vented covers, either there was no ignition, or only a “poof” with no explosion. To evaluate the ability of vented covers to relieve the gas pressure caused by a hydrogen explosion, it was necessary to disable the prior venting mechanism by means of plastic sheets over the manhole openings to allow containment of the hydrogen gas and an explosion to take place. The plastic sheet then blows off immediately upon the explosion, allowing the effect of venting on relief of combustion products to be assessed. No attempt was made to quantify the dispersal of gas by vented covers before ignition by actual measurements of gas concentration over time.

“During the explosion itself, the openings provide the possibility of relieving the pressure resulting from the explosion.” The tests showed that the openings in slotted covers relieve the pressure and generally result in reduced cover displacement for the same explosive conditions compared to solid covers. Conversation with the researchers included the statement: “It was gratifying to see an explosion with a vented cover and not to see it lift.”

In two tests with hydrogen gas the slotted iron cover did not lift, but a solid iron cover lifted 1 foot 6 inches and 4 feet 10 inches. In a test with 8% hydrogen the slotted iron cover lifted 10 inches, but the solid iron cover lifted more than 20 feet 10 inches.

Manhole movement was more severe with the UL gas mixture than it was with hydrogen. The slotted iron cover lifted for all the tests. The displacement was generally less for the slotted iron cover than for the solid iron cover for the same percentage combustible gas. At 4% combustible gas the solid cover moved about 4 inches compared to 6 to 8 inches for the slotted iron cover, but there was also a double pressure release with the solid cover. At 6% combustible gas the entire manhole roof slab displaced about 1 inch with the solid cover. While the slotted cover did not prevent significant lifting of the cover, it did prevent damage to the manhole structure. The test manhole did incur damage during some tests with the solid cover. This is why bolting the cover to the manhole is not acceptable, because several tests at Lenox resulted in movement of the roof slab and/or damage to the vault.

A galvanized steel cover was also tested. While the tests indicated it was effective in preventing cover lifting when clean and new, its design was considered to be vulnerable to clogging with debris and so would probably be no different from a solid cover over longer-term use. Page 8-1 of the Lenox report states “During the tests the linemen noted that it is difficult to remove the galvanized steel cover from the frame because of its depth and the sharp edges.” The grated covers have other disadvantages besides debris, and so were not considered further.

With one exception, the tethered slotted iron cover lifted higher than the untethered slotted iron cover. While this sounds unusual, it is a result of the different trajectory of the cover caused by the tether. An untethered cover would likely lift straight up with the cover horizontal. A tethered cover lifts up into a vertical position because of the action of the tether, flips over, and lands outside the manhole. The report's results list distances to the highest point on the cover. So the highest point of a cover flipping end over end would be above than a cover that is not flipping. There is also a possibility that the tether restrains the cover motion and concentrates the force of the explosion in much the same manner as wadding in a gun concentrates the force of the expanding gases.

A.1.6 Critique

The study was carefully conducted using appropriate laboratory technique and instrumentation. Since the study was based on previous work, it represents a broader investigation than just the specifics of these few tests.

However, this study is illustrative rather than definitive because of the limited selection of combustible gases. Page 4-2 of reference 2 states “Intense heating in a starved oxygen environment without an arc will produce a wide variety of combustible fuels.” New cable insulation materials that may be used in the future may produce a unique set of combustible gases. Also, it was not possible to replicate all manhole geometries on the Pepco system. Dr. Black’s analytical research at Georgia Tech illustrates the number of variables involved and their effects. At least 32 variables affect an explosion, and no experimental program can address them all. Because of limitations on the number of tests and variables that could be investigated, it was necessary to select a few to try in the Lenox tests.

The illustrative nature of the study does not invalidate its general conclusions, because they are based on a reasonable laboratory reproduction of conditions observed in the field. The study’s conclusions can provide guidance and a basis of comparison with manhole events in Pepco. However, we caution against the application of the study's detailed results, such as measured values of cover lift, to a specific manhole because the manhole's size and gas mixture may be significantly different.

The introduction to the EPRI report correctly makes reference to manhole events resulting from cable joint failures. Experience with arc damage to electrical equipment (where explosions of combustible gases were not a factor) and analysis of pressure rise resulting from arcing[17] indicates that a high current arc by itself can have sufficient energy to result in a manhole event. This is especially possible in the case of a manhole with a significant depth of water. In such a case the arc energy could cause a water hammer that could lift a manhole cover.

Dr. Black’s analytical research at Georgia Tech also showed that there are two distinct causes of manhole events, arcs and explosions of combustible gases. The shape of the calculated curve of pressure vs. time is different for these two causes. In addition, some manhole events may be a result of a combination of the two causes. One result of this analytical work is the observation that what might be done to mitigate damage from arcs would not be the same as what might be done to mitigate damage from explosions of gases. For example, a large vault is better from an arcing standpoint, because there is more air to absorb energy from an arc. But a large vault may be worse from a gas standpoint because there is a greater volume of combustible gas.

The discussion of manhole events resulting from arcs or burning gas is relevant to Pepco. It might turn out that manhole events resulting from secondary cable faults may be primarily a result of liberated gas, and manhole events resulting from primary cable splice failures may be primarily a result of arc energy. Mitigation methods may be different for primary and secondary cable-caused events.

Manhole events resulting from arcs in 138 kV transmission cable stop joints were investigated in a project sponsored at the Hydro Quebec Institute of Research (IREQ) by EPRI and the Los

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[17] G. Friberg and G. J. Pietsch, “Calculation of Pressure Rise Due to Arcing Faults,” IEEE Transactions on Power Delivery, Volume 14 Number 2, April 1999, pages 365-370.

Angeles Department of Water and Power (LADWP).[18] Fault currents up to 20,000 Amperes were investigated at IREQ. Considerable damage to the test manhole was sustained in these tests, which demonstrates the energy released by power arcs. The IREQ report also discusses the combination of arc energy and gases released by the stop joint prior to the full fault arc. A LADWP researcher believes that arcs are "worse than gas explosions."

The LADWP/IREQ tests on transmission cables are not directly applicable to Pepco's distribution cables. A valuable area of future research would be to perform tests of 4 and 13 kV arcs to directly obtain insight into their impact on the Pepco system, and also to calibrate the Georgia Tech analytical model.

Arc energy tests were not performed as part of the Lenox project because the Lenox laboratory site does not have sufficient fault current available for a realistic test. It is unrealistic to expect that Lenox would have performed arc tests. In assessing arc damage, it is common to use some surrogate impulse, such as a blast of high-pressure compressed air, to investigate arc damage. The consequences of rapid expansion of gas would be expected to have some similarity, whether the source was an explosion of a gas or an arc. Therefore, the test results in the EPRI report give reasonable guidance concerning the effects of slotted covers on mitigating the effect of expanding gases as a result of arc blasts.

Remember, the EPRI Lenox report deals with mitigating the consequences of a cable or splice failure, not with reducing or eliminating the frequency of failures themselves. It also does not deal with questions relating to reduction of energy released in the failure beyond the use of a vented cover to disperse combustible gases before ignition. Within its scope, the study demonstrates that slotted (vented) iron covers can reduce the severity of manhole events, but also demonstrates that slotted covers do not solve all the problems related to manhole events.

The work on tethers appears to be inconclusive. Tethers do limit the amount of vertical motion possible, but tethers increase the probability of a cover landing alongside the manhole rather than back on top of it. There is further concern expressed by the researchers about flame propagation from an explosion. There is evidence that flame due to an explosion propagates upward for an untethered cover, but flame may propagate sideways for a tethered cover. In one case the tether broke. Additional research on flame propagation with tethered covers is warranted.

A.1.7 Evaluation of Pepco's Response to the EPRI Report

Pepco's May 22, 2001 press release states:

> "Pepco also installed about 2,500 slotted manhole covers in high pedestrian traffic areas in Georgetown and the central business district. None of the slotted manhole covers Pepco has installed has become dislodged during incidents this year."

Given the indications in the EPRI report that slotted manhole covers can reduce the severity of a manhole event, installation of slotted covers in these locations is a reasonable decision. Pepco has not installed tethers on the slotted covers, which is also a reasonable decision based on the test data given in the EPRI report that shows tethers could actually increase the severity of a manhole event. Only experience over a period of years will determine the effect slotted covers

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[18] "138 kV Maintenance Hole Restraining System Testing," EPRI & LADWP, 1999, EPRI report TR-113556.

has had. It is important for Pepco to keep accurate records of underground system failures to make this assessment. The Pepco records should cover all failures, not just manhole events. Otherwise, it will be difficult to make a judgement whether installation of slotted covers has restricted a failure that would have produced a manhole event to one that was contained.

Inspection of manholes that have been fitted with slotted iron covers indicates that slots in the covers do allow admission of significant debris into the manholes, as predicted in the EPRI report. For example, in Georgetown on a side street with trees there is a significant deposit of leaves on the manhole floor. The degree to which this becomes a problem will only be apparent after years of experience with these covers. If debris covers cables, this may impact cable temperature. Flammability of debris may increase the severity of a manhole fire. If a single failure starts a fire on the manhole floor, other cables may be damaged as a result. Therefore, Pepco should investigate and document the effect of debris resulting from the use of slotted covers when performing an investigation of any type of failure within a manhole.

Pepco's experience to date reveals the fact that no slotted covers have lifted due to a manhole explosion. Also, there have been several manhole events where smoke escaped through the slotted covers but did not result in an explosion. Fire fighters consider a build-up of smoke as a potentially explosive condition, and respond by ventilating a fire scene. Dispersal of smoke through slotted covers indicates that combustible material can escape and possibly prevent an explosion. While not definitive nor a statistically valid sample, Pepco's experience indicates that installation of slotted covers has helped to relieve the severity of manhole events.

Appendix A.2

REVIEW OF

Report of Potomac Electric Power Company

in Response to Commission Order No. 12036

Prepared by Stone & Webster Consultants

For the Public Service Commission of the District of Columbia

Submitted September 13, 2001

A.2.1 Purpose of This Document

At the request of the Public Service Commission of the District of Columbia, Stone & Webster reviewed the document "Report of Potomac Electric Power Company in Response to Commission Order No. 12036".

A.2.2 Introduction

This section contains summaries of our review of Pepco's compliance with Order No. 12036 regarding the implementation of the fourteen (14) recommendations made by ABB in its report titled "Georgetown Area Low-Voltage Network", ABB Final Report, Dated January 15, 2001. Specifically, we are commenting on sections 39 through 43 in the Pepco report, and on certain Pepco responses requiring clarification.

A.2.2.1 Summary of ABB Recommendations - Implementation Plan (Section 39)

Overall, Pepco is implementing the recommendations made by ABB in the modification of standards that will be used in the rebuilding of the Georgetown system. Specifically:

- Pepco is revising the ratings assigned to cables, used for primary circuits, installed in ducts, to take into account the heating effects of low-voltage cables in the same duct bank. This will result in a more conservative design (derating of cables). Pepco will be measuring the soil thermal resistivity, which will be useful when Pepco calculates the ampacity ratings of the cable circuits.
- Load flow models are being developed for the new system in Georgetown, using software recently obtained by Pepco. They are working with the software vendor to develop interfaces that permit electronic transfer of existing data into the load flow program model. Pepco will have a valuable tool for assessing the status of each low-voltage network system. Potential

overload problems will be identified through simulation before they can cause equipment failures and possibly outages.

- Pepco is implementing ABB's recommendation into the investigation of the application of sectionalizing switches for certain portions of the underground network feeders. We feel that these switches would not provide a great benefit. Instead, resources could be directed towards equipment and methods that result in shorter fault location times and shorter cable repair times.

A.2.2.2 Review of Slotted Manhole Covers - Installation Plan (Section 40)

EPRI Solutions conducted tests for Pepco by igniting combustible gasses in a manhole with either solid or slotted covers. The test results demonstrate that slotted covers either do not launch, or the height of the launch is significantly reduced. The effectiveness of the slotted design depends upon the concentration of gasses and the mixture of gasses. Furthermore, some explosions may be prevented when the combustible gasses can escape through slotted manhole covers before the gasses accumulate to potent concentrations.

Based on available research data, the installation of slotted covers appears to be a prudent approach for reducing the number of manhole cover launchings. Pepco has installed a total of 3,722 slotted manhole covers through July 15, 2001. As the manhole inspection program continues, additional solid covers in sidewalk and crosswalk locations will be replaced with slotted covers.

A.2.2.3 Summary of Georgetown Modernization Plan (Section 41)

The Georgetown plan is described in general terms of new manholes, ducts and cables without much of the details of the engineering design. The project will relocate the ducts and cables to the street in the business corridor along Wisconsin Avenue and M Street. All of the business corridor customers will be served from the re-built low-voltage network. The project also involves upgrades in the residential sections with the elimination of the low-voltage network and the conversion of the 4 kV radial feeders to 13 kV radial feeders designed to operate in an open-loop configuration.

Through our interviews, it appears that the system is being designed in an appropriate fashion, and that the new design, materials and construction will be a significant improvement over the present system. The new systems should improve reliability and should allow for system capacity enhancements to accommodate future load growth. The preliminary electrical design will be modeled with a power flow computer program to confirm that it will function as desired under normal and single contingency conditions.

A.2.2.4 Review of EPR Cable Installation (Section 42)

In 1999 Pepco established an internal task force to investigate alternative designs to the well proven paper-insulated lead-covered (PILC) cable construction. Several specific requirements need to be met for a direct replacement product:

- The must be able to fit in the inside diameter of existing ducts

- The ampacity rating should the same or better than the existing PILC cable construction.
- Terminations and splices should be available and have proven operating records.
- Transition joints between PILC and new design should be available and have proven operating records.
- “Y” or “T” transition joints should be available or developed for the approved replacement product.

Pepco’s investigation resulted in the development of an Ethylene Propylene Rubber (EPR) insulated cable with a flat strap copper neutral and polypropylene jacket. The study by Pepco showed that this combination of materials is used by several other large US utilities.

Pepco also initiated the development of a transition Y joint that will be able to be installed in an existing manhole. The laboratory work to date has been successful, and it is expected the product will be available for field trials in the very near future.

The Georgetown Project will use an EPR insulated cable design with flat strap copper neutrals and polypropylene jacket and industry proven accessories.

A.2.2.5 Review of Manhole Inspections Report (Section 43)

The Manhole Inspection Report summarizes the inspection of 1,492 manholes during the first quarter of 2001. Of the seventy-seven (77) reportable items listed,

> Six (6) items relate to the primary cable circuits.
>
> Twenty-six (26) items relate to the secondary cable circuits,
>
> Three (3) to structural items within the manhole,
>
> Forty-two (42) other items reported conditions such as high water levels and high content of debris and removal of grease from the manhole.

Of the thirty-two (32) cable related items, only three (3) items have been rectified. None of the structural items have been completed.

The following are comments on the table titled “First Quarter 2001 - Manhole Inspection Progress Report”:

1. Items #19 (1700 17th St. NW), #23 (NEC R/W 15th St. & P St. NW), and #27 (9th 7 “E” St. NW) list the condition of primary joint or cable leaking with the action, "inspect & repair as needed". The priority of these items is not listed, it is uncertain when the repairs will be made. A leak has potential for an electrical failure and also for environment contamination (removal of fluid with manhole debris). **Therefore PILC cable/joint fluid leaks should get a high priority for swift repair, with the scheduled repair date based on the severity of the leak.**
2. Item #32 (F/O 1903 4th St. NW) has the condition "Burned sec. Cable" with action to "Inspect & repair as needed". **Burned cable indicates overheating, and should get a high priority for swift repair.**
3. The table should have a column labeled "Priority Code."

4. The “Action” column should be split into two columns for dates, "Repairs Scheduled" and "Repairs Completed."
5. The table should have a column called "Item No."
6. Item #15 (SEC 27th & “O” St. NW) shows repair completed in the month (2/01) prior to the report month (03/01). The dates should be corrected.

A.2.3 Detailed Review of Georgetown Modernization Plan (Section 41)

Appendix B of Pepco's response to the Order 12036 discusses the Georgetown Plan in broad terms. The plan mentions new manholes and ducts and generalities of the electrical system, but there is apparently still a lot of engineering to be done that requires proper detailed studies. This work has probably not been completed yet, but will have to be done at some time soon, especially to ensure that enough ducts and cable will be installed in the right places.

The Pepco standard practice in designing new network systems will be incorporated into the Georgetown modernization project. New network systems have dedicated 13 kV cables (primary feeders), network transformers, and low-voltage secondary network cables. The new design should allow the greatest flexibility in the operation and protection of the network system. In contrast, with non-dedicated primary feeders for the secondary network, both network transformers and radial transformers are supplied from the feeder. This creates operating limitations, and results in a degradation of the protection that is offered for faults on the primary feeders and in the network transformers.

The project will relocate the ducts and cables from the sidewalk to the street in the business corridor along Wisconsin Avenue and M Street. Pepco will construct separate duct banks for the 13 kV primary feeders and the low-voltage secondary cables of the network, thus enhancing the ratings of the cables, and minimizing the chance of an arcing fault in a secondary cable from burning into a primary cable. Pepco has made a preliminary electrical design for the low-voltage secondary system and selected the network transformer sizes and locations. It appears that Pepco is designing the new system in an appropriate fashion. This impression was generated from our meetings with Pepco representatives on Tuesday August 7, 2001, not from the Pepco response to the Order.

The preliminary electrical design of the new system will be modeled with a recently acquired power flow program, EasyPower, to determine the required number of primary feeders, transformers, secondary main cables, and conduits throughout the integrated system. The simulations will be used to size the new system so that it will not be overloaded under normal and single contingency conditions. Load magnitude and connectivity data for input into the EasyPower Program is presently available from the studies done on the existing Georgetown system by ABB.

The civil engineering design for the system (duct banks, number of ducts, manholes, and vaults) is proceeding based upon the preliminary electrical design. The final electrical design must be completed in time to complete civil design prior to the scheduled start of construction. Although many of the existing network transformer vaults will be re-used, cables will be in new ducts located in the street.

Secondary network topology should be carefully considered in the redesign of the Georgetown system. From our meetings with Pepco representative on August 7, 2001, it appears that the new design differs significantly from the present design, and should improve reliability. All secondary cables will be of a standard size (i.e. 500 kcmil), which is a normal practice in many utilities. Cable capacity requirements are met by using the appropriate number of cables in parallel. Cable limiters will be installed in both ends of all cables in secondary mains, and in both ends of all cables between the transformer (protector) and the bus holes.

For the new Georgetown system, short circuit protection for the primary feeders from the station end will consists of phase and ground time overcurrent relays, and phase and ground instantaneous current relays. With only delta grounded-wye connected network transformers, the ground relays can be set quite sensitive. They must be set so that they do not trip from false residuals for faults in the secondary network, and from faults on other primary feeders (sympathetic tripping). The phase instantaneous relay must be set high enough so that it will not trip for faults in the secondary system. If it did look through the transformers, a fault in a bus hole of a spot network could trip 2, 3 or more primary feeders, and the whole system will go down. By the nature of the system, where there are multiple transformers on the primary feeder, the phase time overcurrent relay usually will not respond for faults in the secondary system, or if it does, the time overcurrent relay will coordinate with the network protector fuse.

The overlap of the low voltage network and the 4 kV radial systems in Georgetown causes several problems. One problem concerns the presence of 4 kV fed loads in the commercial section and the need to relocate 4 kV facilities in connection with reconstruction of the low voltage network. From this alone it will be necessary to make modifications on the 4 kV radial system. The small number of customers served from the 4 kV radial system within the business corridors will be converted to the new low-voltage network system. The remaining Georgetown loads served by the 4 kV radial systems will be converted to 13 kV radial systems, to be operated in an open loop configuration.

The Georgetown Project will re-construct the low-voltage secondary network only along the business corridor of Wisconsin Avenue and M Streets. The loads served from the low-voltage secondary network in the residential area in the side streets will be connected to the 13 kV radial system. It appears that the elimination of the low-voltage secondary network in the residential sections will alleviate some of the ongoing problems in Georgetown. From the ABB network analysis study, loss of a 13 kV network feeder can result in overload of secondary network cables is the residential area. Elimination of the low voltage secondary network in the residential area has been proposed by Pepco to solve this problem.

ABB network analysis study shows that the 4 kV system has sufficient capacity to supply the load at the present time. In the last couple of years, the number of customer interruptions has been relatively high (for underground systems) because of the high failure rate of the existing 4 kV cables. The ABB studies predicted that new cables should result in a significant improvement in reliability because the new cables will fail less frequently. Also, with the 13 kV radial system operated in an open-loop configuration, service can be restored much faster than in the 4 kV system, to all or most customers following a fault

The addition of the load presently supplied by the low voltage network in the residential area to the 4 kV radial system would increase the stress on the 4 kV system. Conversion of the 4 kV radial system to a 13 kV loop system in the residential area would increase the ability to supply additional load.

The new 13 kV radial systems planned for Georgetown should result in a significant improvement in reliability. The installation of new primary cables in the radial system will reduce the number of faults, and thus, the number of customer interruptions.

The 13 kV system will operate in a radial fashion, but be configured as an open loop system, on both the main feeders and the branch feeders. The open loop configuration will allow rapid restoration of service to most of the customers after a fault occurs. The 13 kV radial systems will use EPR cables, elbow connectors, and incorporate switches to allow rapid isolation of faults, and quick restoration of service to most of the customers before the fault is repaired. In contrast, service can be restored in the 4 kV radial system in many situations only after the fault has been repaired. The average duration of a customer outage served from the existing 4 kV radial feeders is relatively long because of the hours required to locate the failure and repair faulty 4 kV paper-lead cables.

In summary, the rebuilding of the low-voltage network system in the commercial areas of Georgetown, and the conversion of the 4 kV radial system to 13 kV loop systems will result in an improvement in reliability. It further will allow for system capacity enhancements to accommodate future load growth as the need arises.

A.2.4 Detailed Review of ABB Recommendations - Implementation Plan (Section 39)

Section 39 reviews Pepco’s Implementation Plans that were prepared in response to the recommendations made by ABB for the Georgetown LV network systems. The ABB recommendations were in the report dated January 15, 2001. Pepco’s Implementation Plans are in Appendix A of the Pepco response dated July 23, 2001 to Commission Order 12036.

Overall, Pepco is implementing the recommendations made by ABB in the modification of standards that will be used in the rebuilding of the Georgetown system.

Following are comments on selected items in the Implementation Chart of Appendix A. The numbers used are consistent with those in the Implementation Chart.

A.2.4.1 ABB Recommendation 2

“The maintenance/inspection scope of work should be expanded in selected manholes/handholes, as defined by the load analysis results to include: spot ground testing, spot checking of soil resistivity measurement and verification of proper cable limiter application.”

Status Report On Recommendation 2 By Pepco:

“A testing procedure has been developed to allow for selective testing of ground resistance and soil resistivity. This work will be conducted during the normally hotter and dryer period of the summer and will be completely reviewed by December 2001.”

Review Of Response To Recommendation 2

Through our interviews with Pepco's staff, it has been clarified that Pepco will be measuring the soil **thermal** resistivity. This data will be useful when Pepco calculates the ampacity ratings of the cable circuits.

A.2.4.2 ABB Recommendation 4

"The results of the load model, initiated by Pepco, should be used to validate the engineering design assumptions and to assist with more efficient maintenance resource management."

Status Report On Recommendation 4 By Pepco:

"Pepco has addressed the problems identified in the ABB studies by installing additional sets of cables where indicated to alleviate the identified base case overload conditions. These modifications to the system are considered interim measures until the Georgetown modernization project can be completed."

Review Of Response To Recommendation 4

We recommend that the emergency ratings of the network unit (transformer and protector) and the emergency rating of the secondary mains should not be exceeded under a single contingency of any one of the six primary feeders out of service. We recommend that Pepco secondary network systems be designed such that emergency ratings of cables are not exceeded during any possible single contingency, as well as normal conditions when all feeders in service.

Pepco indicates that modeling of its 47 networks is an aggressive multiyear effort which will require up to five years to complete. To create the model of each of the low-voltage networks, and to keep the model current, due to the dynamic nature of the network system, will require a significant effort and expense. However, it will be a valuable tool for Pepco to assess the status of each low-voltage network system if the topology model is accurate, and accurate load data is available from billing information. Potential overload problems will be identified through simulation before they can cause equipment failures and possibly outages.

A.2.4.3 ABB Recommendation 5

"Review the network ampacity design criteria for Terracotta ductbank applications based on the results of the detailed load model and a re-validation of present and past design assumptions."

Status Report On Recommendation 5 By Pepco:

"A complete review of Pepco's design assumption when using terracotta duct, as well as when multiple primary and secondary cables are contained within the same ductline is currently underway."

Review Of Response To Recommendation 5

In the past, many utilities have calculated the primary cable rating neglecting the effect of secondary cables in the same duct bank. However, studies have revealed that the ratings for the primary cables are lower when the calculations include the effect of the heating from secondary cables in the same duct bank. The de-rating of the primary cables depends upon the number of secondary cables, their loading, and proximity to ducts with the primary cables. We encourage Pepco to adopt a cable rating design guideline that includes the effects of secondary cables in the same duct bank.

Pepco is installing microprocessor relays in some network protectors. These relays have the capability to provide real time load data on the secondary side of network transformers. From this, it is possible to determine the loading on the different segments of each primary feeder, providing every network protector on the feeder has a communicating microprocessor relay. If every feeder to a network had such real time monitoring, and the occupancy of each duct bank were known, it would be possible to have real-time load data on each primary feeder in the duct bank, and real time temperature calculations for the primary feeder cables. At this point in time, no such system has been installed, but they are being considered and evaluated technically by one utility. Although it will be many years before such a system might be available, Pepco is encouraged to monitor the developments in this area.

A.2.4.4 ABB Recommendation 7

"Based on the results of the short circuit model being developed, Pepco should review the Georgetown system. Based on the results of this review, Pepco should determine if it is necessary to adjust short circuit levels in the system to improve the clearing of faults. Three phase and line to ground (arcing) fault clearing should be evaluated independently."

Status Report On Recommendation 7 By Pepco:

Pepco states in the IN PROGRESS Section that, "Present standards require the installation of current limiters when the available short circuit current is less than 3200 amperes. The study, filed with the Commission on June 13, 2001, shows that the available fault current in Georgetown is significantly more than 3200 amps three phase faults. In the majority of cases, fault current levels are sufficient to clear faults. For those cases that are less than 3200 amps, the installation of limiters is being considered."

Pepco states in the COMPLETE Section that, "The clearing of arcing faults is still under review; however, this is an industry problem that has currently no available solution. The levels of fault current in Georgetown are high enough to obtain the shortest fault clearing times. No benefit would be obtained by changing the transformer designs to increase fault current. Therefore no additional actions will be taken on this recommendation."

Review Of Response To Recommendation 7

The Pepco response in the IN PROGRESS Section is inconsistent. Present Pepco standards require installation of cable limiters on 250 kcmil mains when the available short circuit current is less than 3200 amperes. However, Pepco states it is considering limiters for those cases where the available fault current is less than 3200 amperes. ABB specifically suggests that Pepco should consider the installation of cable limiters in areas where available fault current is predicted to be greater than 3200 amperes.

Industry practices on the use of cable limiters in 208-volt secondary mains vary widely. At one extreme, some utilities install no limiters in secondary cables. They rely on faults burning clear and not re-striking at a later time. At the other extreme, some utilities apply cable limiters on all secondary main cables, including 4/0 and 250 kcmil cables, irrespective of the number of cables in the duct. Pepco's practice in 208-volt secondary mains seems to be between the two extremes. Limiters are used on all 500 kcmil mains, and on 250 kcmil mains when two or more sets are installed in the same duct. If there is one set of 250 kcmil cables in a duct and the available fault current from all directions to the point of fault is less than 3200 amperes, then limiters are installed. Otherwise, limiters are not installed.

The basis for the Pepco statement that, "The levels of fault current in Georgetown are high enough to obtain the shortest fault clearing times" is not known. When cable limiters are installed, the time for the cable limiter to clear a fault for a given or specified current can be determined from the limiter time-current characteristic curve, as published by Burndy or others. But when cable limiters are not installed, as is the Pepco practice when there is a single set of 250 kcmil cables in a duct, the time for a fault to burn clear is not known. We are not aware of any curves giving the burn clear time.

We agree with the Pepco argument that the clearing of ***arcing*** faults is an industry problem that presently has no available solution. Even in systems that have cable limiters, there have been cases where arcing faults did not blow all cable limiters, necessitating cutting the fault clear. There seems to be some evidence suggesting that this is more likely to happen in the fringe areas of the network where available fault currents are low. The evidence of this can be gleamed from the technical literature, where it is seen that over 40 years ago industry groups were investigating solutions to this problem.

However, we would argue that installing cable limiters in all 250 kcmil secondary mains, regardless of the number of cables in the duct, increases the likelihood that a fault will be cleared quicker, and is less likely to restrike at the fault point after clearing. Thus less gasses may be generated from the heat due to arcing at the fault point. However, unfortunately, we can not quantify the impact of the universal application of cable limiters. We do recommend that Pepco continue to evaluate benefits that might exist from applying limiters on 250 kcmil cables when the available fault current is above 3200 amperes, just as recommended by ABB. Consideration must be given to cost and benefit when evaluating changes in cable limiter application standards. We recognize that to retrofit cable limiters to an existing system can be very costly and disruptive, and that adequate space may not be available in some manholes. Installation in new systems is not as difficult and costly.

We would further agree with the Pepco position that no benefit would be achieved by changing transformer designs in the Georgetown system to increase available fault currents. However, we recommend that in redesigning the Georgetown system, Pepco should design the secondary system topology and secondary mains such that sufficient fault current is available to either blow cable limiters, or burn clear, considering both the three-phase fault, phase-to-phase fault, and the single phase-to-neutral fault in a duct. Pepco's past experience should be used in determining what current levels are needed to burn clear or blow cable limiters.

One other advantages of installing limiters over relying on burn clear should be considered by Pepco in evaluating if standards on cable limiter application should be changed. If a cable fault in a duct burns clear in absence of limiters, the cable in the duct on both sides of the burn clear point will remain energized. At a later time, tracking from ingress of contaminants may occur at the fault location, resulting in re-establishment of the fault, and the associated additional energy input at the fault point. In contrast, if a fault is cleared from both ends by blowing of cable limiters, the cable is de-energized on both sides of the fault, and the likelihood of tracking and re-establishment of the fault is greatly reduced.

A.2.4.5 ABB Recommendation 8

Based on the results of the short circuit model, Pepco should consider increasing the use of cable limiters to determine if improvements can be achieved in the area of cable protection.

Review Of Response To Recommendation 8

See the previous section titled “Review of Response to Recommendation 7”.

A.2.4.6 ABB Recommendation 10

“Pepco should continue investigating the application of sectionalizing switches for certain portions of the underground network feeders. The configuration of the (3) sub networks in Georgetown are more suited to the application of sectionalizing than other parts of the Pepco low-voltage network.”

Status Report On Recommendation 10 By Pepco:

In part, Pepco states: “Switches on low voltage network systems have limited application due to the design of the network system. Switching of individual cable circuits could result in overloads on the secondary cable system. In addition, due to the high fault current available on a network system, there are a limited number of switch manufacturers for this application”.

Review Of Response To Recommendation 10

While switches on the secondary may not be feasible for several reasons, there could be situations where switches on the primary have merit. There are several ways that switches could be applied on network primary feeders.

Primary feeder faults would always result in tripping of the station breaker. If a switch is installed near the middle of the feeder, and the fault is downstream from the switch, then the switch could be opened so that the first half of the feeder could be re-energized by closing the station breaker. The network transformers on the first half of the feeder would be re-energized, and thus feed the secondary networks. Such a switch should have appropriate grounding provisions so that repair work could be performed safely on the second half of the feeder. Its incorporation in a network would require careful review of operating and work practices. The switch provides no benefit for faults between the substation breaker and the switch.

The secondary network system is designed to operate with any one primary feeder out of service. Therefore, switches in network primary feeders would not provide a great benefit. Instead, resources could be directed towards equipment and methods that result in shorter fault location times and shorter cable repair times. This allows quicker return of service for the faulted feeder, and reduces the time duration of the incremental load applied to the in-service feeders as the result of the faulted feeder being out of service.

Appendix A.3

REVIEW OF

Georgetown Area Low-Voltage Network

ABB Final Report Dated January 15, 2001

Prepared by Stone & Webster Consultants
For the Public Service Commission of the District of Columbia
Submitted September 26, 2001

A.3.1 Purpose of This Document

At the request of the Public Service Commission of the District of Columbia, Stone & Webster reviewed the document "Georgetown Area Low-Voltage Network," ABB Final Report Dated January 15, 2001.

A.3.2 Executive Summary

Pepco operates both low-voltage network systems and radial distribution systems. Section A.3.9 contains a description of the topology of the radial distribution system and the low-voltage network system, and an explanation of how each system responds under normal conditions and faulted conditions. This section also discusses how a low-voltage network system provides much higher reliability of service than that provided with a radial system. This is the main reason that low-voltage networks frequently are installed in commercial and other select areas.

Pepco retained ABB Power T&D Company to perform the following studies for its low-voltage network systems in Georgetown:

- A system analysis
- An evaluation of Pepco engineering design practices
- A diagnostics and condition assessment of the Pepco low-voltage network systems in Georgetown.

The purposes of these studies were to obtain an independent perspective on how Pepco could improve the predictive and preventative aspects of its underground system strategy.

ABB also conducted load modeling studies of Pepco’s Georgetown low-voltage network systems and radial systems. The results of these studies were contained in a separate report, and therefore are not included in this review.

We found the ABB report to be very thorough and complete since it considers all major areas related to the design, operation, engineering diagnostics, and the protection of low-voltage networks.

The ABB report concludes that the Pepco low-voltage network designs meet or exceed industry standards, that the Pepco standards are based on sound and solid engineering principles, and that their material specifications are consistent with those of other system operators.

The ABB report contains 14 recommendations for the low-voltage network systems. Pepco has outlined in Appendix A of its response to Commission Order 12036 the status of its implementation plans for the 14 recommendations made by ABB. If Pepco follows these recommendations, they will improve the performance of the low-voltage network systems. The Stone & Webster review discusses several areas where the design of Pepco's low-voltage network systems would be considered superior to that of many other utilities, yet they were not highlighted in the ABB report.

Stone & Webster makes three additional recommendations for Pepco to consider with regards to the design, operation, and protection of their low-voltage network systems:

A.3.2.1 Stone & Webster Recommendation No. 1

Evaluate the effectiveness of high-voltage current-limiting devices installed in each primary feeder at the substation as a means of reducing the probability of a fault in a primary cable splice causing a manhole explosion (manhole lid displacement).

Tampa Electric has installed these devices and has found them to be very effective for this purpose in their low-voltage network systems. Tampa Electric has also determined that these devices are effective in preventing the rupture of cable terminal compartments and switch compartments on the high-voltage side of network transformers, events which can result in oil fires in transformer vaults.

A.3.2.2 Stone & Webster Recommendation No. 2

Evaluate the applicability of new technologies for locating faults on the high-voltage feeder cables of the low-voltage network systems. The faster a fault on a high-voltage feeder cable can be located and repaired, the shorter the duration of the higher loading placed on the other components of the low-voltage network system. This reduces the likelihood that a fault on one high-voltage feeder circuit will cause a second fault in another cable due to overloading. Pepco low-voltage network systems, like those of most other utilities, may overload when two high-voltage primary feeders are out of service.

A.3.2.3 Stone & Webster Recommendation No. 3

Pepco is installing newer microprocessor relays in the isolated spot networks. By programming of these relays, Pepco can select either a circular close characteristic or a conventional straight-line close characteristic. Pepco is encouraged to consider the application of the circular close characteristics in each spot network whenever the microprocessor relays are incorporated into all protectors in the spot network.

A.3.3 Evaluation of the ABB Study

Overall, the ABB report is very thorough and complete, considering all major areas related to the design, operation, engineering diagnostics, and the protection of low-voltage secondary network systems.

ABB's basic approach was to first conduct a survey of other operators of low-voltage network systems, so that they could compare the practices of Pepco with those of other operators, and identify the best practices in the industry. The survey considered the areas of reliability, design standards, material standards, network supervisory control and data acquisition, and maintenance practices.

The twelve respondents to the survey included ten utilities and two consultants. The ABB study data would have given more insight into the practices of the low-voltage network operators had it been directed to a larger number of utilities. The inclusion of more respondents may not have changed the conclusions, but it certainly, in some areas, would have given a higher confidence in what are perceived to be industry practices.

ABB also reviewed Pepco design standards and guidelines, material standards, and construction standards to determine how Pepco practices compared with those of other utilities. Further, they performed random inspections of Pepco facilities, and in particular facilities in Georgetown, and conducted tests on network transformers. The purpose was to ascertain if Pepco's installed systems were in compliance with the most recent Pepco standards, and to identify weaknesses in the network systems in Georgetown. To perform its work, ABB used both its in-house experts, and sub-contractors, such as CTI Power Systems for much of the field inspection and review of Pepco standards.

In some instances the ABB report incorrectly confuses industry practices with industry standards. One example involves the application of cable limiters on low-voltage cable circuits where ABB states that, "Pepco's design guidelines for the application of cable limiters exceed industry standards." Another example is the statement, "Pepco's application of secondary neutrals is consistent with industry standards." There are no industry standards with regards to the application of cable limiters and the sizing of secondary neutrals. However, there are practices, and the practices of utilities vary.

Section 8.0 of the ABB study lists technologies that may be effective in reducing the number of manhole events. Listed for Pepco's consideration were "currently available technologies recommended for implementation", "emerging technologies - commercially available", and "emerging technologies - not commercially available". The ultimate result from this was the development of 14 recommendations, from which Pepco has developed an implementation plan and is providing status reports in accordance with Commission Order 12036.

A.3.4 ABB's Evaluation Of Pepco LV Network Systems

ABB evaluated Pepco's LV network system considering design practices, construction standards, and material specifications. Below is a brief summary of their findings.

A.3.4.1 Design Practices

The major design practices considered by ABB were:

- Substation arrangement for network primary feeders
- Primary feeder loading and calculations
- Primary feeder regulation and protection
- Use of Paper Insulated Lead Covered (PILC) cable for primary feeders
- Network transformers and network protectors
- Size of the secondary neutral conductors
- Cable limiter application.

ABB's controversial recommendation that Pepco should consider use of cable limiters on 250 kcmil secondary cables even when the fault current is above 3200 amperes is further discussed in Section A.3.10.

ABB concluded that Pepco design practices meet or exceed industry standards, except cable loading design criteria for areas with large duct ways where multiple cable sets have been installed in ducts, in areas where terracotta ducts are prevalent and where overloading is an issue. Further, ABB pointed out that the design assumptions that Pepco uses with regards to soil thermal resistivity and load factor, for calculating cable ampacity ratings, need to be re-evaluated. Section A.3.14 contains additional comments on the ampacity study.

A.3.4.2 Construction Standards

ABB reviewed the following construction standards:

- Manhole construction
- Duct bank construction
- Transformer vault construction
- Cable support systems

The review by ABB showed that current Pepco standards are thorough and based upon sound engineering practices. However, for some of the older parts of the system, such as found in Georgetown, the system does not satisfy Pepco's present standards. This is no surprise considering the condition of portions of the Georgetown system. These exceptions will be rectified with the rebuilding of the network systems in the Georgetown area.

A.3.4.3 Material Specifications

ABB reviewed the following material specifications:

- Network protectors
- Network transformers
- Cable limiters
- Primary feeder cables
- Secondary network cables
- Arc resistant tapes

ABB concludes that Pepco material specifications are consistent with those of other low-voltage network operators.

ABB concludes that failures of splices in paper insulated lead covered cables (PILC) represent the highest incident rate of contributing causes for manhole events. However, they did not identify measures that Pepco might take to reduce the number of failures in splices made on PILC cables.

ABB recommend that Pepco evaluate changes in material specifications that might reduce the number of splice failures, such as using EPR insulated primary cables with pre-molded splices as an alternative to the PILC primary cables.

A.3.4.4 Advanced Diagnostics Testing of Primary Feeders

Attachment #11 to the ABB report lists several diagnostics testing methods for distribution feeders. Other methods than the ones listed may also be available. All of the methods are relatively new and the interpretation of the test results requires a high level of technical skill and extended experience with each test method. Therefore the value of the diagnostic testing needs to be examined closely to verify that the test results can be correctly interpreted, and the results can be implemented in a cost-effective manner.

None of the methods being utilized by the electric utility industry has reached a state of confidence that would suggest developing a diagnostics testing program for the distribution feeders at the Pepco system. Pepco should continue to monitor the progress being made on existing and new diagnostics testing methods.

A.3.5 Superior Aspects of Pepco’s LV Network Systems

In four important areas, the designs of Pepco’s low-voltage network systems are superior to those of many system operators. Three of these areas are alluded to in the ABB report, but the fourth is not mentioned at all. Those evaluating and judging Pepco’s low-voltage network system should be cognizant of these aspects.

A.3.5.1 Low-voltage Network Size

Each of Pepco's low-voltage networks has six 13,800-Volt (13 kV) high-voltage feeders. In any network, any one high-voltage feeder can be removed from service, and the remaining five feeders can supply the peak load. This is referred to as single contingency design. See Section A.3.9 for a description of the low-voltage network system and its topology.

Pepco limits the size of each low-voltage network to the range of 30,000,000 to 45,000,000 Volt-Amperes (30 MVA to 45 MVA). These numbers give an indication of the peak power that can be supplied from a given low-voltage network. In terms of mechanical power, each network can supply a load in the range of 30,000 to 45,000 horsepower. With the size of each network limited to 45 MVA, the maximum load that could be dropped upon a catastrophe in a single low-voltage network system is 45 MVA. In comparison, there are low-voltage secondary networks operating in other large metropolitan areas where the load on a given network is in the range of 100 to 200 MVA or larger, and the number of high-voltage feeders is much larger than six. For these systems, a catastrophe necessitating a network shutdown drops a much larger block of load, affecting a greater number of customers. Furthermore, the larger the network, the more difficult it is to restore the network to operation following complete shutdown from a major catastrophe.

A.3.5.2 Substation Bus Configuration

For each low-voltage network, there are six high-voltage feeders. Pepco distribution substations that supply the network's 13,800-volt high-voltage primary feeders have a ring bus configuration with at least six sections. Each feeder connects to a different section of the ring bus, as shown in the simplified system in Figure A.3-3 in Section A.3.9, except that the simplified system has just three feeders, and there are just three sections to the ring bus.

With the ring bus arrangement, a fault on any one section of the ring bus will result in the loss of only one high-voltage primary feeder to the network. This single contingency condition does not result in customer outages since the low-voltage network is designed to carry the peak load with any one of the six high-voltage primary feeders out of service. In comparison, a fault on the substation bus in some network systems will result in the loss of two high-voltage feeders to the network, which may result in dropping of the entire network.

A.3.5.3 One Network Unit Per Vault

Pepco installs only one network unit (network transformer and network protector) in below grade vaults. When there are two or more network units in separate vaults at the same location, this greatly reduces the probability of a disturbance in one network unit propagating to another network unit, or the primary feeder cables supplying the other network unit. As illustrated in Figure A.3-1, each of the three network units for a spot network is in a separate vault. In addition, the paralleling bus for the spot network is in a separate vault, referred to as a bus hole.

Should a fault occur in the high-voltage disconnect and grounding switch of one of the network units, the compartment may rupture and an oil fire may ensue. With each unit being in a separate vault, it is very unlikely that the fault will propagate to another network unit or to another primary feeder in a separate vault, or to the paralleling bus in the bus hole.

In contrast, some utilities will locate all of the network units and the paralleling bus in the same vault, exposing multiple primary feeders and unfaulted equipment to the effects of a disruptive failure of liquid filled apparatus.

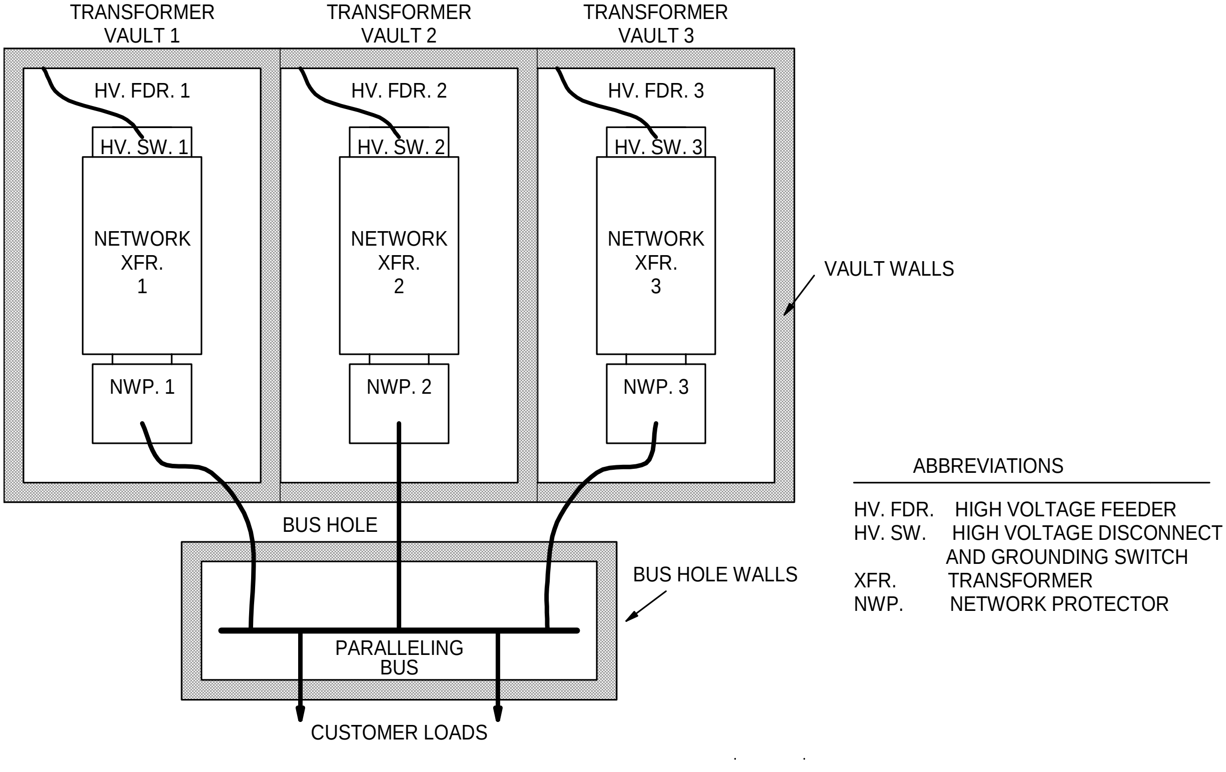


Figure A.3-1 Three-unit Spot Network Where Each Network Unit and the Paralleling Bus Are In Separate Vaults

A.3.5.4 Relays

Pepco, on the 13 kV feeders that serve just network transformers, referred to as dedicated network feeders, installs phase instantaneous current relays and ground instantaneous current relays. These are the relays that will detect a fault in a high-voltage feeder cable, in a splice in a PILC cable, a fault in the terminal compartment or in the disconnect switch of a network transformer, or a fault within the transformer itself (see Figure A.3-1). When the fault is detected with these relays, the circuit breaker at the distribution substation is opened to interrupt the flow of fault current.

By necessity, the pickup of the phase instantaneous current relay must be high so that it will not respond to faults in the low-voltage portion of the systems. The pickup of the ground instantaneous current relay, with network transformer configured as purchased by Pepco (delta connected high-voltage winding), can be set much lower than the phase instantaneous current relay. The lower the pickup setting, the more sensitive the protection for ground faults in the primary (13 kV) winding of the network transformer and for faults in splices.

Data submitted by Pepco in response to Stone and Webster data request 5 show that Pepco sets the pickup of the ground instantaneous current relay lower than most other utilities. Although the Pepco setting varies from substation to substation, most ground instantaneous current settings do not exceed 300 to 400 amperes, and in some cases they are much lower than this. This means that ground faults will be detected instantaneously, and cleared from the substation end in the shortest possible time when conventional circuit interrupting devices are used. Sensitive settings and the associated short clearing times are important as they minimize the chance of a ground fault in a network transformer primary winding resulting in rupture of the transformer tank and the associated oil fire. In comparison, the minimum settings used by some operators are three to four times higher than the minimum setting used by Pepco.

However, even with the sensitive ground relay setting, a ground fault in the high-voltage terminal compartment or switch compartment of a network transformer usually will result in the rupture of the compartment and an oil fire, due to the clearing time of the circuit breaker at the substation. However, there are means of further reducing the clearing time for such faults, as well as for faults in the splices of PILC cables, as discussed in Section A.3.7.

A.3.6 Evaluation of ABB Recommendations

The ABB study contains 14 recommendations to Pepco. Adoption of these recommendations by Pepco will enhance the overall reliability and security of the network systems, as well as reduce the probability of manhole explosions. In response to Commission Order No. 12036, Pepco has provided an implementation chart to the Commission indicating the extent to which it will implement the ABB recommendations.

For the most part, Pepco is implementing the recommendations made by ABB. However, some of the recommendations made by ABB would be subject to debate by operators of low-voltage network systems. As a result, in these cases Pepco has indicated that they are continuing to investigate the recommendation and its applicability to the Pepco systems. This is the appropriate response when there are considerable differences of opinion amongst practitioners who are knowledgeable with the issue.

For example, Pepco is continuing to evaluate the ABB recommendations with regards to the application of cable limiters in the low-voltage network system, and with regards to increasing fault currents to help faults burn clear or blow cable limiters, when installed.

A.3.7 Areas Not Considered In The ABB Study and Additional Recommendations

A.3.7.1 Current-Limiting Devices and Phase Reactors

The sections of the ABB Report dealing with Engineering Design Practices failed to investigate two practices that might have an impact on manhole explosions (lid blowings) for faults in splices of PILC cables for the network primary feeders operating at 13 kV. These may also have an impact on the rupturing of cable terminal compartments, and the rupturing of switch compartments on network transformers for faults in these compartments.

The first involves the installation of phase reactors on the primary feeders of the low-voltage networks. This will not reduce the time required to isolate a fault in a splice from the source at the distribution substation. However, it will reduce the available short circuit current, and it will reduce the energy into the splice at the point of fault. Regardless of the available short circuit current on the primary feeder of the Pepco system, the fastest clearing time from the substation end will be 5 cycles (0.0833 seconds).

The second involves the application of current-limiting devices on the primary feeder at the substation. The current-limiting device, in effect, performs the same function as the phase instantaneous current relays presently installed in the Pepco system. However, high-current faults in cable splices and network transformers would be interrupted from the substation side in less than 1 cycle, in comparison to 5 cycles as in the present system. Furthermore, with the current-limiting devices, the magnitude of the current flowing into the fault will be reduced. The net effect of this is that the energy into the fault in a splice, or into the fault in a cable compartment or switch compartment in a network transformer can be reduced by a factor of 10 or more, depending on particulars.

These current-limiting devices have been installed by just one utility in the USA in their network systems. This is the Tampa Electric Company. They report that this device is very effective in preventing manhole cover displacements from faults in primary cables. It also has been very effective in preventing the rupture of terminal compartments and switch compartments on the high-voltage side of network transformers. A description of the installations and the effectiveness on the Tampa Electric system is contained in the Electrical World Magazine article, “Electronic Fuses Protect Cable, Network Transformers”, the January 1994 edition.

The application of current-limiting devices is discussed further in Section A.3.11.

Stone & Webster Recommendation No. 1

Pepco should evaluate the applicability of current-limiting devices to its system. Although Pepco does not install phase reactors on their primary feeders supplying the low-voltage networks, such devices are installed on distribution circuits fed from some substations that also supply networks. Pepco should also evaluate their existing databases to determine if installation of just phase reactors on network primary feeders would have a significant impact on manhole explosions for faults in primary cable splices, due to the reduction of available fault current. These reactors will also reduce heating in cable sheaths and splices for most ground faults.

A.3.7.2 Fault Location Time in Network Systems

Each of Pepco's low-voltage networks has six 13,800 volt primary feeder circuits. When a fault occurs on any one primary feeder circuit, it is automatically isolated, and the remaining five primary feeders carry the load of the network. When this happens, the load on the remaining five feeders will increase about 20% or more, depending on the interlacing of the feeders and the load distribution. The corresponding I^2R losses and heating on some primary feeder cables will go up by at least 44%. Furthermore, in the 208-volt grid network the loading on secondary cables will increase.

Operating at higher loading levels increases the likelihood of a failure occurring in a second component of the system, and in turn causing a manhole event or an outage.

It is therefore important that faults on network high-voltage primary feeders are rapidly located, repaired, and the high-voltage primary feeder place back into service as soon as possible. At present, Pepco uses sheath coils to pre-locate faults on primary feeders, and picks to pinpoint the fault location on feeders with PILC cable. This can be a time consuming process, as it requires opening manholes so that personnel can enter to make measurements. If a manhole is flooded, additional delays are incurred until the water is removed.

Stone & Webster Recommendation No. 2

Pepco should evaluate some of the newer technologies and equipment recently developed for locating faults on network primary feeder circuits. These were developed for the Consolidated Edison Company of New York, the operator of the largest low-voltage network systems in the world. The particular device that Con Edison is presently using is the "above ground" meter, which allows pre-location of the fault without the need to open and enter manholes. The device was originally developed by AT&T Bell Laboratories, and is now available in commercial form from the Technology Enhancement Corporation. The operator of the above ground meter need only travel the route of the primary feeder to locate the fault, without need to enter manholes.

In addition, Pepco is encouraged to monitor the progress being made on real-time fault location schemes being developed for Con Edison. With these schemes, the objective is to have a system that will tell system operators, almost instantaneously after feeder breaker opening, the distance of the fault from the substation or some other reference point. When such devices or systems become available, Pepco is encouraged to evaluate their applicability to the Pepco low-voltage network systems.

A.3.7.3 Network Relay Close Characteristics

Section 7.1 of the ABB report reviews the settings used by Pepco for their network protector relays, and concludes that, "Pepco's settings as summarized in Table 1, are typical settings found among many network utilities. No changes to these settings are recommended at this time." We are in complete agreement with this.

However, the newer microprocessor relays available today have both the conventional straight-line master close characteristic and the straight-line phasing close characteristic, as well as the newly developed circular close characteristic. The user selects the type of close characteristic and settings. For isolated spot networks fed from dedicated primary feeders, the use of the circular close characteristic will allow an open protector to automatically reclose at a lower load on the network, without unduly increasing the number of protector operations. The net effect of this is to have all protectors in the spot network closed over a greater period of the time. This in turn enhances the reliability of the system, especially in two-unit isolated spot networks. Pepco has spot networks fed from dedicated primary feeder circuits, emanating from the same substation.

Section A.3.12 contains a discussion of the straight-line and circular close characteristics of network relays used in low-voltage network protectors.

Stone & Webster Recommendation No. 3

Pepco is encouraged to consider the application of the circular close characteristics in each spot network whenever the microprocessor relays are incorporated into all protectors in the spot network.

A.3.8 Technical Critique

As indicated earlier in this report, the ABB study is very thorough and complete in its evaluation of Pepco with regards to System Analysis, Engineering Design Practices, and Diagnostic and Condition Assessment. The main exception is the failure to include recommendations to evaluate the applicability and effectiveness of current-limiting devices for the protection of primary feeders, and as a means of reducing manhole explosions.

Furthermore, several technical inaccuracies appear in the ABB report. They are discussed in Section A.3.13. It is emphasized, however, that these inaccuracies do not impact the findings and recommendations of the ABB report.

A.3.9 Distribution System Topology

Pepco operates both radial distribution systems and low-voltage network systems in the DC area. The purpose of this Section is to describe the topology of the two systems, explain how the systems operate under normal and faulted conditions, and to emphasize the differences.

Radial systems have a simpler configuration and lower cost than low-voltage network systems. Low-voltage network systems are used mainly in commercial areas and other areas where it is desired to supply the highest level of reliability that is possible with conventional types of power systems. Figure A.3-2 shows a simplified radial primary distribution system.

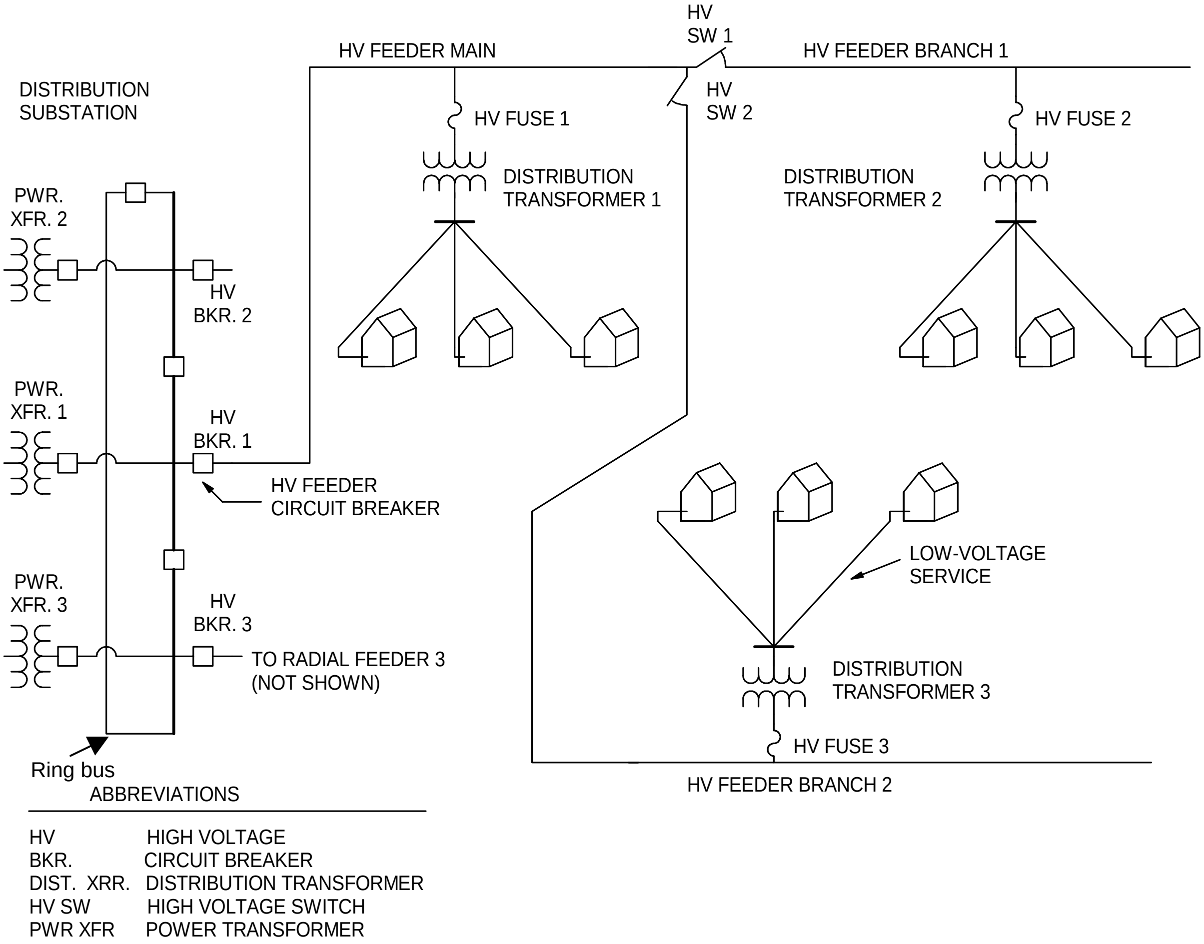


Figure A.3-2 Simplified Radial Primary Distribution System

The radial distribution system originates in the Distribution Substation. The main components of the radial system are the high-voltage (HV) feeder circuit breaker located in the Distribution Substation, the high-voltage (HV) feeders, the distribution transformers, and the low-voltage services to the customers. Other important components are the high-voltage switches located in the HV feeders, and the high-voltage fuse on the input side of each distribution transformers.

The voltage level of the HV feeders in the Pepco system usually is either 4000 volts (4 kV) or 13,800 volts (13 kV). As most customer load will not operate at these high voltage levels, distribution transformers are connected to the HV feeders to step the voltage down to the utilization level, the voltage levels at which consumer equipment operates. This might be the familiar 120 volts found in residences, although other utilization voltage levels are used for commercial and industrial applications. Low-voltage secondary circuits and low-voltage services carry the power from the distribution transformer to the customer’s premises.

The simplified system of Figure A.3-2 shows only one radial HV feeder emanating from the distribution substation. In an actual system, there would be many such feeders emanating from the substation, going in different directions to supply the loads.

The power flow in each component is always away from the distribution substation under normal (unfaulted) conditions in the radial system. The topology of the radial system is similar to that of a tree with the roots being the substation bus. The HV feeder main corresponds to the tree’s trunk, the HV feeder branches correspond to the tree branches connected to the tree’s trunk, the distribution transformers correspond to second-level branches of the tree, and the low-voltage services correspond to third-level branches of the tree. As long as there are no interruptions in any of the paths of the radial distribution system, power will flow from the distribution substation to all customers fed from the system. This is analogous to nutrients flowing from the earth to the tree’s leaves as long as the trunk and none of the branches are completely severed.

Should a short circuit (fault) occur on the HV feeder main, or one of the HV feeder branches, very high electric currents flow from the substation to the point where the short circuit exists. If these high currents were allowed to flow uninterrupted, the conductors of the HV feeders carrying the current would overheat, and could melt and fuse, causing massive damage. To prevent this, relays are installed at the distribution substation to detect these high currents. The relays initiate opening of the HV feeder breaker at the substation, which interrupts the flow of short circuit current and prevents further energy input and damage to the system. In interrupting and isolating the short circuit on the HV feeder in this fashion, all customers supplied from the radial feeder experience a loss of power.

All customers in Figure A.3-2 will be out of service until the fault can be located. After the fault is located, all or a portion of the customers will still be without service until the fault can be repaired and the feeder re-energized. If the fault were on the HV feeder main in Figure A.3-2, all customers are without service until the fault is located and repaired.

If the fault were on HV feeder branch 1 in Figure A.3-2, all customers are without service until the fault is located. After the fault is located, high-voltage switch 1 (HV SW 1) can be opened to isolate the faulted section of the HV feeder. Then the HV circuit breaker at the substation is closed to energize the HV main feeder and HV feeder branch 2. This restores electric service to all customers supplied from the transformers connected to these portions of the radial circuit. After the fault is repaired, service can be restored to the customers supplied from HV feeder branch 1 by the closing of high-voltage (HV) switch 1.

What should be clear from the proceeding is that when faults occur in radial HV systems, a large number of customers can be affected, and the length of the power outage can be quite long. This is especially true in radial distribution systems that are located below ground, because it may be difficult and time consuming to locate the fault. However, Pepco does install faulted circuit indicators in 13 kV radial systems, to reduce the time required to locate faults. The 13 kV radial circuits also have a loop configuration, which allows service restoration, in many cases, without need to repair the fault.

Low-voltage secondary network systems were developed in the 20’s to provide highly reliable service to commercial areas of cities and towns.

Figure A.3-3 shows a simplified low-voltage secondary network system that serves the same loads as the radial system in Figure A.3-2. As will be seen from the following discussion, a short circuit on a high-voltage feeder circuit, in a network transformer, and in a low-voltage secondary main does not cause a loss of power to the customers.

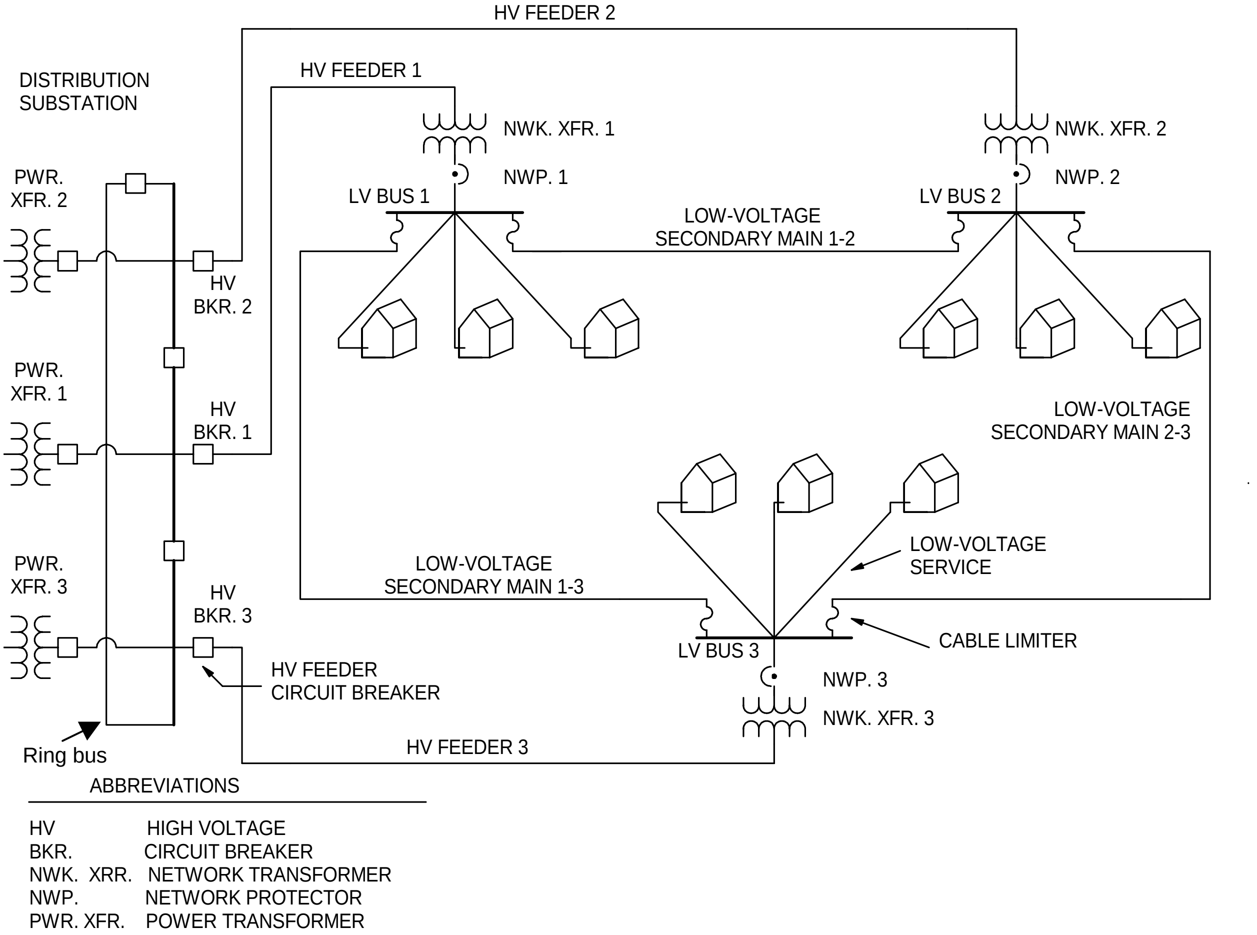


Figure A.3-3 Simplified Low-Voltage Secondary Network System

The low-voltage network system originates at the Distribution Substation in Figure A.3-3. The main components of the low-voltage network system are the high-voltage feeder circuit breakers located at the Distribution Substation, the high-voltage (HV) feeders, and the network units (consisting of a network transformer and a network protector). Each network unit feeds a low-voltage (LV) bus adjacent to each network unit. Low-voltage secondary mains connect the low-voltage buses at different locations in the load area. Low-voltage services to the customers are fed from the low-voltage buses. Sometimes, customers are fed directly from taps to the low-voltage secondary mains, although this is not shown in Figure A.3-3.

In the simplified system of Figure A.3-3, there are three high-voltage feeders with just one network unit fed from each high-voltage feeder. Each of Pepco’s 47 networks has 6 high-voltage feeders supplying it, with there being a multiplicity of network units fed from each high-voltage feeder. The voltage level of the high-voltage feeders in the Pepco system is 13 kV.

The low-voltage network (low-voltage buses and low-voltage secondary mains in Figure A.3-3) is a three-phase system which supplies both three-phase power load, such as motors for air conditioning and elevators, and single-phase lighting load (such as lighting, computers, or anything that is plugged into a wall receptacle). The voltage level of the low-voltage network from which the load is served is either 208 volts, or 480 volts depending on the requirements of the customer.

Under normal conditions in the low-voltage network system of Figure A.3-3, the power flow in each HV feeder is from the distribution substation to the network unit (network transformer and protector). In each network unit the power flow is from the network unit to the low-voltage buses, and along the secondary mains. There is more than one path for the power to flow from the distribution substation to any one customer. The system is protected such that if a short circuit (fault) occurs in any one path, the short circuit is automatically isolated without causing an interruption to the customers served from the network.

Consider a short circuit on high-voltage feeder 1 in Figure A.3-3. When this occurs, high currents flow in HV feeder 1 from the distribution substation to the short circuit. Relays detect this high current and open high-voltage (HV) breaker 1 located in the substation. After HV breaker 1 at the distribution substation automatically opens, there is a reverse power flow in network protector 1 (NWP 1), and it automatically opens. The automatic opening of HV breaker 1 and NWP 1 isolates the fault on HV feeder 1. Although this disconnects network unit 1 from low-voltage bus 1 (LV bus 1), the loads on LV Bus 1 are supplied through low-voltage secondary main 1-2 and low-voltage secondary main 1-3, and do not experience an outage.

From Figure A.3-3, no matter which high-voltage feeder has the short circuit, all customers served from the low-voltage network will not experience an outage. The system is designed so that with any one HV feeder and its associated network transformers removed from service, the remaining parts of the system can carry the peak load. This is referred to as single-contingency design.

A short circuit in a network transformer is automatically isolated in the same fashion as a short circuit on the HV feeder, and customers supplied from the low-voltage network will not experience an outage. A HV feeder of the network can be removed from service for inspection, maintenance, testing, or repair, and customers supplied from the network do not experience an outage.

Pepco also designs their low-voltage network systems such that if a short circuit occurs on any one bus section in the Distribution Substation in Figure A.3-3, or if there is a failure of any one main power transformer (PWR. XFR) in Figure A.3-3, no customer will experience an outage.

If a short circuit occurs on a 208-volt low-voltage secondary main, it will either burn clear or be isolated by the cable limiters at each end of the secondary mains. This also will not result in an outage to any customers served from the low-voltage buses. However, if there are customers tapped directly from the secondary main which has the short circuit, the customers on the shorted secondary main will loose power until repairs can be made. Section A.3.10 gives a brief history behind the cable limiter, and a description of its basic functions.

Should a short circuit occur on a low-voltage bus in Figure A.3-3, then those customers supplied from the bus with the short circuit will experience an outage.

From the preceding discussion of the response of the low-voltage network system, it is clear that most short circuits in the system do not cause power outages to the customers supplied from the network. This is why the low-voltage network system offers the highest levels of reliability possible with conventional power systems, and is used extensively in many metropolitan areas. Data supplied by Pepco to the Commission confirms this fact.

A.3.10 Cable Limiters

Pepco operates a 208-volt low-voltage network system. In the Executive Summary of the ABB report, it is stated that, "Pepco's cable limiter application exceeds industry standards." There are no industry standards on the application of cable limiters to low-voltage secondary networks, but there are practices. Pepco has guidelines for limiter application in 250 kcmil low-voltage cables in the 208-volt networks. Limiters are not installed with a single set of cables installed in a duct if the fault current in-feed from both sides of a fault on the set of cables is 3200 amperes or higher. Limiters are installed at both ends of 250 kcmil cables only when there are two or more sets installed in a duct, irrespective of the available fault current. ABB recommends that Pepco consider applying limiters on both ends of 250 kcmil cables when there is just a single set in a duct, irrespective of the in-feed current on both sides of the fault.

Cable limiters were not used in the early low-voltage secondary network systems, and today some utilities still do not use cable limiters. Figure A.3-4 shows a portion of a low-voltage network system where cable limiters are not used. In comparison, some utilities install cable limiters on all secondary cables, including 250 kcmil copper cables as used by Pepco, irrespective of the available fault current and the number of sets of cable in a duct. In the Pepco 208-volt secondary systems, cable limiters are installed in some 208-volt secondary circuits. In Pepco's 480-volt secondary system, cable limiters are installed in all low-voltage cable circuits, irrespective of cable size or available fault current.

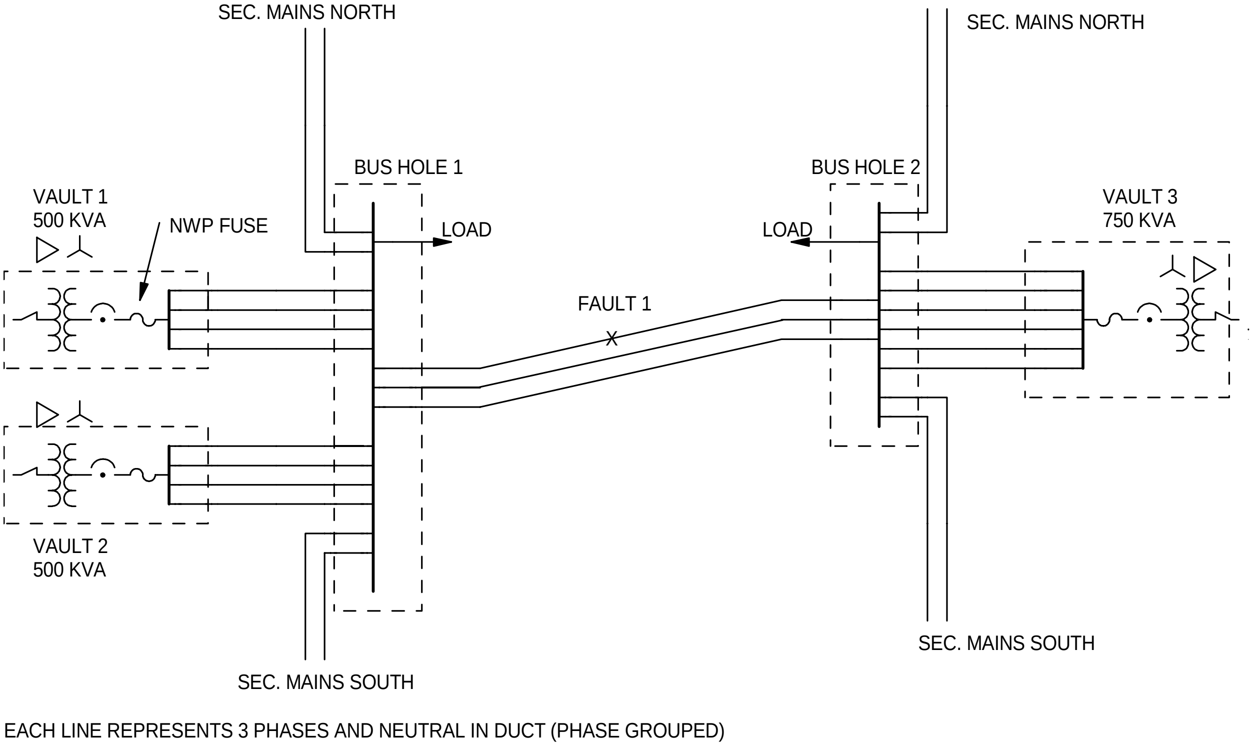


Figure A.3-4 A Portion of a Low-Voltage Network System without Cable Limiters

In 208-volt systems without cable limiters, the intent that was that the short circuit in the cables would burn clear at the fault point at the low-voltages involved (either 120 volts or 208 volts). The burn clear philosophy was based upon tests conducted in the late 20's and reported in a paper presented in 1931 titled, "Burn-Off Characteristics of AC Low-Voltage Network Cables." In these tests, two insulated cables in duct had the insulation stripped from about a 3-inch segment, and the bare conductors were held in contact with tape. Then the circuit was energized to determine how much in-feed current was required on both sides of the fault to burn clear without the fault spreading. In order for burn clear to occur, the I^2R heating at the contact point between the two faulted conductors must produce sufficient temperature rise to melt the copper conductors at the contact point. Yet, at the same time the in-feed current on either side of the fault must not elevate the temperature of the conductor remote from the fault point such that the cable insulation is damaged, thereby allowing the fault to spread. From tests and calculations, it was determined that burn clear would occur as long as the in-feed on both sides of the fault exceeded 3200 amperes for the 250 kcmil cables.

The burn clear philosophy further assumed that after burn through occurred at the point of fault, a physical separation would occur between the conductors at different voltage, and that the voltage between the two conductors would not be sufficient to cause a re-ignition of the fault. Even if burn clear occurs and a physical separation is maintained between the faulted conductors, a voltage difference is maintained at the fault point, as the cables are energized from bus hole 1 and bus hole 2. This voltage could be either 208 volts, or 120 volts depending on which cables were involved in the fault.

As the utility industry gained experience with low-voltage networks, it was found that faults did not always burn clear in the 208-volt system, and the fault could propagate to other portions of the low-voltage cable grid by melting the insulation of the cable remote from the fault point. Even if the fault did burn clear, the cables on both sides of the fault would remain energized, and the fault could re ignite at a later time due to electrical tracking from contaminants in the duct. In the simplified system of Figure A.3-4, if the fault does not burn clear and propagates back to the bus hole, cables from other low-voltage circuits may become involved. Furthermore, the longer the fault takes to burn clear, the more gases are generated from the cable insulation as it is decomposed.

The cable limiter was developed in the thirties to prevent faults that don't burn clear from spreading or propagating to other portions of the network. A cable limiter is basically a fuse installed at both ends of each cable. It was called a cable limiter because its purpose was to limit the damage to the cable insulation at points remote from the point of fault. Of course, the cable limiter also will de-energize the cable after it opens. For currents above a predetermined level, the cable limiter will melt and interrupt the fault current before the cable insulation is damaged. However, for very low fault currents, the exact level dependant upon cable size and thermal characteristics of the cable circuit and duct bank, the limiter may not melt before the cable insulation reaches the damage level of 260 degrees C.

Figure A.3-5 shows the same system as in Figure A.3-4, except that cable limiters are installed at both ends of each low-voltage cable. The cable limiter was designed such that for a fault the limiters at both ends of the faulted cable circuit would melt and clear the fault before the temperature of the copper conductor, remote from the fault point, would reach the level where it would melt the cable insulation. When the cable limiter opens to de-energize the fault, it will remove voltage from the fault, thereby minimizing the probability that the fault will re-ignite. If the cable insulation remote from the fault point melts, the fault may spread, just as when limiters are not used.

When cable limiters are installed in all low-voltage circuits as shown in Figure A.3-5, the cable limiters must be coordinated such that the only limiters that blow are those at both ends of the faulted cable circuit. For Fault 1, the only limiters that should blow are those labeled L1 and L2. With a multiplicity of cables as in Figure A.3-5, selective coordination of limiters usually is possible.

Even when cable limiters are installed, it is not guaranteed that the limiters will clear all faults before fires ensue. If the fault currents are low, regardless of the reason, the fault may produce damage at the fault point that decomposes the insulation and causes fires in the manholes and ducts before the limiters blow. Manhole fires and explosions have occurred in systems that have cable limiters, but the probability of this happening in a system with limiters is lower than in systems without cable limiters.

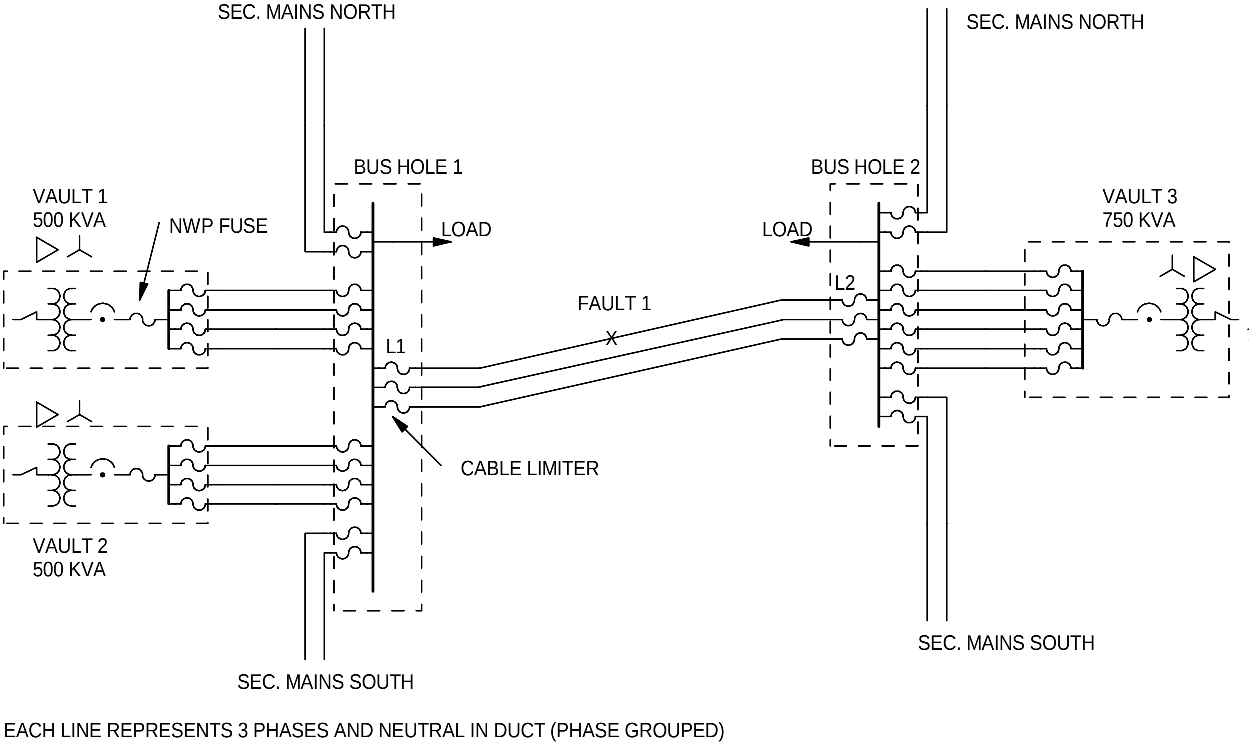


Figure A.3-5 Portion of Low-Voltage Network System with Cable Limiters Installed at Both Ends of Every Cable

Figure A.3-6 shows the same system except that cable limiters are installed in selective low-voltage cable circuits, similar to the practices on some utilities, including Pepco. Pepco installs limiters in all 500 kcmil cables, but not in 250 kcmil cables when there is just one set in a duct.

For faults on cable circuits without limiters, the intent of the design is that the fault burns clear, not only before the fault causes damage to the insulation of the faulted cable remote from the fault point, but before limiters on other "unfaulted" cables can melt. If cable limiters on unfaulted low-voltage circuits melt before the fault burns clear, it may destroy the integrity of the low-voltage network system.

When cable limiters are installed in all cable circuits as in Figure A.3-5, it is possible to determine if the limiters at both ends of the faulted cable will isolate the fault before limiters on any of the unfaulted cables can blow. This is possible because there are curves showing the time for the cable limiter to melt as a function of the current in the limiter. These curves are called time-current curves. By knowing the current in each limiter around the fault point, and having the limiter time-current curves, the coordination between cable limiters can be evaluated.

When cable limiters are not installed in all cables as in Figure A.3-6, the evaluation of coordination is more difficult. The reason for this is that there are no data sources giving the time for a cable fault to burn clear as a function of current. For example, for Fault 1, there will be significant current in the secondary mains with limiters, and in the cables with limiters between the transformer vaults and the bus holes. The limiter melting times are known, but there is uncertainty about the self-clearing time of the fault in the cable without limiters.

ABB has recommended that Pepco consider evaluating if limiters should be installed in all 250 kcmil cable circuits, irrespective of the available fault current levels.

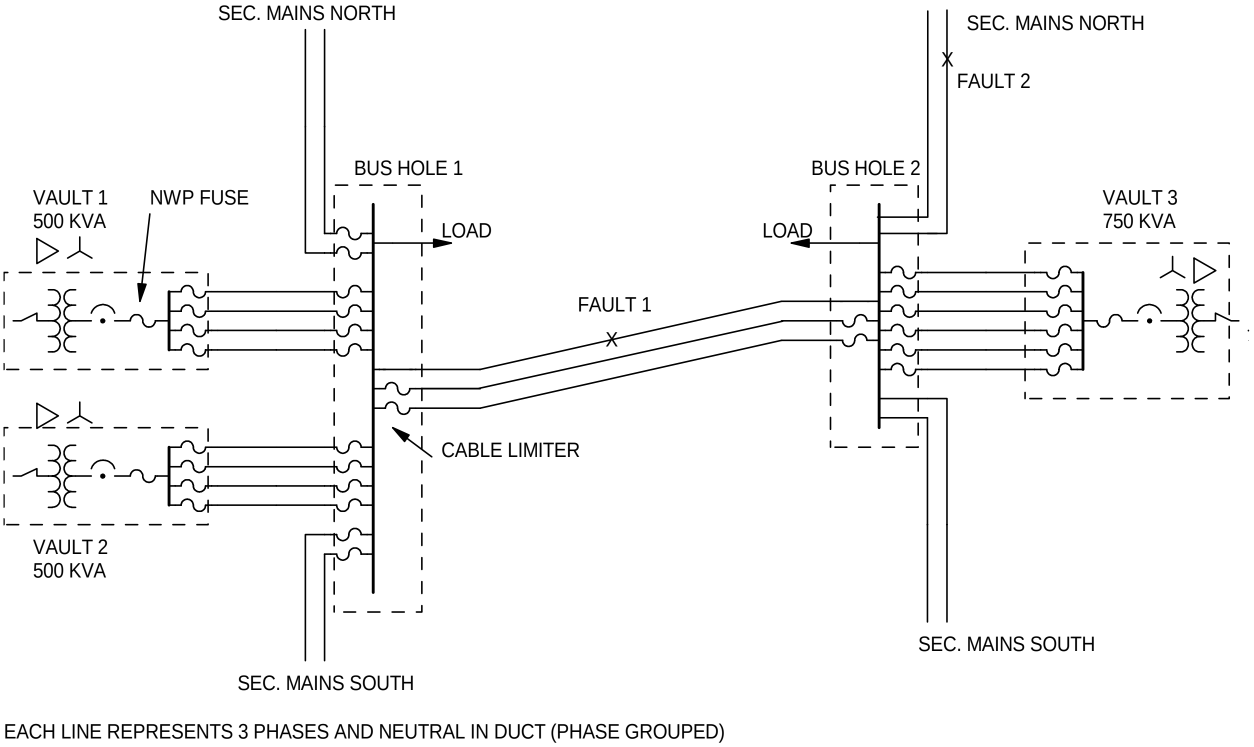


Figure A.3-6 Portion of Low-Voltage Secondary Network System with Limiters Installed in Some of the Low-Voltage Cable Circuits

A.3.11 Fault Current-Limiting Devices

More faults occur on the primary feeders of secondary networks than in the low-voltage cables. This statement is supported by data from Pepco and other utilities participating in the survey. Further, faults in primary cable splices have resulted in ejection of manhole covers. In the system of another utility (not Pepco), the ejection of a manhole cover from a fault in a cable splice on a primary feeder resulted in a fatality to an occupant of a motor vehicle when the manhole cover passed through the windshield.

Researchers suggest that the high pressures ejecting manhole covers may be caused by two separate mechanisms for faults in the splices of PILC cables. One is the ignition of gases generated when the splice insulating materials become decomposed from heating due to tracking. The other is from the heating of air and volatilization of conductor material during the ensuing high-current arc.

In the first mechanism, tracking of splice fill-materials creates heat. The heat generates gases that are explosive, and softens the lead splice. Then if the lead splice ruptures due to internal pressures from the generated gasses, and there is a spark or arc, the gasses generated from the degradation of the splice may explode. If the pressures produced by ignition of the volume of gases generated from the tracking are, by themselves, sufficient to eject a manhole cover, then the use of current-limiting devices probably would not be effective in preventing manhole cover ejections from faults in cable splices.

However, if the manhole lid ejects due to high ampere fault current of the arc, then current-limiting devices may prevent manhole lid ejections.

When a fault path develops in a splice of a high-voltage cable, the resulting power arc has very high currents that flow from the substation to the fault until the circuit breaker at the substation opens. Even after the station circuit breaker opens, fault currents may continue to flow in the fault until all backfeeding network protectors open. The backfeed current typically will be of lower magnitude than that coming directly from the substation. With reference to Figure A.3-3, currents flow into a fault on the high-voltage feeder cable from both the distribution substation and the backfeeding network protectors.

The energy input to the fault is the time integral of the arc voltage and the arc current. Any changes in system design or protection that reduce the magnitude of the available fault current, and any changes that reduce the time that the current flows will reduce the energy into the fault, and the pressures generated in the manhole.

Figure A.3-7 shows with the heavy curve the current flow from the substation to a fault in a splice when current-limiting devices are not installed, assuming a 5 cycle clearing time as in the Pepco system, and a symmetrical current wave. The lighter curve represents the current that flows in the faulted phase from the substation to the fault when current-limiting devices are installed in the feeder at the substation. The current-limiting device limits not only the duration of the current flow in the faulted phase, but also the peak magnitude of the current flow when the available fault currents are high. As the energy input to the fault is the time integral of the arc voltage and the current wave, the current-limiting device can significantly reduce the energy into the fault.

Unfortunately, there appears to be no formal research on the relationship between pressures generated in the manhole for primary cable faults and the electrical energy input to the fault arc from the high-current arc. Reducing energy input will reduce pressures, but studies have not been conducted to quantify the relationship. This is one area that EPRI or other industry groups should consider investigating if indeed a significant percentage of the manhole lid ejections are due to the energy from the effects of the high-current fault arcs in primary cable splices.

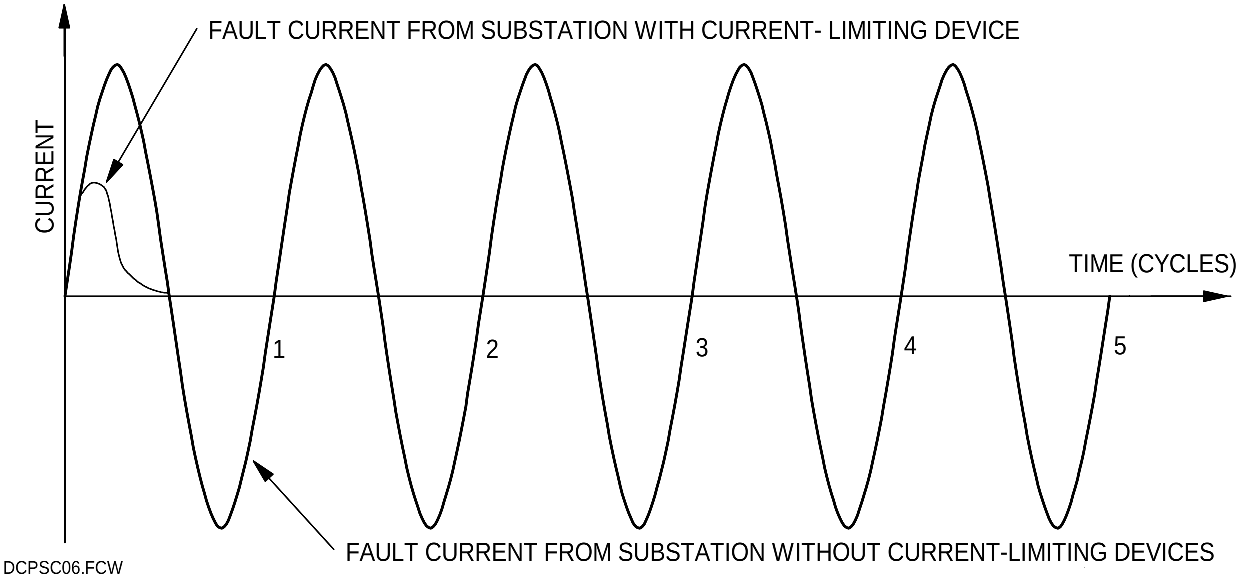


Figure A.3-7 Comparison of Waveform of Fault Current from Substation with and without a Current-Limiting Device at the Station

However, one utility in this country, Tampa Electric, has reported that for their system, that a commercially available device, the S&C Fault Fiter, has been effective in minimizing the chance of a manhole lid ejection for faults in primary cable splices located in manholes filled with water.

These devices are installed in each primary feeder at the substation. In effect, they replace the phase instantaneous current relays (device 50) for the primary feeder. The device limits the flow of the current from the substation, in the faulted phases, to less than one cycle. Furthermore, the device may limit the peak current flow in the first cycle to a value less than the available peak current. When the single-phase current-limiting devices are installed, relaying and control must be incorporated that will trip the circuit breaker for the feeder after the single-phase device operates in the faulted phase.

In comparison, conventional circuit breakers do not limit the magnitude of the fault current, but the current flow in all three phases is interrupted when the breaker opens. The current flow from the station to the fault may last for 5 or 6 cycles, as in Figure A.3-7, with a conventional circuit breaker having phase instantaneous current relays.

Tampa Electric's experience has shown that these devices also significantly reduce the probability of an explosion of the terminal compartment or switch compartment of network transformers for faults within these compartments. These compartments are filled with insulating oil or other insulating compounds. Such a fault did occur in terminal compartment of a 500 kVA transformer in the Pepco Georgetown network, located at 29th and O Street. The fault ruptured the terminal compartment, resulting in a small oil fire. Furthermore, it is recognized that should a fault occur within the switch compartment or the terminal compartment of a network transformer, it is quite likely that the cover plate will be partially or completely blown off, when the fault is cleared with a circuit breaker at the substation.

Pepco should encourage industry research groups, such as EPRI or others, to conduct high-power high-current tests in manholes to evaluate the effectiveness of current-limiting devices at the substation to reduce pressures in manholes for faults in primary cable splices. Tests also should be conducted to evaluate the effectiveness of these current-limiting devices to reduce the likelihood of primary terminal compartment and switch compartment ruptures from internal faults. These current-limiting devices, in effect, would replace the phase instantaneous current relays used with the circuit breaker for the network primary feeders.

If the industry sponsored tests confirm the experience of Tampa Electric, Pepco should determine whether commercially-available current-limiting devices, such as the S&C Fault Fiter, the G&W CliP, or similar devices are applicable to the primary feeders of the Pepco network systems. In evaluating the installation of current-limiting devices in network primary feeders at the substation, the following additional areas need to be considered.

- Application when capacitor banks are located in the substation
- Impact on grounding network primary feeders in the substation using a G&T Device in metal-clad switchgear located at the substation
- Impact on phase and ground relaying for the network primary feeders, and relaying needed to prevent single phasing
- Impact on network protector relaying for faults on the primary feeders
- Effect on reliability (false operation)
- Space availability in existing substations

Furthermore, they should determine if the installation of phase reactors in the primary feeders, in conjunction with the current-limiting devices, would further reduce heating in the affected components of the system during the flow of fault current. The installation of phase reactors, by themselves, would reduce the peak value of the fault current but would not reduce the duration of the current flow, which would still be 5 cycles.

In evaluating the installation of phase reactors on network primary feeders, the following areas need to be considered.

- Impact on load division in primary feeders during normal and contingency conditions
- Space availability in existing substations
- Impact on voltage drop and voltage regulation in the low-voltage network

A.3.12 Isolated Spot Networks

Pepco operates isolated spot networks in the DC area. An isolated spot network consists of two or more network units installed at the same location. A network unit consists of a network transformer and a network protector. The load terminals of the network protectors are connected to the paralleling bus located in the bus hole, adjacent to the vaults with the network units. Customer loads are fed from service cables connected to the paralleling bus in the bus hole, as shown in Figure A.3-8. In the isolated spot network system, there are no ties to the low-voltage secondary mains located in the streets.

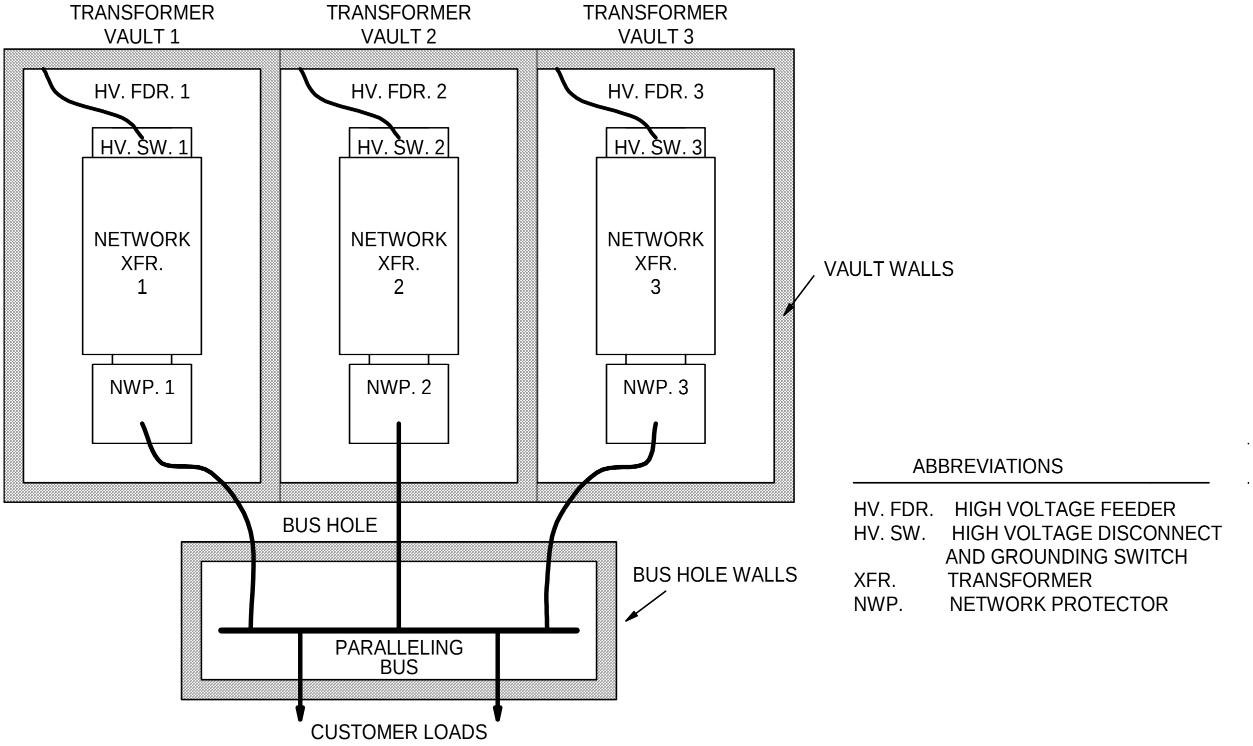


Figure A.3-8 Three unit Isolated Spot Network System

In order for the spot network to provide the highest level of reliability, all network protectors should be closed whenever the associated high-voltage (HV) primary feeder is energized. That way, the disturbance to the load supplied from the spot network, if any, will be minimized for a fault on one of the HV primary feeders of the spot network.

Whenever a high-voltage feeder is taken out of service for maintenance or system modifications, the network protectors associated with that feeder open on a reverse power flow. This creates the condition where not all network protectors in the spot network are closed. Whenever the feeder is subsequently re-energized, it is desired that the open protectors automatically close at the lowest possible load on the network paralleling bus that will not result in an ensuing reverse power and another tripping of the protector. The same applies should a protector be manually opened with its operating handle to allow performance of maintenance or testing of the protector.

It is desired that when the handle is returned to the automatic position at completion of the testing, the protector automatically recloses at the lowest possible load on the network.

Relays control the automatic reclosing of network protectors. Prior to the development of the microprocessor relays for network protectors, automatic reclosing was controlled with two separate electro-mechanical relays, a master relay and a phasing relay. These relays had “straight-line” close characteristics as illustrated in Figure A.3-9(a). The master relay close characteristic is labeled “ML”, and the phasing relay close characteristic is labeled “PL”. For the relay with the straight-line close characteristic to close the protector, the magnitude of the phasing voltage (the voltage across the open contacts of the protector, VP in Figure A.3-9(a)) must lie on or above the line labeled “ML”. Further, VP, must be to the left of the line labeled, “PL”.

Thus, the magnitude of phasing voltage V_P needed to close the protector is a function of the angle (θ_P) by which phasing voltage V_P leads the network line-to-ground voltage (V_N). As angle θ_P becomes larger, a larger phasing voltage is required for the relay to issue a close signal. The electro-mechanical relays, such as the Westinghouse CN-33 and CN-J, and the General Electric CHN and CHL, inherently had straight line close characteristics. The phasing voltage magnitude/angle relationship of the straight-line close characteristic is contrary to the preferred relationship. However, it was incorporated into solid-state network protector relays and the early microprocessor relays for network protectors.

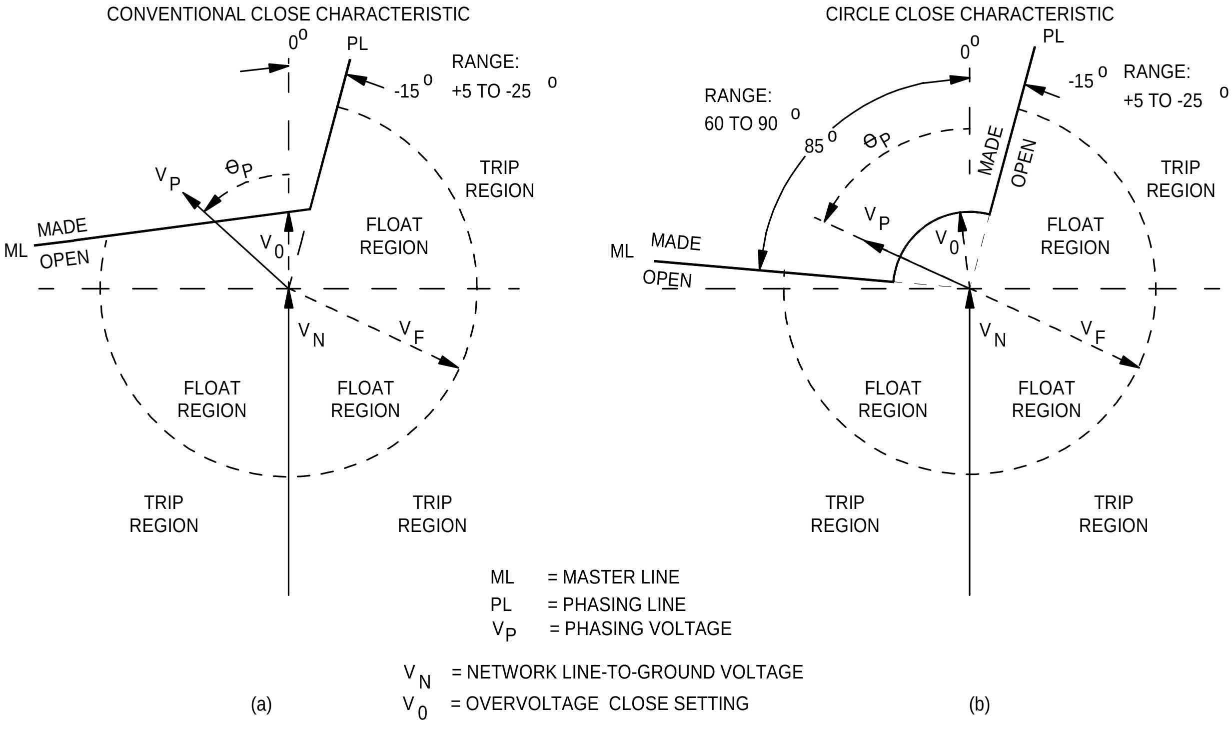


Figure A.3-9 Comparison of the Straight-Line and Circular Close Characteristics for Network Protector Relays (a) Straight Line and (b) Circular Close Characteristic

With the most recent microprocessor relays for network protectors, the user can select the type of close characteristic that the relay will exhibit, either straight line or circular as in Figure A.3-9(a) and (b) respectively. With the circular close characteristic, the magnitude of the phasing voltage V_P needed to make the close contacts and issue a close signal to the protector is independent of the phasing voltage angle, θ_P. Whenever V_P equals the circle radius, V_0 in Figure A.3-9(b), the relay issues a close signal. Practically, this means that the load on the spot network needed to get a protector to automatically close is independent of the load power factor angle. Furthermore, a more leading phasing voltage does not require a greater load on the network to cause automatic closing of the protector, as is inherent with the straight-line close characteristics.

With the straight-line close characteristic, as the phasing voltage angle goes more leading, the ensuing real power flow in the protector following closure is higher. Therefore, it is not logical to require a higher phasing voltage magnitude at larger phasing voltage angles, as inherent with the straight-line close characteristic.

With reference to Figure A.3-9(b), a relay with the circular close characteristic, having a radius V_0, also has blinders defining the extremities of the close characteristics.

The circular close characteristic is recommended for use in network protectors for isolated spot networks. This allows the protector to close at a lower load on the network, thereby helping to keep all network protectors closed regardless of the load on the spot network. This in turn enhances the reliability of the network system.

A.3.13 Technical Inaccuracies

The ABB study is very thorough in its evaluation of Pepco with regards to System Analysis, Engineering Design Practice, and Diagnostic and Condition Assessment. However, several technical inaccuracies will be mentioned even though they do not alter the main findings of the ABB study.

A.3.13.1 Cable Burn Thru Currents

The following is written in Section 4.8.2, subsection "Cable Burn-thru". "It is stated in this section that 3200 A (based on figure 4-15 on page 4-78 of the Standard Handbook for Electrical Engineers, 13th ed.) is sufficient to burn clear a 250 kcmil copper cable, and therefore limiters need only be applied if predicted fault currents are less than this value".

Figure 4-15 on page 4-78 of the Standard Handbook for Electrical Engineers, gives the time to raise the temperature of copper conductors from 40 degrees C to 1083 degrees C when a current is in the conductor for short times where radiation is neglected. In effect, the equation assumes that all heat generated from the I^2R losses in the conductor is stored in the conductor and raises its temperature. These times are based on the equation developed by Onderdonk, equation 4-36 in the handbook. This equation is given below.

$$33\left(\frac{I}{A}\right)^2 t = \log_{10}\frac{T_m + 234}{T_a + 234} \tag{4-36}$$

In this equation, the terms are:

I = Conductor current in amperes rms

A = Conductor cross sectional area in circular mils

t = Time in seconds

T_m = Melting temperature of copper = 1083 degrees C

T_a = Ambient temperature of copper = 40 degrees C for the curves

Both the EEI Underground Systems Reference Book , 1957 edition, and the Westinghouse Electrical Transmission and Distribution Reference Book , 1950 edition, contain a table giving the "minimum current in Amperes in each conductor on both sides of a solid fault on single-conductor cables to burn off the fault". Neither of these references is clear in the basis for the numbers in the table. Regardless, for the 250 kcmil copper cable, the current is given as 3200 amperes, the same value cited in the ABB report and Pepco documents. The EEI publication references the Westinghouse publication, and the Westinghouse publication indicates the tables are based on tests reported in a 1931 paper, and unspecified calculations. The paper is titled, "Burn-Off Characteristics of AC Low-Voltage Network Cables", by Sutherland and MacCorkle, AIEE Transactions, Vol. 50, No. 3, September 1931.

In summary, the curve in the Standard Handbook for Electrical Engineers gives the time to raise the temperature of copper to the fusing temperature when a current is passing through the conductor. There is no heat generated by arcing or by I^2R losses from contact resistance as when two bare conductors are touching one another. In contrast, the tests described in the AIEE paper resulted in tables giving the time to burn clear for faults initiated in accordance with the test conditions. Specifically, the AIEE paper states,

> "Copper to copper faults, in single-conductor a-c low-voltage (120/208 volts) network cables, made by the taping of the bared conductors overall and thereby obtaining a contact length of approximately three inches between conductors will clear at the location of the fault within a period of the order of one minute (usually less) provided the following minimum values of short-circuit current flowing into the fault are maintained during the short circuit."

There is no indication of the contact pressure between the two bare conductors when taped together, but apparently it is such that when energized the losses in the contact resistance result in melting and burning clear of the cables at the cited current level and higher.

The table in the original AIEE paper is reproduced below. Note that the 250 kcmil conductor size is not included. It is believed that the value for the 250 kcmil cable was obtained by either interpolation or calculation.

Conductor Size	**Constant Values of Short Circuit Current, Amps**	
	Per Conductor in Test Circuit	**Total**
4/0	3000	6000
350 kcmil	4000	8000
500 kcmil	5000	10,000

A.3.13.2 Network Protector Relay Characteristics

Section 7.0 of the ABB Report discusses the settings used by Pepco for the network relays that control the automatic operation of its network protectors. On page 65, it is stated that, "If phases have been reversed across the network protector, the phasing relay will not allow it to close. This is an important safety feature of the network protector".

Network protectors with the electro-mechanical relays typically have two separate relays, the master relay and the phasing relay. The master relay is used to control both the automatic tripping and automatic closing of the protector. The phasing relay is used only to control the automatic reclosing of the protector. For a protector to automatically close, both the master relay close contact and the phasing relay close contact must make. If phases are reversed, the master relay close contact will be open, but the phasing relay contact will be open or closed depending on how the phases are reversed. Thus, if phases have been reversed across the network protector, it is the master relay that prevents the network protector from closing automatically.

A.3.14 Review of Attachment #6

Attachment #6 of the ABB Report details the ampacity study performed by CTI Power System for ABB T&D Company. The following are comments on the ampacity study.

- On the drawing for grid # 781390-381588, Case #2, the paper-insulated cable does not show a lead sheath. Paper Insulated Lead-Covered Cables (PILC) are standard on Pepco's system.

Calculations with the heading 100a501f.txt:

- The page layout makes it very difficult to read and interpret the input data and the calculated results.
- The listing shows "No Shield Losses." There will be sheath losses for the 13.8 kV single-conductor PILC cables listed.
- The load factor for the secondary 208 V cables is correctly listed as 50%.
- The load factor for the 13.8 kV primary cables is listed as 50%. Pepco's design criterion is 75%.
- In one of the tables, the sheath thickness for both the 208 V and the 13.8 kV cables is listed as 0.0001. No dimension is listed.

The factors listed above will have an effect on the ampacity rating of the cable circuits but it is not possible to determine the effect without performing the calculations. Therefore, it is proposed that additional ampacity calculations be performed where the cables are correctly modeled.

Appendix A.4

REVIEWS OF

Georgetown Area Network System Evaluation

ABB Final Report May 21, 2001

And

4 kV System Load Flow and Reliability Analysis

Final Report March 9, 2001

Prepared by Stone & Webster Consultants

For the Public Service Commission of the District of Columbia

Submitted September 28, 2001

A.4.1 Purpose of This Document

At the request of the Public Service Commission of the District of Columbia, Stone & Webster reviewed the two documents “Potomac Electric Power Corporation Georgetown Area System Evaluation Washington DC” ABB Final Report dated May 21, 2001 which is bound with "Pepco 4kV System Load Flow and Reliability Analysis" ABB Final Report dated March 9, 2001. This review includes information obtained during a visit to ABB's offices in Raleigh, NC.

A.4.2 Summary

The intention of Pepco's design criteria for its network systems is to be able to operate at system peak without overloading secondary cables, even with one feeder out of service. From the results of the ABB load flow analysis, the Georgetown East and North networks are not able to handle peak load conditions without overloading some secondary cables, even with all primary feeders in service. During a single contingency many secondary cables are severely overloaded as well as some network transformers. **This is the most significant result of the ABB analysis, because secondary cables have been implicated in a number of manhole events.** This finding also raises concerns about the performance of the remaining network systems in DC, which emphasizes the need to expedite the underground network modeling. Pepco has reinforced secondary cables in Georgetown based on this analysis to improve reliability until the Georgetown plan is implemented.

The 4 kV study analyzed performance of the Georgetown 4 kV system based on reliability indices and load flow analysis. Overall, the study found:

- The reliability indices (SAIDI, SAIFI) of the 4 kV radial distribution system in Georgetown reflect substandard performance. The 5-year record of outage statistics indicates significantly higher failure rates than experienced in new underground systems.
- Overloaded 4 kV cables under peak system load conditions.
- A primary feeder with a voltage drop in excess of 4%.

The study supports Pepco's decision to convert the 4 kV radial distribution system in the residential area of Georgetown adjacent to the network system to a 13 kV loop system.

A.4.3 Purpose of the Network System Evaluation

From the introduction to the ABB report (page 3):

> "The objectives of the evaluation were to:
>
> - Develop a computer model representative of the distribution system in the Georgetown area, and perform a loading and contingency evaluation of that system.
> - Use the results from the loading and contingency evaluation to identify critical equipment and potential weak spots in the distribution system.
> - Integrate the findings of this system analysis with conclusions of the condition assessment performed earlier, as well as other PEPCo knowledge, to create short-term and long-term recommendations for the system in the Georgetown area.
>
> The scope of the analysis was limited to the following:
>
> - Modeling and analysis of all 13.8 kV feeders from Substation #12 supplying the Georgetown area.
> - Modeling and analysis of the Georgetown distributed low-voltage grid (120/208V) supplied from Substation #12."

A.4.4 Summary of Results and Critique of the Network System Evaluation

As presented in the report, the work involved development of an analytical model of the Georgetown network systems using ABB software, and simulation of a number of load flow cases to investigate cable loading under system normal and contingency conditions. ABB's written interpretation and discussion of the results is brief if viewed as a freestanding study with carefully drawn conclusions. However, our interview of ABB consultants provided significant insight to their methodology and interpretation of study results. ABB's investigation provided Pepco with an analytical simulation of the Georgetown network system together with selected calculation results. Pepco has used the results to assess the condition of the Georgetown system. The value of the study lies in the calculation results themselves as graphically presented in the report. Moreover, since Pepco worked closely with ABB in developing and calibrating the models, Pepco gained knowledge of these analytical techniques that can be applied to the modeling of the other networks in DC.

The analytical model was based on the highest system load level Pepco experienced prior to date of the study. This occurred at midday on July 6, 1999. Measured values of primary feeder current for the four Georgetown networks were available for the peak hour. After developing the electrical interconnection model and individual loads, the analytical model was scaled to make feeder currents correspond to the measured loads. Within the scope of the study it does not appear that any extensive attempt was made to check the model against measured current in the secondary conductors. In several ways the ABB study is a work-in-progress rather than a finished product. This is discussed further below.

It was not possible for Stone and Webster to analyze the detailed data that ABB used to develop the network system electrical connections. ABB appears to have applied well known procedures for digital computer load flow simulations, which have been performed by the industry for nearly 40 years.

ABB presented their results in the form of drawings of the system configuration with cables operating within ratings shown in green and overloaded cables shown in red. Some significant observations from the cases presented are:

- Figure 1, page 7 shows overloaded secondary cables under system normal peak load conditions in the East Network. In other words, with all feeders in service some secondary cables are overloaded during system peak.
- Figure 5, page 11 shows overloaded secondary cables under system normal peak load conditions in the North Network.
- Additional overloaded secondary cables in the East Network are also shown

  with Feeder 15401 outage (Figure 8, page 15),

  with Feeder 15402 outage (Figure 10, page 17),

  with Feeder 15404 outage (Figure 14, page 21).
- Additional overloaded secondary cables in the North Network are also shown

  with Feeder 14556 outage (Figure 41, page 48),

  with Feeder 14559 outage (Figure 47, page 54).
- Figure 34, page 41, (and others) shows primary cable overloading in the West Network under single primary feeder outages.

The intention of Pepco's design criteria for its network systems is to be able to operate at system peak without overloading secondary cables, even with one feeder out of service. From the results of the ABB load flow analysis, the Georgetown East and North networks are not able to handle peak load conditions without overloading some secondary cables, even with all primary feeders in service. During a single contingency many secondary cables are severely overloaded as well as some network transformers. **This is the most significant result of the ABB analysis, because secondary cables have been implicated in a number of manhole events.** It also raises concerns about the performance of the remaining network systems in DC, which emphasizes the need to expedite the underground network modeling

The accuracy of the ABB analysis might be argued based on several considerations. For example, the model was checked on overall total primary feeder loading for each network. A more accurate check would be to use the individual feeder currents at the time of the overall peak load. Secondary current distribution could be verified by clamp-on ammeter measurements taken as part of the manhole inspections. Even considering the limitations on the accuracy of the model, there is no reason to suspect the overall observation that secondary cables are overloaded in Georgetown with one primary feeder outage and likely under system normal peak load conditions. Pepco has reinforced secondary cables in Georgetown based on this analysis to improve reliability until the Georgetown plan is implemented.

It will be necessary for Pepco to develop an analytical model for the network system as it will appear after completion of the Georgetown plan to assist in specifying the size and number of secondary cables. Pepco has purchased the EasyPower load flow software, which has the capability of performing the required analysis. Once the Georgetown plan has been completed, the analytical model should be calibrated by spot measurements of primary and secondary cable currents.

Identification of overloaded cables in the ABB report is an incentive for Pepco to proceed to the analysis of the other secondary networks in their system to try and identify other areas of overloads that could develop into fault conditions.

The manhole inspection program provides measurements of secondary cable currents at the time of that particular manhole inspection. While the use of these measurements is limited by normal load variation over time, availability of measured currents will be of benefit to engineers developing analytical models of the remaining Pepco networks.

A.4.5 4 kV System Load Flow and Reliability Analysis

The 4 kV study analyzed performance of the Georgetown 4 kV system based on reliability indices and load flow analysis. Overall, the study found:

- The reliability indices (SAIDI, SAIFI) of the 4 kV radial distribution system in Georgetown reflect substandard performance. The 5-year record of outage statistics indicates significantly higher failure rates than experienced in new underground systems.
- Overloaded 4 kV cables under peak system load conditions.
- A primary feeder with a voltage drop in excess of 4%.

Planned changes to the low voltage network system in Georgetown will impact the 4 kV radial distribution system because the two systems overlap in many manholes. The Georgetown plan will move some residential load off of the low voltage network system. This load if added to the 4 kV radial distribution system in Georgetown would only increase the stress on it. **The results of this study support Pepco's decision to convert the 4 kV radial distribution system in the residential area of Georgetown adjacent to the network system to a 13 kV loop system.**

Appendix A.5

A.5.1 Pepco's Original Priority Definitions - Manhole Reliability Inspection

Priority I: Immediate corrective action required within 6 months

- Cable smoking (CS)
- Joint smoking (JM)
- Insulation damage (ID)
- Overloading > 120% in summer
- Overheating > 175º F

Assess cable leak (CL), joint swelling (JS), burnout visible (BV) & joint leaking (JL) condition information to determine Priority I or II; assess deformed joint (DJ) condition information to determine Priority I, II or III

Priority II: Corrective action required within 12 months of inspection

- Braided cable (BC)
- Overloading: 100 % > load > 120%
- Overheating: 150º F > measured max. temp > 200º F

Assess neutral corroded (NC), deformed joint (DJ) & upright support (US) condition information to determine Priority II or III.

Priority III: Corrective action required within 18 months of inspection

- Deformed joint (DJ) condition not warranting priority I or II status
- All remaining reportable cable or joint conditions
- Overheating: 150º F > measured max. temp > 175º F

Reportable Condition Not Prioritized:

- Water
- Debris
- Asbestos
- Minor-rereacking
- Cables not tied.

D.C. Case No. 991
S&W D.R. No. 3, Q.1
Response No. 1
Attachment A

A.5.2 Pepco's Revised Priority Definitions - Manhole Reliability Inspection

Revision: 10-19-01

Priority 0 (Urgent): Corrective action required Immediately or within 5 days

Perform repairs immediately or within 5 days where the identified deficiencies have caused outages, or present imminent risk of causing outages, or serious safety or environmental risk.

- Cable smoking (CS)
- Joint smoking (JM)
- Insulation damage (ID) – Bare Conductor
- Burnout Visible
- Loading greater than 140% of rating
- Heating greater than 200º F
- Elevated Gas Readings Reported to Gas Company

Priority 1: Corrective action required within 6 months of inspection

- Insulation damage (ID)
- Loading between 120% and 140% of rating
- Heating between 175º F and 200º F
- Open Limiters

Assess cable leak (CL), joint swelling (JS), joint leaking (JL), deformed joint (DJ) & neutral corroded (NC) condition information to determine Priority 1 or 2.

Priority 2: Corrective action required within 12 months of inspection

- Braided cable (BC)
- Loading between 100 % and 120% of rating
- Heating between 150º F and 175º F

Assess upright support (US) condition information to determine Priority 2 or 3.

Priority 3: Corrective action required within 18 months of inspection

- Re-Racking
- Cables not secured
- Structural Repairs
- Retag Feeders and Buses
- All remaining Reportable Non-electrical conditions

Non-Reportable Referrals:

- Water
- Debris
- Cracked Wall
- Other

D.C. Case No. 991
S&W D.R. No. 3, Q.1
Update to Response No. 1
Attachment A

APPENDIX B

ANALYSIS OF REPORTS & FILINGS PREPARED BY OTHER PARTIES

Contents

Appendix B.1

REVIEW OF

Downes Associates Report

Dated October 31, 2000

Prepared by Stone & Webster Consultants

For the Public Service Commission of the District of Columbia

Submitted September 27, 2001

B.1.1 Purpose of This Document

At the request of the Public Service Commission of the District of Columbia, Stone & Webster reviewed the document "Report to the District of Columbia Public Service Commission Formal Case 991 in the Matter of the Investigation into Explosions Occurring in or Around the Underground Distributions Systems of the Potomac Electric Power Company," submitted by Downes Associates, Inc. on behalf of the Office of the Peoples Council of the District of Columbia.

B.1.2 Summary

The Downes report contains several reasonably valid conclusions and recommendations. As the report is about ten months old, it appears that Pepco has taken action on many of the recommendations made by Downes. However, we disagree with Downes' assertion that age is the primary causative factor and GIS the primary solution to failures of the underground system.

On pages 26 to 29, the section "Long-Term Solutions to Problems" relies heavily on the premise that age is the primary factor in failures, and that a Geographic Information System (GIS) is the solution. We do not support these assertions. Instead, we believe loading is the most significant factor. Therefore, Pepco's immediate need is an electrical analytical model of the underground distribution system, especially the secondary networks, to determine loading patterns both with all circuits in service and during single contingencies. Such models would identify locations of excessive electrical loading and potential cable failures. GIS does not perform the analytical electrical system modeling and simulation that is crucial for predicting overloads and planning system improvements. In order to accomplish this, Pepco has acquired EasyPower, which is a load flow program.

Downes also criticizes Pepco's failure analysis. Pepco does not send a forensic investigator to every failure event. Regarding failure analysis, Pepco issued the document "Investigating Equipment Failure" on January 24, 2001, marked "pending approval." Completion and implementation of the procedures contained in that document would meet the requirements of the Downes first recommendation.

B.1.3 Comments on the Downes Recommendations

Pepco has already addressed some of the recommendations in the Downes report dated October 31, 2000. The comments below refer to the number of the Downes recommendations found on pages 31-33.

B.1.3.1 Downes Recommendation 1

This recommendation regards failure analysis. Pepco issued the document "Investigating Equipment Failure" on January 24, 2001, marked "pending approval." Completion and implementation of the procedures in this document would satisfy the intent of this recommendation.

B.1.3.2 Downes Recommendation 2 and 3

Pepco is continuing its reliability inspection reporting and its manhole inspection program, similar to these recommendations by Downes.

B.1.3.3 Downes Recommendation 4

Some of the "data gaps" referenced in this recommendation will be filled by the manhole inspection program, such as determining operating temperatures of cables. However, other information such as cable and splice age is difficult to obtain. . We believe the most important gap in data relating to Pepco's underground distribution system is knowledge of electrical loadings, which can only be determined by load flow studies under system normal and contingency conditions supported by field measurements. Focusing and expediting effort on analyzing cable loads would be far more valuable than trying to assess age.

B.1.3.4 Downes Recommendation 5

This is part of the continuing assertion in the Downes report that age is the major issue. We maintain that loading is the major issue, not age alone. Age can be a primary factor for specific equipment such as braided cable, but it must be ascertained on a case-by-case basis. For example, Pepco automatically replaces braided secondary cable when found. The braided secondary cable has deteriorated over time and is considered as old equipment. PILC, on the other hand, is a hermetically sealed system that takes indeterminate decades to deteriorate under normal operating conditions. Therefore, even if a braided cable and a PILC cable are the same age, only the braided cable will be considered as old. The Georgetown Project will replace the terra cotta (clay pottery) duct banks because many of them are now damaged. Although terra cotta does not deteriorate over time, the brittle nature of this material often results in breakage under mechanical forces. Thus, terra cotta duct has been declared obsolete because other materials (e.g., fiberglass, PVC, PE, etc.) are stronger.

B.1.3.5 Downes Recommendation 6

This overstates the advantages of GIS. On page 32, "Finally, circuit loading data from….could then be correlated to network loading and age of equipment." Loading on the secondary cable circuits (mains) of the low-voltage network is not available through SCADA data, contrary to what is stated on page 32. There is no instrumentation measuring loads on the secondary cable circuits (mains), and installation of such instrumentation would be prohibitively expensive. Low-voltage cable loads are presently being measured by use of clamp-on ammeters during manhole inspections, and are only valid for the conditions specific to the moment the measurement is taken. Pepco is presently evaluating the use of microprocessor relays for network protectors. These relays perform the normal control functions, and in conjunction with a communications system, have the capability to detect overloads on network transformers and sound an alarm at a field office. However, this system does not monitor the loads in secondary cables. This is why Stone and Webster is recommending that first priority be given to analytical load flow modeling of the secondary networks.

B.1.4 Geographical Information System and Load Modeling

B.1.4.1 Page 28

Downes states: "With the development during the last few years of powerful analytical software programs for the utility industry, utility computer systems can now be employed to develop just such preemptive planning thus affording the utilities mitigation options previously unattainable." "Such software solutions are referred to as Geographical Information Systems ("GIS")." On page 29 Downes states: "Yet, the power of GIS system properly populated by comprehensive data bases would probably be the single most valuable tool Pepco could employ to understand the pattern of system failures and to develop effective mitigation and remediation strategies." These statements may indicate confusion regarding what GIS can and cannot do. Note that a GIS is primarily a means for tracking physical equipment installed on the system.

Stone & Webster believes the number one priority should be to develop the electrical load flow models from which the loads on the distribution system components can be determined with all circuits in service and during single contingencies. Such models would identify locations of excessive electrical loading and potential cable failures. GIS is not the analytical tool required to perform the electrical studies needed to detect system overloads.

B.1.4.2 Page 26

Downes says that an accurate electrical system model using a load flow computer program should enable Pepco to identify components that will be overloaded. GIS does not handle the analytical electrical system models that are crucial for predicting overloads and planning system improvements. Electrical models for performing electrical analyses of the loads on circuits are simulated by load flow programs. Pepco plans to use EasyPower, which is a load flow program.

System modeling is briefly discussed on page 26, but misses the point of how crucial analytical electrical models are to assessing the loading of individual cables, especially the secondary networks. Development of an analytical model of a secondary network includes careful analysis of amount and geographical location of load so the load can be applied at the proper electrical location within the network. Even knowing the location of loads, a computer evaluation is necessary to determine the loading on individual cables because it is not possible to predict by inspection how the load divides among the individual cables.

From the physical equipment location standpoint (GIS's purpose), Pepco's distribution systems have been evolving over the last 100 years, so one should not be very critical for Pepco not having its system recorded with GIS which only became available in the last few years. A tremendous amount of time and resources are required to input the data of a large system into a GIS database. Any system that will electronically link energy databases, GIS databases, CAD databases, with the load flow program will help in reducing costs and eliminating errors. However, creating these databases and linking them to the load flow program, EasyPower, will require a significant investment. It appears that Pepco has programs in place that will ultimately provide for this. However, it will take ongoing efforts and resources to keep it up-to-date.

B.1.4.3 Page 2

Downes states: "Pepco's implementation of an advanced geographical information system should be accelerated so that it can be used to track, predict, and prevent future manhole failures." We don't think there is anything that can be done that will prevent all failures in manholes in the future. Perhaps the data available from such systems will help in reducing the number of failures, but certainly will not prevent all such failures.

B.1.5 Failure Analysis

B.1.5.1 Page 12

Downes states: "Secondary cable faults apparently resulted from cable connector failures, splice failures, and basic cable insulation breakdowns." On pages 15 and 16 Downes criticized Pepco for not preserving failed equipment and performing failure analysis.

Had Pepco conducted more failure analyses, more insight into common failure causes may have been gained, particularly in PILC primary cable splices where many failures occurred. Indeed, Pepco does not send a forensic investigator to every failure event, which may occur in the middle of the night. The failures of August 8 and 9, 2001 occurred at 10:20 PM and 3:19 AM, respectively. Pepco has said that each manhole event is examined to determine what happened, but most often they don't conduct a formal investigation into the root cause of the failure.

A forensic investigator gathers data for the failure investigation, takes measurements, documents the site, and carefully removes the failed components. Such activities can delay restoration of service, particularly in the radial systems. The need to restore service to customers as quickly as possible places a practical limit on the amount of post-mortem analysis possible. When a circuit fails, the repair crew is pressed to find the failure, repair it, and return the feeder to service in as short a time as possible. Repair crews may inadvertently destroy evidence in the process of removing, repairing and replacing failed equipment to restore service in the least possible time. Moreover, the point of failure may be destroyed by the event itself.

B.1.5.2 Page 19

Downes states, "Based on the data provided, it is the opinion of Downes Associates that a specified and related common cause (or causes) of the recent failures experienced by Pepco will be difficult to discover without better organized data and more advanced tools for analyzing such data." Stone & Webster agrees with this and that Pepco should enhance their failure analysis, in particular for primary splices and low-voltage cable failures.

Regarding failure analysis, Pepco issued the document "Investigating Equipment Failure" on January 24, 2001, marked "pending approval." Completion and implementation of the procedures contained in this document would meet the intent of the first Downes recommendation.

B.1.6 Equipment Age

There seems to be a premise in the Downes report that equipment **age** is the major factor involved in equipment failures.

B.1.6.1 Page 2 - Recommendation 5

Downes alleges that a significant cause of the failures in cables and splices is due to the age of the equipment.

We don't argue the validity of the typical bathtub failure curve (shown below) that might apply to cables, transformers, and perhaps splices. However, we question the **significance of age solely** on failure rates for cables, splices, and transformers, and at what point in time the curves start to turn up steeply. A more important measure of when to change out a cable, transformer, or a piece of equipment is the failure rate or performance. Figure B.1-1 illustrates how loading might affect the life of an underground distribution system.

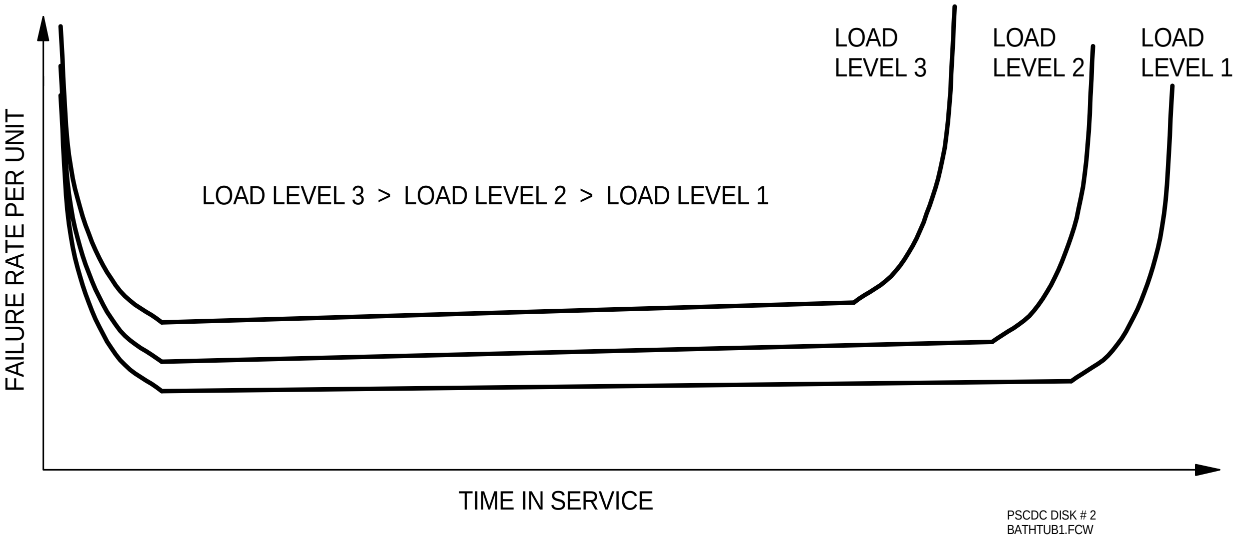


Figure B.1-1 Bathtub Failure Curves for System Components

In Figure B.1-1, the point at which the failure rate increases rapidly is not known, but in PILC cables and transformers, and perhaps in splices, the turn-up will occur earlier as the loading levels are raised. Other factors, such as submersion in water and chemicals, may affect the point where the turn up occurs. Transformer standards, as well as AEIC standards for paper cables show that there is a loss of normal life expectancy when the operating temperatures exceed a certain value. In transformers, as the cellulose paper degrades from high temperatures, electrical and mechanical strength is lost. Perhaps they can withstand the stresses of normal currents and voltages, but faults or transient overvoltages are more likely to initiate a breakdown.

B.1.6.2 Page 10

Downes quotes from Pepco’s 1997 plan for “L” Street Substation No. 21:“L Street Sub 21 is the oldest 13.8 kV substation on the Pepco system. Two of the four 34.5 /13.8 kV 20 MVA transformers were installed in 1940 and the other two in 1941 and 1942. Past Studies by Civil and Substation Engineering indicated that no spare 20 MVA transformers are available. Also, switchgear is beyond its expected life and no replacement parts are available.” We interpret this to mean that the concern with the transformers is the lack of a spare unit should one of the 20 MVA units fail, not the transformer's age. However, Pepco’s standard transformer size is 50 MVA and they probably have a spare 50 MVA unit or mobile unit. In any case, transformer failures have not been a significant cause of manhole events in DC, which renders this discussion of transformers somewhat irrelevant to the manhole event issue.

Similarly, the main concern with the old switchgear is the lack of spare parts available for repairs. Some utilities operating 60-plus-year-old network protectors are concerned not so much with the age, but whether they can purchase spare parts when required (motors, arcing contacts, shunt trip, etc.). A common practice in the industry (and military) is to salvage spare parts from units retired at other locations. On page 11 Downes states: “Assuming that records are complete, one could use the maintenance record of each individual transformer to determine the age of facilities which serve areas that have been subjected to manhole incidents in the past few months.” A transformer's age does not accurately indicate the age of the cables in the area. The transformers at opposite ends of secondary mains are often installed years apart. Transformers are sometimes replaced by a larger size. Also, the secondary mains between two transformers may consist of multiple sets of cables installed years apart. Since about 1993, Pepco replaces a network transformer by using an elbow connector on a short length of solid dielectric cable spliced to the existing PILC cable. The transformer's age does not indicate of the age of the PILC cable.

B.1.6.3 Page 7

Downes states while discussing Pepco plat plan drawings: “to determine if the necessary information was readily available for determining either a cause of the recent cable and splice failures or a pattern to the failures. Of particular interest was any information on the plats and drawings that would indicate the age….” There may indeed be common mode problems with certain types of equipment of certain ages, but other factors beside age may be more important in an underground electric distribution system. New cables may be overloaded and fail. New secondary cables could be installed and quickly become overloaded if the load growth in the local area is significantly greater than the planners anticipated. On the other hand, old PILC cable that has not been overloaded or externally damaged may continue to have satisfactory reliability for indeterminate years.

Installed equipment drawings by their very nature do not contain loading information crucial to the design of the system or for diagnosing failures. They also do not include the record of operating conditions that have to be reviewed in a failure investigation. While age is a consideration, we believe the primary factor is system loading related to the rated capability of installed equipment.

B.1.6.4 Page 18

Downes states: “OPC requested information concerning Pepco’s records regarding the age of primary and secondary underground cable circuits in the Company’s distribution system. In its response dated May 21, 2000, Pepco responded that records designating age for circuits were not available.” Also on page 32 Downes states in part: “an excellent correlation exists to link the installed age of most of Pepco’s cable system to the age of the transformers in the various networks.” Since a network primary feeder consists of many segments of cable between manholes, all of the segments may not have been installed at the same time. Further, the distribution system is very dynamic, i.e., certain cable segments may have been associated with different circuits over time. Moreover, certain segments may have been fed from different substations as load was transferred over time. Given such circumstances, how would one calculate the age of a network primary feeder circuit? Is it the age of the oldest cable segment? Is it the age of the newest cable segment? Is it the average age of the cable segments? Is it the length-weighted age of all cable segments? We seriously doubt if there is any utility that could give an accurate figure for the age of a primary feeder circuit, if for no other reason than there is considerable ambiguity in the meaning of circuit age. We also doubt that many maintain a database indicating the age of cable segments between manholes.

Stone & Webster agrees with Pepco’s approach: “Plans for replacement or enhancement of equipment are developed based on the expected loading and the historical reliability performance of the particular equipment.”

B.1.6.5 Page 20

Downes states: “ The remaining common attribute of the failures that may link them as to cause is that they have all occurred on a system which, on the whole, is aging, with specific materials and equipment which may have already exceeded their expected useful life span.” Downes cannot logically reach this conclusion because the age of the failed equipment is not known in many cases. In the first paragraph, Downes basis for its conclusion is essentially: "Since Pepco has not pinpointed the causes to anything else, the only thing left is age."

The discussion about old substation transformers and circuit breakers is like saying you have old apples, therefore your oranges must be old too. Old age is a relative term. Age in and of itself does not matter; but strength does. You can only conclude that old is weak if strength can be shown to be a function of age. An analogy from a more common form of material may help to illustrate the point. Is a new 2x4 pine stud stronger than a 50-year-old oak stud?

B.1.6.6 Page 20 (Continued)

Downes quotes an EPRI report: “Manholes, vaults, and service boxes are occasionally subject to smokers, fires, and explosions. As the infrastructure of an underground distribution system ages, the number of these events will likely increase.” We suspect that the above statement made in the EPRI report is the opinion of the report's author, but that the author has no data to support this opinion.

B.1.6.7 Page 21

Downes states: "all manmade materials will undergo molecular and composite degradation over time. This is a basic law of thermodynamics." We disagree since thermodynamics as a science treats the direction of processes, but says nothing about the rates at which the processes take place. Glass is a manmade material that lasts centuries or millennia. The fact that materials degrade is not by itself an indication of the time frame to failure. Degradation rates are a function of more variables than time alone. Temperature is a significant factor in aging, especially with cellulose based materials.

B.1.6.8 Page 23

Downes states: "A normal practice throughout the utility industry is to increase the scrutiny given to operating systems when they reach 20 to 25 years of age." We do not think that is a correct statement. A distribution transformer on a pole that was installed in 1950 receives no more scrutiny than one installed in 1995. Only if it fails and blows a fuse does it get more scrutiny. The same applies in the distribution system to primary and secondary cables.

B.1.6.9 Page 23 (Continued)

Accounting practices for property depreciation are not a metric for insulation degradation. Life for accounting purposes is not based on actual anticipated physical life of the equipment in question.

B.1.7 Other Comments

B.1.7.1 Page 3

Downes states: "Although Pepco may characterize the violent explosions in electrical distribution manholes as "relatively rare", they are nevertheless too frequent when viewed in light of system reliability and public safety concerns." The Pepco system is designed to maintain service on a network system with one feeder out of service. In most cases, faults on feeders to the low-voltage secondary networks may displace a cover and make some smoke, but the impact on reliability is minimal. For example, the reports for August 8 and 9, 2001, which involved faults on primary feeders to the LV networks, resulted in no customer outages.

B.1.7.2 Page 3 (Item # 2)

Downes states: "Have weaknesses in Pepco's business practices, such as internal record keeping or engineering standards contributed to the recent failures, or could improvements in those systems help to minimize the failures." We are of the opinion that the engineering standards used by Pepco are sound and are not the cause of the failures.

Appendix B.2

REVIEW OF

Office of the Peoples Council's

Comments in Response to Order No. 12036

Prepared by Stone & Webster Consultants

For the Public Service Commission of the District of Columbia

Submitted September 27, 2001

B.2.1 Purpose of This Document

At the request of the Public Service Commission of the District of Columbia, Stone & Webster reviewed the document "Office of the Peoples Council's Comments in Response to Order No. 12036." Our comments are directed to Attachment A, which is a report prepared by Downes Associates, Inc. dated May 16, 2001, Engineering review of the "Final Report on Manhole Event Tests for Pepco at Lenox."

B.2.2 Summary

Downes Associates discredits the EPRI work wherever possible. Five of their observations are discussed below.

B.2.3 Downes Observation 1:

Downes claims that the ability of slotted covers to vent combustible gases is intuitively plausible, but has not been demonstrated by EPRI's tests.

Pepco has installed thousands of slotted manhole covers since release of the EPRI report. The list of manhole incidents, January 2001 to date, has several cases of solid covers displacement, with just one instance of a slotted cover displacement. The slotted cover displacement occurred during restoration, not from the initial fault. This limited history supports the premise that use of slotted covers will reduce the number of manhole cover displacements.

Slotted covers may prevent the build-up of gas and resultant explosion. Regarding dispersal of combustible gases: smoke has been observed rising from slotted covers during manhole events that did not result in an explosion. Fire fighters know that a build-up of smoke is a potentially explosive condition and respond by ventilating a fire scene. Dispersal of smoke with slotted covers is indicative that combustible material is being vented. The concept that slotted covers help to remove combustible gases is reasonable, and nothing in the EPRI tests contradicts that impression.

It appears that EPRI did not attempt a quantitative analysis of gases in the manhole before each test. Verbal indications in discussion indicate they had difficulty obtaining ignition, which would support the premise that gases were being dispersed. It is hard to separate from the test results whether observed differences in movement between manhole cover types were related to gas dispersal or pressure relief.

B.2.4 Downes Observation 2:

Downes claims "The test results indicate that vented covers, especially slotted covers, are ineffective in substantially reducing the movement of manhole covers during an explosion."

The comparison of cases in Tables 7-2 and 7-3 indicate one comparison (4% gas UL mixture) where the slotted cover rose 6 to 8 inches and the solid cover rose 4 inches. The solid cover case has a footnote "The cover came up, released pressure, went down into the frame and then rocked releasing pressure again." It would be reasonable to deduce from this case that the two covers moved about the same. All the other comparisons showed less movement for the slotted cover than for the solid cover. The worst case (6% gas UL mixture which the report authors considered to represent the worst possible case) had the slotted cover rising 9½ feet and the solid cover rising 10½ feet, not a large difference.

These cases in general show that slotted covers rise less than solid covers, and could provide some benefit in all but the worst cases.

B.2.5 Downes Observation 3:

Downes claims: "In all tests when tethers were used, manhole covers were restrained. No measurements were made of the possible damage caused by tethered covers."

Compare tests 2-6 and 2-7 for slotted covers without and with tethers and 5% UL gas mixture. Without a tether the cover rose 1 foot 6.5 inches. With a tether the cover lifted 4 feet 2.5 inches to the top edge. What this means is without a tether the lid rose flat and came back down again. With the tether the lid flipped over, with the top rising over 4 feet. The situation with the tether is potentially more dangerous than without the tether because without the tether the effect of the movement is directly over the cover, but with the tether the cover can move into space adjacent to the hole.

On page 9 Downes claims "The only way to achieve this result (given the maximum explosive power assumed in the EPRI tests) is to use a vented cover and bolt it to the manhole frame." (Emphasis Downes's) Bolting the cover to the manhole is not at all acceptable, because several tests at Lenox resulted in movement of the roof slab and/or damage to the vault. An explosion sufficiently serious to raise a slotted cover could do additional damage if the cover were not free to lift and relieve the pressure. Movement of a section of sidewalk or street beyond the cover itself is unacceptable.

B.2.6 Downes Observation 4:

Downes claims: “The effect of street debris is not adequately addressed in either report.”

Debris entering the manhole is an important consideration, and one that led to Pepco installing slotted covers in sidewalks and crosswalks but not in streets. We observed a slotted manhole cover in a sidewalk under a tree where a number of leaves have already entered the manhole. This is an area that will have to be monitored by Pepco.

Downes says the grated manhole covers were rejected because they were more likely to clog with debris than the slotted covers. Page 8-1 of the EPRI report states “During the tests the linemen noted that it is difficult to remove the galvanized steel cover from the frame because of its depth and the sharp edges.” The grated covers have other disadvantages besides debris, and so were not selected for installation.

B.2.7 Downes Observation 5:

Downes claims: “There are a number of details in the report that are unclear.”

The section on a “baffle” raises an interesting question, but not one that would change interpretation of the report.

The discussion of discharged hot gases refers to measurements that do not appear to have been part of the test protocol, but in retrospect would have been useful data. Perhaps the videotape of the tests would shed some light and help answer the concern expressed by Downes (p12) about the comparison of hot gases for the different types of covers.

Granted, the EPRI report could have been more thorough, especially in discussion of observations and conclusions. The report led Pepco to try installation of slotted covers, and is now accumulating experience that alone will determine their effectiveness.

APPENDIX C

STONE & WEBSTER'S DATA REQUESTS TO PEPCO

C.1 Stone & Webster Data Request No. 1

Date: May 24 , 2001

1. Organization charts and discussion of the distribution, transmission, engineering, planning, construction, and/or any other functional areas relevant to our assessment

2. A description of the Pepco electrical system

3. A copy of all ABB, EPRI, other consultants, and Pepco reports relevant to our assessment and to Pepco's proposed modernization plans and projects for the Georgetown area

4. A copy of the proposed modernization plan

5. The names, titles, and phone numbers of all ABB, EPRI, and other consultants to Pepco who have studied, analyzed, and/or prepared reports relevant to our assessment

6. A copy of Pepco's maintenance, testing, and inspection policies, practices, and schedules for the subject manhole facilities

7. A copy of Pepco's engineering design and construction standards and materials for the subject manhole facilities

C.2 Stone & Webster Data Request No. 2

Date: June 1, 2001

1. Five (5) street maps of the Georgetown area showing the locations of manhole incidents for each of the years 1997, 1998, 1999, 2000, 2001 to date
2. Five (5) street maps of DC showing the locations of manhole incidents for each of the years 1997, 1998, 1999, 2000, 2001 to date
3. Five (5) street maps of the Georgetown area showing the locations of primary faults on the underground system for each of the years 1997, 1998, 1999, 2000, 2001 to date
4. Five (5) street maps of DC showing the locations of primary faults on the underground system for each of the years 1997, 1998, 1999, 2000, 2001 to date
5. Street map showing the areas of DC served by Pepco's underground distribution system
6. The manhole inspection sheet that lists what is actually being looked at during each manhole inspection
7. From the recent PHB Hagler Bailly Benchmark Survey T&D: results including reliability indices, O&M cost comparisons, operational comparisons, etc.
8. EPRI TR-106394, "Evaluation of Gases Generated by Heating and Burning of Cables" April 1996 [Ref. 1 to EPRI WO-049296 Final report]
9. EPRI TR-109741, "Manhole and Service Box explosion Suppression and Mitigation" January 1998 [Ref. 2 to EPRI WO-049296 Final report]

C.3 Stone & Webster Data Request No. 3

Date: July 6, 2001

1. The manhole projects prioritization scheme.
2. The current backlog of manhole projects by priority.
3. Underground line, maintenance, and conduit staffing levels located in DC, by classification for years-end 1990, 1995, 2000, and current.
4. Power Point or other presentations given to Productivity Improvement Working Group regarding power delivery staffing, and system reliability.
5. Description of the four alternative plans considered for the Georgetown modernization and the decision process and factors leading to the adopted plan.
6. Plans and timetables for implementation of GIS, OMS, mobile unit dispatch, and MAXIMO. Include current status and expected benefits of each (e.g., response time, reliability, cost savings, etc.)
7. Written description of the manhole inspection, data collection and recording processes including quality control of data input, random manhole reinspections, pick lists, and plans for the MicroTrax project.
8. Training courses given to UG personnel in years 2000 and 2001. Include course titles, length, number of attendees, etc.
9. Composition, charter, and results of joint management/bargaining unit committee for training of UG line personnel.
10. Provide the training plan for the 33 new hires into the UG department.
11. Copy of the Power Distribution Group - Performance Measures 2001, dated 5/8/01.
12. Copy of the Power Distribution Group - Four Year Budget Analysis (1998-2001).
13. Copy of Customer Care - Historical Annual Distribution System Construction Spending (1995-Budget 2001).
14. Copy of the DC UG maintenance budget versus actual expenditures for the years 1995 to date.
15. Copy of the 2001 Customer Service and Power Distribution Construction Budget including project detail information sheets.
16. All internal reports on manhole incidents for the years 2000 and 2001 to date, both within and outside Georgetown.
17. Plats of all manholes examined during the manhole inspection tour of June 19 and 20. Please submit in electric format readable by Word or 8.5" x 11" paper format (similar to what is provided to the crews).
18. Procedure "for collection of data and materials for selected equipment failures" referenced in Comments to Recommendation No. 1 in Pepco's appendix "Supplemental Report to

Comments Filed on May 15, 2000, Evaluating Pepco's Reports About the Cause or Causes of the Manhole Explosions and in Response to the June 8, 2000, Staff Report".

19. Provide the SAIDI, SAIFI, and CAIDI indices for the DC service territory for the five years 1996 - 2000 and 2001 to date.

C.4 Stone & Webster Data Request No.4

Date: July 9 , 2001

Basis for Request:

Many of the type “E” events in year 2000 were “Cable Joint” or “Branch Joint” failures. Devices are available which can limit the magnitude as well as the duration of the fault current flow from the substation to faults on network primary feeders. Whether the devices will be effective in reducing or preventing “E” type failures can not be stated at this time. However, knowledge of the available fault currents and clearing times for faults on the substation bus and network feeders will yield insight into whether the devices may be effective.

For each substation supplying 13 kV network feeders, provide the following information:

1. The current available for the three-phase fault on the bus to which the network primary feeders are connected. Provide the rms value of the symmetrical component, and the approximate X to R ratio of the positive-sequence impedance.
2. The current available for the single line-to-ground fault on the bus to which the network primary feeders are connected. Provide the rms value of the symmetrical component of the single line-to-ground fault current, as well as the X to R ratio ($(2*X_1 + X_0)/ (2*R_1 + R_0)$).
3. For a three-phase fault on the feeder side of breakers in the substation supplying the network feeders, the total time in cycles for the feeder breaker to interrupt the fault current from the substation end (relay time and breaker interrupting time).
4. For a single line-to-ground fault on the feeder side of the breakers in the substation supplying the network feeders, the total time in cycles for the feeder breaker to interrupt the fault current from the substation end (relay time and breaker interrupting time).

Note: This request assumes that the substation supplying the network primary feeders has a bus arrangement where the available fault current is the same on the feeder side of each feeder breaker.

C.5 Stone & Webster Data Request No. 5

Date: July 13 , 2001

1. Provide the range in primary amperes for the pickup settings of the phase instantaneous current relays used on dedicated network feeders supplied from 13 kV stations in the Pepco systems in the DC area.
2. Provide the range in primary amperes for the settings of the ground instantaneous current relays used on dedicated network feeders supplied from 13 kV stations in the Pepco systems in the DC area.

   Note: Dedicated network feeders are those primary cable circuits supplying just Pepco network transformers with delta connected primary windings.
3. For government 13 kV primary feeders, are phase instantaneous current relays applied at the station? If yes, provide the range in primary amperes for the pickup settings of the phase instantaneous current relays.
4. For distribution 13 kV primary feeders, are phase instantaneous current relays applied at the station? If yes, provide the range in primary amperes for the pickup settings of the phase instantaneous current relays.
5. Provide a narative or a description of the procedures, methodologies, or calculations that are presently employed by Pepco when designing a secondary network system, and when evaluating the performance of an existing secondary network system, to determine if the components of the system will be loaded above their rating under both normal conditions and single contingency conditions. For request 5:
   a) Normal conditions are when all primary feeders of the network are in service and all network transformers on each feeder are connected to the low-voltage network with their associated network protector, excluding the situation where a protector may be out of service for maintenance, or open due to light loading.
   b) A single-contingency condition is when any one primary feeder of a given network is out of service such that all network transformers on the feeder can not supply power to the secondary network. With one primary feeder out of service, the remaining primary feeders and the associated network transformers and protectors must supply the peak load of the network.
   c) The components of interest are the primary feeder cables, the network transformers, and the street mains (sometimes called secondary mains or bus tie circuits).
6. Provide a copy of any standards or design guides describing the methodology for selecting the size of the street mains (number of sets of cable and the size of the cable) in the low-voltage network systems.
7. Provide a copy of any standards or guides defining the frequency at which the loading of the components in an existing secondary network system are determined to ascertain the system performance under both normal and contingency conditions.

C.6 Stone & Webster Data Request No. 6

Date: July 26, 2001

1. A DC map where the manholes visited by Stone & Webster is plotted. Please use different nomenclature for manholes and transformer vaults.
2. List of all of the network systems within DC - mark on DC map if possible.
3. Please provide the detailed series and time schedule of job experience training, job progression, testing, skills acquisition and demonstration, and certification process required to become a journeyman splicer. After attainment, what continuous education, refresher training, skills demonstration, or recertification requirements exist?
4. On an annual basis, please estimate the range (i.e., minimum to maximum) and average number of splices made by a certified splicer.

C.7 Stone & Webster Data Request No. 7

Date: August 15, 2001

From August 7 through 14, Pepco's underground distribution system in DC experienced a number of equipment failures, including a number of manhole events. Please respond to the following set of question with two lists:

List A - Manhole events

List B - Equipment failures without manhole events

1. Where did it occur (manhole by grid number and street location, and sidewalk vs street location, and substation/feeder, failure date & time)?
2. What is the approximate physical dimension of the vault?
3. What type of manhole covers, solid or slotted?
4. What was the manhole cover event type (List A)?
5. What type of equipment was in the vault, (cable type, voltage, radial/network, transformers, etc.)?
6. What type of equipment failed?
7. What was the reason(s) for the failures?
8. When had the manhole last been inspected?
9. What were the findings during inspection?
10. Had repairs been made, or scheduled but not repaired?
11. Has the peak load on the subject equipment been determined through calculation, measurement or both?
12. What were the findings with regard to peak loads on the subject equipment?
13. Was the equipment operating under a contingency (another circuit out)?
14. Submit any failure investigating reports prepared on the events.

C.8 Stone & Webster Data Request No. 8

Date: September 7, 2001

Of 56 manhole events in Washington, DC, 15 occurred in manholes that had been inspected.

1. The manhole inspection sheets of the 15 inspected manholes where events occurred.
2. The event reports from the 15 manholes.
3. The failure investigation reports for the 15 events.

APPENDIX D

STONE & WEBSTER'S MONTHLY REPORTS TO THE DCPSC

D.1 Pepco Assessment Monthly Report - May and June 2001

Stone & Webster initiated the subject project with a data request to Pepco on May 24, and kickoff meetings with the DCPSC and Pepco on May 30 and 31, at which time Pepco responded to our initial data request. During the month of June, the following project activities were performed:

- Initiated review of Pepco data responses
- Submitted and received responses to second data request
- Developed criteria for selection of manholes to be inspected
- Developed checklist for recording manhole inspection data
- Held a project team meeting with Pepco (June 18) to provide more detailed technical information and Q&A regarding the underground electric distribution system
- Performed inspections of 13 manholes in Georgetown and 5 manholes in other areas of DC (week of June 18)
- Inspected Substation 12 which supplies Georgetown, Substation 7 near the Benning Service Center, and Substation 10 near manholes inspected along 14th Street (week of June 18)
- Inspected facilities at the Benning Service Center including: (week of June 18)
  - Manhole inspection office with procedures, tracking records, and lists of items requiring attention
  - Transformer shop where failure analysis is performed on cables and transformers
  - Bins of failed cables from recent Georgetown event
- Interviewed six members of Pepco power delivery management (week of June 18):
  - W. Sim, Sr. VP, Power Delivery
  - W. Gausman, Dir, Asset Management
  - W. Sigafoose, Mgr., Benning Service Center
  - C. Knapp, Mgr., Reliability Services
  - M. Weiss, Mgr., Distribution Support Services
  - J. Healy, Mgr., Business Performance
- Met with DCPSC staff to discuss initial observations and submit work plan (June 21) Initiated plans for second field visitation of Pepco under ground facilities (scheduled for week of July 9)
- Requested project team meeting with Pepco engineering department and others to discuss maintenance and construction practices, engineering and design practices, material standards and manufacturer approvals, system relay and protection, the Georgetown modernization

plan, and the collection and analysis of manhole inspection data (scheduled for week of July 9).

With regard to our June 18 and 19 field inspection of manholes, the following observations are note worthy:

- two slightly imploded lead splices were found
- an odor similar to burning insulation was detected at a substation, called in, and quickly responded to by a Pepco crew
- manholes in Georgetown were generally smaller, more crowded, and found to contain older style equipment than those outside of Georgetown.
- close spacing between primary and secondary cables was found in manholes in Georgetown
- newer materials and methods such as elbow connectors were found outside of Georgetown
- debris was found on the floors of manholes with slotted covers
- a generally high quality of workmanship was observed both inside and outside of the Georgetown area.

With regard to the management interviews of June 18 and 19, we note the following:

1. The Reliability Services department was created in August 2000 to focus on outages and equipment failures, tracking and trending reliability indices, analyzing and prioritizing worst performing feeders, failure analysis, standards for equipment and construction, new product evaluation, and related regulatory compliance. The department is headed by a manager with a staff of 20.
2. Pepco is in the first phase of a GIS implementation project. This phase is the development of all feeder maps in GIS format with expected completion by year-end. The next phase will take about 2 years to convert approximately 1500-2000 plats that are currently in electronic format and show the location of facilities such as manholes, poles and wires, and conduit. Transformer records will be entered into the GIS database and a determination made as to what other records and databases should be converted. An oversight committee is guiding this effort.
3. Construction drawings and a PrimaVera spreadsheet have been prepared for the Georgetown Project. Pepco expects to apply for construction permits within a month. The Company reviewed four alternatives and settled on the most comprehensive project plan based on incidents, manhole inspections, load modeling, inspection of cables removed, and lack of duct capacity. The project was initially scheduled for a 10-year implementation but has been accelerated to a 3-year schedule. Feeder maps for the Georgetown Project will go into the GIS.
4. Pepco formed a joint union/management committee to determine training needs and revamp training programs for all underground line personnel. This effort and the resultant training are ongoing.
5. The vision of Power Delivery top management is ‘to provide even more reliability and customer service at less cost.” Strategies and tactics include the Georgetown Project, ongoing conversion of the 4kV system, tracking and reporting reliability indices and call

center response times, installation of slotted manhole covers, load modeling, training, new information technology support systems (e.g., GIS, OMS, and mobile unit dispatch), and cable reratings based on area (as opposed to system) load factors.

6. Pepco's capital and O&M budgeting and variance reporting processes are well defined and appropriate. Multiple years' analyses of power distribution and customer care budgets and spending are compiled and reported by the Business Performance department.
7. The manhole inspection database (version 3) is an ACCESS program with associated business rules. Version 4, which contains additional and expanded data columns, is being debugged. The next version will incorporate direct data entry into a lap top computer rather than paper records. MicroTrax has been retained to assist in system development, which is expected to be completed this year.
8. The manhole inspection process provides for 2 quality control reviews. The first is an examination of data recorded on paper prior to entry into the ACCESS database. The second is a random reinspection of some manholes to compare certain data with that collected by the original inspector. Reinspection data for comparison includes cable type, cable joint condition, amp readings, temperature readings, gas readings, corrective action, and priority. Eventually the database will outgrow the capabilities of ACCESS and will migrate to an Oracle system.

In addition to the above activities, we established a communications protocol with the DCPSC staff in order to facilitate timely receipt and response to requests for information among the parties to this project. We also finalized and executed a confidentiality agreement with Pepco.

D.2 Pepco Assessment Monthly Report – July 2001

During the month of July, Stone & Webster performed the following activities:

- Prepared and submitted the June Monthly Report to the DCPSC
- Revised and submitted a detailed work plan and Gantt chart to the DCPSC
- Reviewed responses to second Pepco data request including the following:
  - street maps showing locations of manhole incidents, which we used to help determine which areas to inspect outside of Georgetown;
  - a map of the underground distribution system to determine its boundaries vis-à-vis the overhead system;
  - Pepco's manhole inspection data collection form, which we found to be appropriate, and we used to assist in the design of our own manhole data collection form; and
  - documents referenced (but not included) in the EPRI report, which were helpful in interpreting and understanding various aspects of EPRI's manhole cover study.
- Submitted data requests 3, 4, 5, and 6; received partial responses to data request #3
- Developed criteria for selection of second set of manholes to be inspected
- Held project team interviews with Pepco (July 11) to discuss underground maintenance and construction practices, training of underground field personnel, engineering and design practices, system relay and protection, and the manhole inspection process. Interviewed four members of Pepco power delivery management (July 11):
  - M. Weiss, Mgr. Distribution & Transmission Engineering
  - K. Smith, Supv. Manhole Inspection Program
  - L. Bobb, Engineering Consultant
  - W. Blackwell, Mgr. Planning & Analysis, System Protection Dept.
- Performed inspections of 13 manholes, 9 transformer vaults, 2 switch vaults, and 1 substation (July 9 and 10)
- Met with DCPSC staff to discuss results of second field inspection and interviews with Pepco, and to initiate plans for third field visitation of Pepco underground facilities (July 12)
- Analyzed EPRI manhole cover report and prepared comments and questions
- Identified and notified DCPSC of EPRI manhole event workshop to be held in DC on August 30-31; received DCPSC authorization to attend with Dr. J. Nwude
- Sent a magazine article along with technical applications data and catalog materials on electronic fuses to Pepco as a result of system protection discussion
- Analyzed ABB facilities report and prepared comments and questions
- Analyzed ABB Georgetown modeling report and prepared comments and questions

- Requested and scheduled meeting with ABB in their Raleigh, NC offices on August 6 to discuss the underground facilities report and Georgetown modeling report
- Requested project team meeting with Pepco Georgetown Project Mgr., General Mgr. Asset Management, Mgr. Reliability Services, and Mgr. System Planning to discuss the Georgetown modernization project and system modeling outside of Georgetown; meeting is scheduled for August 7 at Pepco's Benning Service Center.
- Received and initiated review and examination of Pepco's July 23 filing in response to Commission Order No. 12036; our comments will be submitted to DCPSC staff on August 3. With regard to our July 9 and 10 field inspections of manholes and vaults, the following observations are noted:
- We approve of Pepco's design practice to use a separate vault for each network unit (i.e., network transformer and its protector), with only one primary feeder into the vault. This minimizes the chance of a fault in an oil-filled transformer propagating to a second transformer or protector, and is preferable to multiple transformers in the same vault.
- Workmanship in all underground vaults was found to be good.
- Further evidence of good engineering design and workmanship was found. Bus in busholes is double insulated, consisting of the insulation on 1000 and 1500 kcmil bus cable and the porcelain insulators. Pepco's use of new staggered design (used since about 1987) maintains higher phase spacing than the old design.
- Many manholes in Georgetown contain both primary and secondary cables. This evidence of crowded underground facilities is primarily a result of load growth beyond the originally intended design criteria of the manholes. Due to lack of physical space, the primary was not always below the secondary cable or on an opposite wall from the primary.
- Dual voltage transformers are being installed in the Georgetown radial systems to allow for the planned conversion from 4kV to 13.8kV.
- A hot (290 degrees F) 208-volt splice was found in a Georgetown manhole, called in and repaired by a responding crew. During the repair, the crew found and replaced another splice with deteriorating insulation. This small, crowded manhole contained both 4kV primary and 208-volt secondary cables.

With regard to the management interviews of July 11, we note the following:

1. Pepco has not analyzed the applicability of installing current limiting devices (e.g., Fault Fiter and CliP) at the substation as a means of reducing the probability of both manhole covers blowing and transformer switch/cable compartments rupturing. We cited the positive experience publicized by Tampa Electric and submitted related articles and product information to Pepco. This is a significant finding which will be discussed in more detail in a later report.
2. Although a joint union/management committee has initiated a new refresher training plan for underground workers, no recertification or retesting of splicing skills is required of underground splicers. While our field inspections have noted good workmanship in manholes, a number of incidents have involved problems with splices.

3. In addition to reportable conditions found and included in the manhole inspection reports to the DCPSC, other conditions are found and referred for action but not reported. These may include problems found with other utilities located in the manhole such as fiber optic cables and streetlight wiring.
4. The method by which manholes are prioritized for inspection is primarily dependent on age of facilities and probability of deterioration due to age rather than actual failure experience.
5. Pepco has an alliance with Okinite who provides Pepco with most of its electric distribution system cables. Pepco selected Okinite by administering a manufacturer qualification process to several well-known cable manufacturers. The cable purchased by Pepco is subjected to an acceptance testing procedure. Samples are sent to testing labs at Georgia Power and CTL where a number of measurements and tests are performed. These include thickness of insulation, dimensional requirements per specification, voids in insulation, evidence of contaminants, and other analyses. We find this to be an appropriate cable purchasing and acceptance process.

Due to a last minute requirement, the Georgetown Project Manager was unable to meet with the project team on July 11 to discuss project details, construction standards, and related issues. This meeting has been rescheduled for August 7, beginning at 10:30 am, at Pepco's Benning Service Center.

D.3 Pepco Assessment Monthly Report – August 2001

During the month of August, Stone & Webster performed the following activities:

- Prepared and submitted the July Monthly Report to the DCPSC
- Revised and submitted a detailed work plan and Gantt chart to the DCPSC
- Reviewed responses to Pepco data requests (#3, #5, and #6) including the following:
    - Pepco’s manhole inspection repair priority definitions comprise 3 repair schedules (6 months, 12 months, and 18 months) for which we have proposed revisions to include an urgent category (1 day), and a time limit of 12 months for all electrical repairs;
    - underground and conduit staffing levels have decreased from 267 in 1990 to 186 in 2000 (a 30% decrease) primarily due to underground construction activities which decreased from $35 million in 1990 to $18 million in 1999; however, staffing has risen to 196 in 2001 (a 5% increase);
    - use of contractor personnel is expected to increase from 44 full-time equivalents (FTEs) in 2000 to 59 FTEs in 2001 (a 34% increase);
    - Pepco’s reliability indices for DC (excluding major storms) have improved over the past 5 years (1996-2000) as follows: SAIFI from 1.17 to 1.00, SAIDI from 2.63 to 1.96, and CAIDI from 2.25 to 1.96;
    - ground relay settings on network feeders allow for sensitive detection of ground faults in network transformers and the shortest possible clearing time from the substation when conventional circuit breakers are used;
    - phase instantaneous current relay settings for Pepco’s network feeders are in a range which suggest that current limiting devices similar to those used by Tampa Electric (noted in our July report) could be applied if sufficient space is available in the substations;
    - Pepco has not yet responded to how they determine if secondary cables were overloaded during normal and contingency conditions; and
    - we are awaiting responses to data request #4 regarding short circuit currents for faults on substation buses supplying the network feeders.
- Submitted data request #7 regarding the manhole events during the period August 7-14
- Met with representatives of ABB on August 6 in their Raleigh, NC offices to discuss and clarify issues related to ABB’s Georgetown facilities and Georgetown modeling reports
- Held project team interviews with Pepco (August 7) at the Benning Service Center to discuss the Georgetown modernization plan, network system modeling, engineering and design practices, system relay and protection, and the manhole inspection and repair process. Interviewed five members of Pepco power delivery management:
    - D. Basile, Mgr. Georgetown Project
    - W. Gausman, Genl. Mgr. Asset Management

  - B. Allison, Mgr. Electric System Planning
  - C. Knapp, Mgr. Reliability Services, and
  - K. Smith, Supv. Manhole Inspection Program

- Performed inspections of 10 manholes, 6 transformer vaults, and 1 substation (August 8); we have now completed inspections of 41 manholes, 15 transformer vaults, 3 switch vaults, and 5 substations, which we believe are representative of underground manhole conditions in DC and provide a reasonable basis for assessment
- Submitted underground system map to DCPSC staff showing locations of all Pepco facilities visited by Stone & Webster field inspection teams
- Met with DCPSC staff (August 9) to discuss results of third field inspection and interviews with Pepco power delivery management
- Prepared and submitted (August 9) to DCPSC staff a Draft Review of EPRI's Final Report on Manhole Event Tests
- Prepared and submitted (August 9) to DCPSC staff a Draft Review of ABB's Final Report on the Georgetown Area Low-Voltage Network
- Prepared and submitted (August 13) to DCPSC staff a proposed list of issues and hearing schedule for Formal Case 991
- Prepared and submitted (August 27) to DCPSC staff a memorandum on "Significant Findings" which identified 6 critical items uncovered to date
- Initiated review of Pepco's Response to Commission Order No. 12036
- Prepared and submitted (August 31) to DCPSC staff a Preliminary Assessment of Pepco's Underground Distribution System in DC, which was revised and resubmitted on September 4
- Attended EPRI manhole event workshop, held in DC on August 30-31, with Dr. J. Nwude; gained clarification on several matters related to EPRI's testing of slotted manhole covers which will be incorporated into our review of EPRI's final report on manhole tests
- Initiated review of Downes Associates Report as filed by the OPC
- Initiated review of CTI's Ampacity Study

With regard to our third field inspection (August 8) of manholes and vaults, the following observations are noted:

- Further evidence of good workmanship was found in the manholes inspected.
- Some of the manholes in the Adams Morgan area are small, and with the area changing from residential to small commercial these manholes may become crowded as load increases.
- Also, in an Adams Morgan-area manhole that had recently experienced an event, we observed repair crews installing additional secondary cable to eliminate overload conditions. This further raises concern regarding the future capacity of the underground system in this area.

With regard to the management interviews of August 7, we note the following:

1. Pepco has purchased EasyPower software to model its 47 low-voltage networks; the supplier is modifying the software interface to allow electronic (as opposed to manual) data input from Pepco’s existing databases.
2. Pepco’s distribution engineering group will be responsible for the modeling project, and anticipates a 4- to 5-year timeframe for completion.
3. Currently, Pepco uses an internally developed load flow program that can only analyze an area of about 3 blocks at a time.
4. Pepco acknowledged the removal of low-voltage cable of the same vintage and manufacturer found to be in very different condition, i.e., in some cases good, while in other cases found to have bubbled jacket due to overloading (note: this is consistent with the ABB load flow study findings).
5. When completed, Pepco believes the load flow model along with the manhole inspection program, combined with the use of slotted manhole covers, will be the principle means of prediction and prevention of future manhole events.
6. The Georgetown modernization plan will include the following design elements:
    - installation of 500 kcmil secondary cables (replaces current 250 kcmil design),
    - 12 way primary duct banks and 12 way secondary duct banks will be installed to allow for future addition of both primary and secondary cables to meet load growth without overcrowding manholes,
    - load growth projections for Georgetown based on 1.7% annual growth rate,
    - will use existing network transformer vaults, remove small handholes, and construct new busholes in the street, and
    - anticipates the need for additional network transformers over the next 10 years.

D.4 Pepco Assessment Monthly Report – September 2001

During the month of September, Stone & Webster performed the following activities:

- Prepared and submitted the August Monthly Report to the DCPSC
- Reviewed responses to Items 1 and 2 of Pepco data request #4 (actually received October 1) which indicate the following:
  - the available fault currents on the 13.8kV buses that supply the network feeders are very high; this means that if current limiting devices were installed (such as the ones previously referenced at Tampa Electric), they could result in a significant reduction in energy into faults in the splices of PILC cables;
  - this in turn would reduce the likelihood of displaced manhole covers caused by the pressure generated by high current arcing in the splice;
  - it could also result in a significant reduction in energy into faults in the terminal compartment and high voltage compartment on network transformers;
  - this in turn would reduce the likelihood of rupturing the compartment and creating an oil fire as occurred in Georgetown at 29th and O Street on May 2, 2001
- Submitted data request #8 on September 7 regarding the 15 manhole events which have occurred in manholes that had previously been inspected
- Awaiting response to data request #7 submitted August 15
- Submitted "Preliminary Assessment of the Integrity of Pepco's Underground Distribution System in the District of Columbia" to the DCPSC on September 4. In summary, we found the following
  - the integrity of major components of the underground system are acceptable with the exception of sections of the Georgetown area which are suspect and characterized by overcrowded manhole facilities due to load growth beyond the design criteria of the affected manholes;
  - distribution substations employ designs, materials, and protection practices that are equal to or better than those of other metropolitan utilities;
  - distribution substations are designed to provide a high level of reliability and service continuity;
  - the low voltage network system of 47 networks generally located in commercial areas is well designed, protected in accordance with or better than industry practice, uses equipment and materials that are standard in the industry, and evidence good workmanship in manholes, transformer vaults, and bus holes;
  - the 4kV and 13 kV radial systems are consistent with utility industry standards, and the 13kV system uses the latest materials available in the industry;

  - however, our assessment does not include an examination of actual loading on facilities and equipment during normal and /or single contingency conditions because Pepco has not yet completed development of the load flow models needed to perform this analysis.

- Submitted "Review of Ronald M. Eng, P.E. Memos" to the DCPSC on September 8. We found his "soaked soil propellant like theory" and assumption that manhole explosions result from natural gas stored in the soil to be unfounded.

- Submitted "Review of Final Report on Manhole Event Tests for Pepco at Lenox EPRI Final Report WO 049296" to the DCPSC on September 13. In summary, we found:
  - the study was carefully conducted using appropriate laboratory technique and instrumentation;
  - the study results are based on a reasonable reproduction of conditions observed in the field;
  - a high current arc by itself can have sufficient energy to result in a manhole event, i.e., no combustible gases are necessary;
  - mitigation methods may be different for primary versus secondary cable-caused events if for example primary cable splice failures result from arc energy while secondary cable faults result from combustion of liberated gases;
  - Pepco's decision to install non-tethered slotted manhole covers is appropriate, given that such equipment can reduce the severity of a manhole event;
  - to date, no slotted covers have lifted due to the primary explosion of a manhole event.

- Submitted "Review of Report of Potomac Electric Power Company in Response to Commission Order No. 12036' to the DCPSC on September 13. In summary, we found:
  - overall, Pepco is implementing the recommendations made by ABB in the modification of standards that will be used in rebuilding the Georgetown system;
  - Pepco is revising the ratings assigned to primary circuit cables installed in ducts, to take into account the heating effects of low-voltage cables in the same duct bank, which will result in a more conservative design;
  - Pepco will measure soil thermal resistivity when calculating ampacity ratings of cable circuits;
  - load flow models of the networks are being developed using the recently purchased EasyPower software;
  - Pepco's installation of slotted manhole covers, based on EPRI test results, appears to be a prudent approach to reducing manhole cover displacements;
  - the Georgetown modernization plan appears to be appropriately designed, will use EPR insulated cable (instead of PILC), and should improve reliability and allow for system capacity enhancements to accommodate future load growth.

- Submitted "Review of Georgetown Area Low-Voltage Network ABB Final Report Dated January 15, 2001" to the DCPSC on September 26. The ABB report contained 14 recommendations for the low-voltage network systems. Our review proposes three additional recommendations:

  - evaluate the applicability of high-voltage current-limiting devices such as used by Tampa Electric to reduce the probability of a fault in a primary splice causing a manhole explosion, and prevent the rupturing of cable terminal compartments and switch compartments;
  - evaluate the applicability of new technologies for locating faults on the high-voltage feeder cables of the low-voltage network systems;
  - consider the application of the circular close characteristics in each spot network where microprocessor relays are being installed into all protectors.

- Submitted "Review of Downes Associates Report Dated October 31, 2000" to the DCPSC on September 27. The report contains several reasonably valid recommendations which Pepco has acted upon (e.g., failure analysis, manhole inspections, and reliability inspection reporting). However, we disagree with Downes' assertion that age is the primary causative factor and GIS the primary solution to failures in the underground system. Instead, we believe loading is the most significant factor, and the most immediate need is for electrical analytical modeling and load flow studies of the underground system, particularly the secondary networks.

- Submitted "Review of Office of the Peoples Council's Comments in Response to Order No. 12036" to the DCPSC on September 27. In general, Downes' comments discredit EPRI's manhole cover tests. We found the tests to be carefully conducted using appropriate laboratory technique and instrumentation, and that the installation of non-tethered slotted covers can reduce the severity of a manhole event. With regard to the issue of street debris, we note that although Pepco is only installing slotted covers in sidewalks and crosswalks, the impact of exposure to debris will require monitoring.

- Submitted "Hearing Issue Questions Regarding Potomac Electric Power Company Before the Public Service Commission of the District of Columbia, Joint Direct Testimony of William J. Sim and William M. Gausman, Formal Case 991" to the DCPSC on September 28. Our submission contains 25 questions related to the direct testimony of Messrs. Sim and Gausman on the seven designated hearing issues per Order 12112.

- Submitted "Reviews of Georgetown Area Network System Evaluation ABB Final Report May 21, 2001, and 4kV System Load Flow and Reliability Analysis Final Report March 9, 2001" to the DCPSC on September 28. From the results of the ABB load flow analysis, some Georgetown networks are not able to handle peak load conditions without overloading secondary cables, even with all primary feeders in service. Moreover, during a single contingency (e.g., loss of one primary feeder) many secondary cables are severely overloaded, as well as some network transformers. This is the most significant finding of the ABB analysis because overloaded secondary cables have been implicated as a cause of manhole events. With regard to the 4 kV system study, its results support Pepco's decision to convert the 4kV radial distribution system in the residential area of Georgetown (adjacent to the network system) to a 13 kV loop system.

- Submitted "Substantive Findings and Recommendations" to the DCPSC on September 28. The following summarizes our major findings and recommendations:

- the Georgetown Project will separate primary from secondary cable circuits, reduce temperature buildup and improve heat dissipation, reduce the probability of a secondary cable failure propagating into a primary circuit failure (and vice versa), and make repairs easier;
- based on the ABB Georgetown study and other elements of our assessment, it is our professional opinion that overloading rather than age is a primary factor in cable and splice failures, and we recommend the analytical electrical modeling of the network system be expedited from its four-year plan to a targeted completion date of the spring, 2003;
- based on our physical inspections and observations, we recommend that the networks serving the Adams Morgan area be given high priority in terms of the modeling effort;
- we recommend Pepco perform a technical feasibility study of the application and installation of high speed, electronically controlled fuses and other current limiting devices designed to limit fault currents by fast fault clearing, similar to those installed by Tampa Electric Company;
- based on the anticipated Georgetown construction activity, the manhole inspection and repairs program, our suggested expediting of the modeling of electrical networks, and the 30% decrease in underground and conduit staffing levels which occurred over the past decade, we recommend Pepco conduct a work force staffing analysis;
- we recommend that Pepco capture all as-built Georgetown Project construction records in a form suitable for input into its GIS database;
- although our field inspections have noted good workmanship in manholes, primary splice failures have been involved in a number of manhole incidents, and we recommend a splicing /repair log be kept containing dates of installation, crew members performing the work, materials used, and other information deemed suitable for GIS database entry;
- we have also recommended changes to the manhole repair prioritization schedule and additions to the information contained on the manhole inspection reports;
- we recommend Pepco continue its trial installation of a remote monitoring system for network transformers and protectors, and we note that Consolidated Edison of NY employs real time monitoring on all 24,000 of its network transformers and protectors.

In accordance with our work plan, we expect to submit a draft final report on or about October 22, and make a subsequent presentation to the DCPSC at a mutually convenient date prior to the November 5-7 hearings.

D.5 Pepco Assessment Monthly Report – October 2001

During the month of October, the Stone & Webster team performed the following activities:

- Prepared and submitted the September Monthly Report to the DCPSC
- Received and reviewed responses to data requests #7 and #8.
- Completed and submitted Draft Final Report to the DCPSC for comments on October 22.
- Completed and submitted draft Power Point presentation to the DCPSC for comments on October 22.
- Finalized Power Point draft and made project team presentation to the DCPSC on October 29 at DCPSC Offices in Washington, DC.
- Prepared additional background information and context expanding upon our previously submitted (September 28) Hearing Issue Questions regarding the joint testimony of Messers. William B. Sim and William M. Gausman. This addition was submitted to the DCPSC on October 24.
- Received and initiated review of Direct Testimony of Messers. George E. Owens, PE, and Karl R. Pavlovic, Ph.D., filed by the Office of the People's Counsel on October 25.

With regard to Pepco's response to Data Request #7, we note the following:

- During the period August 7 through 14, Pepco's underground system experienced 55 failures involving 66 manholes and vaults.
- Of these, there were 4 smoking manholes and 2 explosions, all of which involved primary and/or secondary cables.
- Of the 55 failures, 23 occurred in manholes that had previously been inspected by the company.
- Of the 55 failures, 41 occurred on the primary system and 14 occurred on the secondary system.
- Secondary cables and primary cables and splices were implicated in 37 (67%) of the 55 failures. Similar to previous findings, primary and secondary cables were implicated in all the manhole events resulting from these failures.
- Transformers were implicated in 11 of the failures, leading us to speculate that the system was operating under unusually high multiple contingency conditions. None of the transformer failures were implicated in any manhole events.

With respect to Pepco's response to Data Request #8 dealing with 15 manhole events which occurred in previously inspected manholes, we note the following:

- Failure in 2400 Block of 18th Street August 7, 2001
  - This manhole was inspected May 2, 2001. The inspector checked "Secondary Cable Problem," and made the following notation: "OR – Joints Are Turning White From Over Heating. Will ReInspect When Cables Are Fixed. Called In To PEPCO Office.

  Location: Cross St – Columbia St. In Front of Bldg # 2435." (capitalization as on form) Additionally, under corrective action the inspector wrote: "high amps on two sets of mains."

  - The failure report listed: "Underground secondary cable failure. Slotted manhole cover found in place with secondary cable burned." The classification of the event was "Smoking Manhole" and resulted in an outage of 13 hours 33 minutes affecting 55 customers.
  - There is no indication of repairs that were made as a result of the manhole inspection report and also no indication of any re-inspection. This appears to be a case where prompt follow-up on something discovered during a manhole inspection could have prevented a manhole event.

- Failure at Connecticut Avenue and "L" Street, NW, August 8, 2001
  - This manhole was inspected November 11, 2000. The Cable/Joint Condition Information had a check mark at "No" next to the entry Good (no prob.): (OK) No correction action required was indicated on the form. All of the other boxes under Cable/Joint Condition Information were checked "No, " providing no indication why the inspector did not consider the cable and/or joint condition to be good. This appears to be an inconsistency in the data on the inspection form.
  - The failure report listed "Underground primary cable failure. Slotted manhole cover found in place with smoke. No load affected." The classification of the event was "Smoking Manhole."
  - There is no indication of any action to be taken as a result of this inspection. Had the inconsistency in the data on the form been noted, there is a chance the manhole event could have been prevented.
- Failure at 1660 "L" Street, NW, August 10, 2001
  - This manhole was inspected October 5, 2000. As with the inspection at Connecticut Avenue and "L" Street NW on November 11, 2000, the Cable/Joint Condition Information had a check mark at "No" next to the entry Good (no prob.): (OK) No correction action required was indicated on the form. All of the other boxes under Cable/Joint Condition Information were checked "No, " providing no indication why the inspector did not consider the cable and/or joint condition to be good. This appears to be an inconsistency in the data on the inspection form. Additionally, there was no entry under "coordinator review date."
  - The failure report lists "Underground secondary cable failure. Slotted manhole cover found in place with smoke. No load affected." The classification of the event was "Smoking Manhole."
  - As with the inspection at Connecticut Avenue and "L" Street NW on November 11, 2000, there is no indication of any action to be taken as a result of this inspection. Had the inconsistency in the data on the form been noted, there is a chance the manhole event could have been prevented.

In accordance with our work plan, we expect to submit a final report on or about November 21, subject to receipt of comments on the draft report from the DCPSC, and timely review of same by Pepco for factual verification and identification of confidential issues (if any).

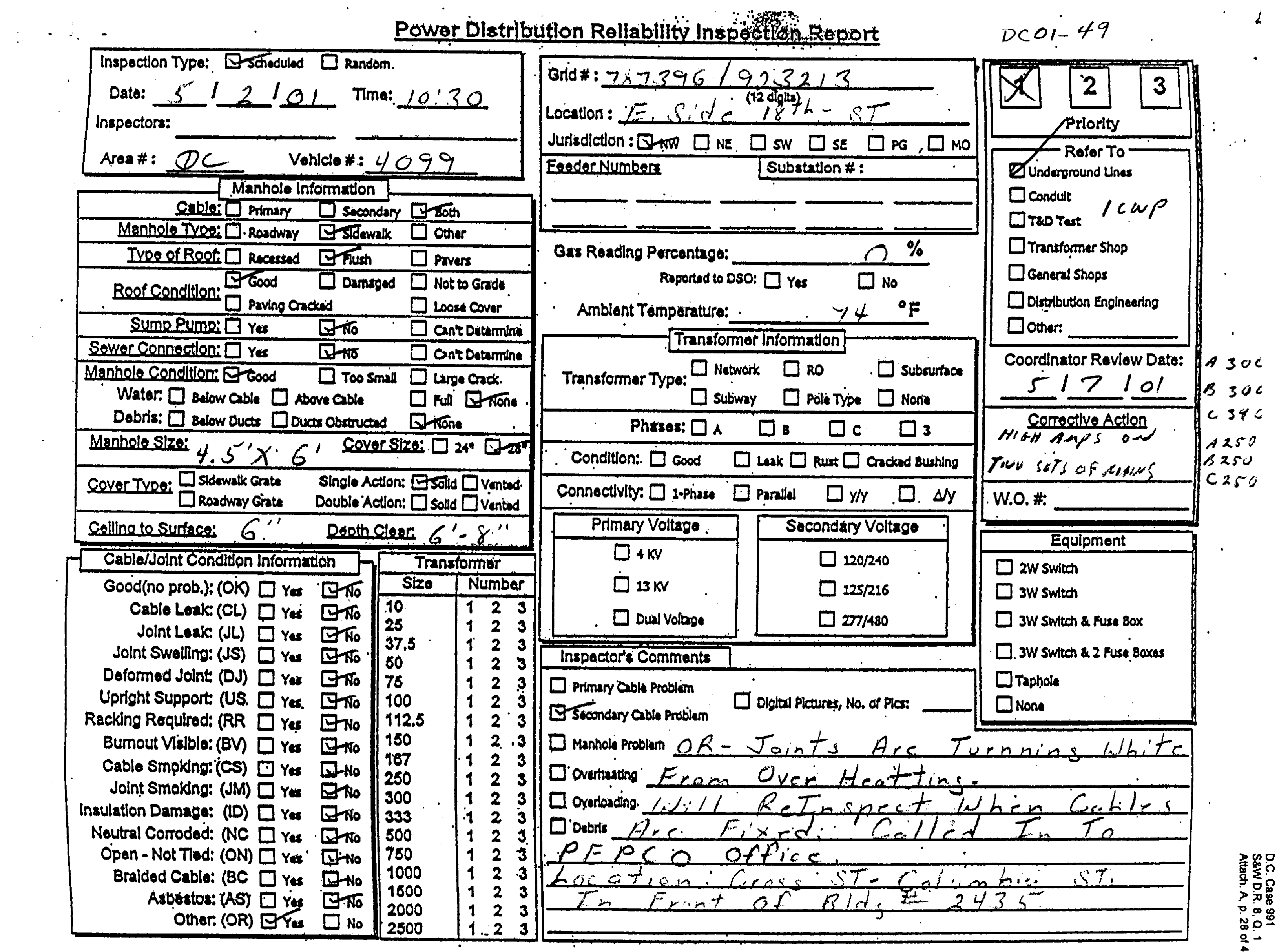
Attachments - Pepco reliability inspection reports and outage reports for:

- Failure in 2400 Block of 18th Street August 7, 2001
- Failure at Connecticut Avenue and “L” Street, NW, August 8, 2001
- Failure at 1660 “L” Street, NW, August 10, 2001

OUTAGE ON ____August 7,___, 2001

Outage Cause / Incident Description	Location	Ward	Time of Outage/ Incident	Actual Restoration Time	Duration of Outage (hrs/min)	Max Number of Customers Affected
(See Below)	2400 block of 18th Street, NW	1	2157 hrs	1130 hrs (8/8)	13 Hours 33 Minutes	55

Manhole / Incident Description	Location	Ward	Time of Event	Number of Manholes	Classification of Event
Underground secondary cable failure. Slotted manhole cover found in place with secondary cable burned.	2435 18th Street, NW	1	2157 hrs	1	Smoking Manhole



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DC01- 49

Power Distribution Reliability Inspection Report

Inspection Type: ☑ Scheduled ☐ Random.
Date: 5 / 2 / 01 Time: 10:30
Inspectors:
Area #: DC Vehicle #: 4099

Grid #: 727396 / 923213 (12 digits)
Location: E. Side 18th - ST
Jurisdiction: ☑ NW ☐ NE ☐ SW ☐ SE ☐ PG , ☐ MO
Feeder Numbers
Substation #:

☒ 1 ☐ 2 ☐ 3
Priority

Refer To
☑ Underground Lines
☐ Conduit
☐ T&D Test ICWP
☐ Transformer Shop
☐ General Shops
☐ Distribution Engineering
☐ Other:

Coordinator Review Date: 5 / 7 / 01

Corrective Action
HIGH AMPS ON
TWO SETS OF MAINS

W.O. #:

A 300
B 300
C 340
A 250
B 250
C 250

Manhole Information

Cable: ☐ Primary ☐ Secondary ☑ Both
Manhole Type: ☐ Roadway ☑ Sidewalk ☐ Other
Type of Roof: ☐ Recessed ☑ Flush ☐ Pavers
Roof Condition: ☑ Good ☐ Damaged ☐ Not to Grade ☐ Paving Cracked ☐ Loose Cover
Sump Pump: ☐ Yes ☑ No ☐ Can't Determine
Sewer Connection: ☐ Yes ☑ No ☐ Can't Determine
Manhole Condition: ☑ Good ☐ Too Small ☐ Large Crack.
Water: ☐ Below Cable ☐ Above Cable ☐ Full ☑ None
Debris: ☐ Below Ducts ☐ Ducts Obstructed ☑ None
Manhole Size: 4.5' X 6' Cover Size: ☐ 24" ☑ 28"
Cover Type: ☐ Sidewalk Grate ☐ Roadway Grate
Single Action: ☑ Solid ☐ Vented
Double Action: ☐ Solid ☐ Vented
Ceiling to Surface: 6" Depth Clear: 6'-8"

Gas Reading Percentage: 0 %
Reported to DSO: ☐ Yes ☐ No
Ambient Temperature: 74 °F

Transformer Information

Transformer Type: ☐ Network ☐ RO ☐ Subsurface ☐ Subway ☐ Pole Type ☐ None
Phases: ☐ A ☐ B ☐ C ☐ 3
Condition: ☐ Good ☐ Leak ☐ Rust ☐ Cracked Bushing
Connectivity: ☐ 1-Phase ☐ Parallel ☐ Y/Y ☐ Δ/y

Primary Voltage
☐ 4 KV
☐ 13 KV
☐ Dual Voltage

Secondary Voltage
☐ 120/240
☐ 125/216
☐ 277/480

Equipment
☐ 2W Switch
☐ 3W Switch
☐ 3W Switch & Fuse Box
☐ 3W Switch & 2 Fuse Boxes
☐ Taphole
☐ None

Cable/Joint Condition Information

Good(no prob.): (OK)	☐ Yes	☑ No
Cable Leak: (CL)	☐ Yes	☑ No
Joint Leak: (JL)	☐ Yes	☑ No
Joint Swelling: (JS)	☐ Yes	☑ No
Deformed Joint: (DJ)	☐ Yes	☑ No
Upright Support: (US.	☐ Yes	☑ No
Racking Required: (RR	☐ Yes	☑ No
Burnout Visible: (BV)	☐ Yes	☑ No
Cable Smoking: (CS)	☐ Yes	☑ No
Joint Smoking: (JM)	☐ Yes	☑ No
Insulation Damage: (ID)	☐ Yes	☑ No
Neutral Corroded: (NC	☐ Yes	☑ No
Open - Not Tied: (ON)	☐ Yes	☑ No
Braided Cable: (BC	☐ Yes	☑ No
Asbestos: (AS)	☐ Yes	☑ No
Other: (OR)	☑ Yes	☐ No

Transformer	
Size	Number
10	1 2 3
25	1 2 3
37.5	1 2 3
50	1 2 3
75	1 2 3
100	1 2 3
112.5	1 2 3
150	1 2 3
167	1 2 3
250	1 2 3
300	1 2 3
333	1 2 3
500	1 2 3
750	1 2 3
1000	1 2 3
1500	1 2 3
2000	1 2 3
2500	1 2 3

Inspector's Comments

☐ Primary Cable Problem
☑ Secondary Cable Problem
☐ Digital Pictures, No. of Pics:
☐ Manhole Problem
☐ Overheating
☐ Overloading.
☐ Debris

OR- Joints Are Turning White From Over Heating. Will ReInspect When Cables Are Fixed. Called In To PEPCO Office.
Location: Cross ST- Columbia ST.
In Front Of Bldg # 2435

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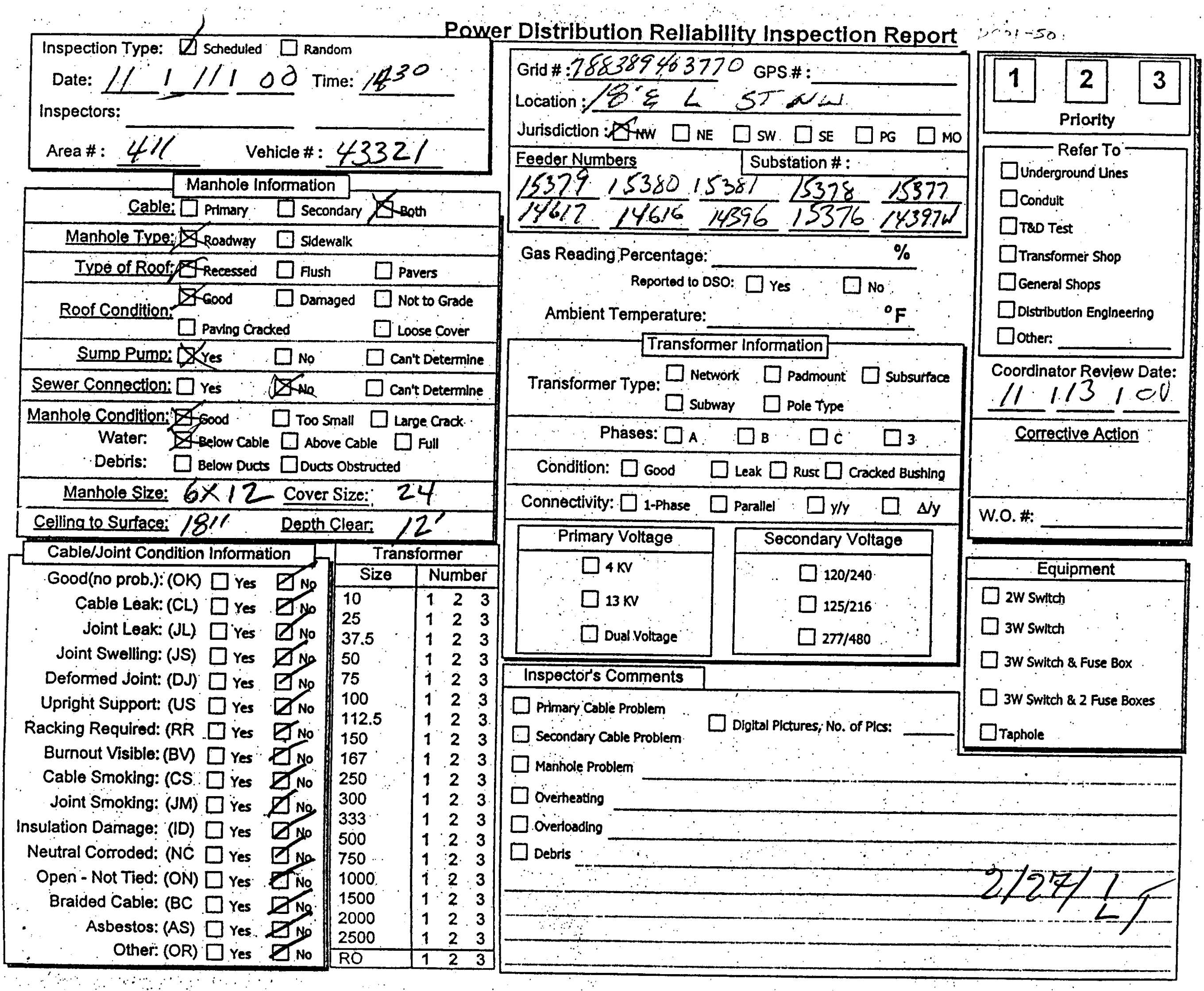
OUTAGE ON August 8, , 2001

Outage Cause / Incident Description	Location	Ward	Time of Outage/ Incident	Actual Restoration Time	Duration of Outage (hrs/min)	Max Number of Customers Affected

Manhole / Incident Description	Location	Ward	Time of Event	Number of Manholes	Classification of Event
Underground primary cable failure. Slotted manhole cover found in place with smoke. No load affected	Connecticut Avenue and "L" Street, NW	2	2220 hrs	1	Smoking Manhole

D.C. Case 991
S&W D.R. 8, Q. 1
Attach. A, p. 32 of 46



Power Distribution Reliability Inspection Report

2021-50

Inspection Type: ☑ Scheduled ☐ Random
Date: 11 / 1 / 1 / 00 Time: 1430
Inspectors: ______ ______
Area #: 411 Vehicle #: 43321

Grid #: 788389463770 GPS #: ______
Location: 18'E L ST NW
Jurisdiction: ☒ NW ☐ NE ☐ SW ☐ SE ☐ PG ☐ MO

Feeder Numbers			Substation #:	
15379	15380	15381	15378	15377
14617	14616	14396	15376	14397W

Priority: 1 2 3

Refer To
- ☐ Underground Lines
- ☐ Conduit
- ☐ T&D Test
- ☐ Transformer Shop
- ☐ General Shops
- ☐ Distribution Engineering
- ☐ Other: ______

Coordinator Review Date: 11 / 13 / 00

Corrective Action

W.O. #: ______

Manhole Information

Cable: ☐ Primary ☐ Secondary ☒ Both
Manhole Type: ☒ Roadway ☐ Sidewalk
Type of Roof: ☒ Recessed ☐ Flush ☐ Pavers
Roof Condition: ☒ Good ☐ Damaged ☐ Not to Grade ☐ Paving Cracked ☐ Loose Cover
Sump Pump: ☒ Yes ☐ No ☐ Can't Determine
Sewer Connection: ☐ Yes ☒ No ☐ Can't Determine
Manhole Condition: ☒ Good ☐ Too Small ☐ Large Crack
Water: ☒ Below Cable ☐ Above Cable ☐ Full
Debris: ☐ Below Ducts ☐ Ducts Obstructed
Manhole Size: 6X12 Cover Size: 24
Ceiling to Surface: 18'' Depth Clear: 12'

Gas Reading Percentage: ______ %
Reported to DSO: ☐ Yes ☐ No
Ambient Temperature: ______ °F

Transformer Information

Transformer Type: ☐ Network ☐ Padmount ☐ Subsurface ☐ Subway ☐ Pole Type
Phases: ☐ A ☐ B ☐ C ☐ 3
Condition: ☐ Good ☐ Leak ☐ Rust ☐ Cracked Bushing
Connectivity: ☐ 1-Phase ☐ Parallel ☐ y/y ☐ Δ/y

Primary Voltage
- ☐ 4 KV
- ☐ 13 KV
- ☐ Dual Voltage

Secondary Voltage
- ☐ 120/240
- ☐ 125/216
- ☐ 277/480

Equipment
- ☐ 2W Switch
- ☐ 3W Switch
- ☐ 3W Switch & Fuse Box
- ☐ 3W Switch & 2 Fuse Boxes
- ☐ Taphole

Cable/Joint Condition Information

Good(no prob.): (OK)	☐ Yes	☒ No
Cable Leak: (CL)	☐ Yes	☒ No
Joint Leak: (JL)	☐ Yes	☒ No
Joint Swelling: (JS)	☐ Yes	☒ No
Deformed Joint: (DJ)	☐ Yes	☒ No
Upright Support: (US	☐ Yes	☒ No
Racking Required: (RR	☐ Yes	☒ No
Burnout Visible: (BV)	☐ Yes	☒ No
Cable Smoking: (CS	☐ Yes	☒ No
Joint Smoking: (JM)	☐ Yes	☒ No
Insulation Damage: (ID)	☐ Yes	☒ No
Neutral Corroded: (NC	☐ Yes	☒ No
Open - Not Tied: (ON)	☐ Yes	☒ No
Braided Cable: (BC	☐ Yes	☒ No
Asbestos: (AS)	☐ Yes	☒ No
Other: (OR)	☐ Yes	☒ No

Transformer

Size	Number		
10	1	2	3
25	1	2	3
37.5	1	2	3
50	1	2	3
75	1	2	3
100	1	2	3
112.5	1	2	3
150	1	2	3
167	1	2	3
250	1	2	3
300	1	2	3
333	1	2	3
500	1	2	3
750	1	2	3
1000	1	2	3
1500	1	2	3
2000	1	2	3
2500	1	2	3
RO	1	2	3

Inspector's Comments

- ☐ Primary Cable Problem
- ☐ Secondary Cable Problem
- ☐ Manhole Problem ______
- ☐ Overheating ______
- ☐ Overloading ______
- ☐ Debris ______

☐ Digital Pictures; No. of Pics: ______

2/27 L

D.C. Case 991
S&W D.R. 8, Q. 2
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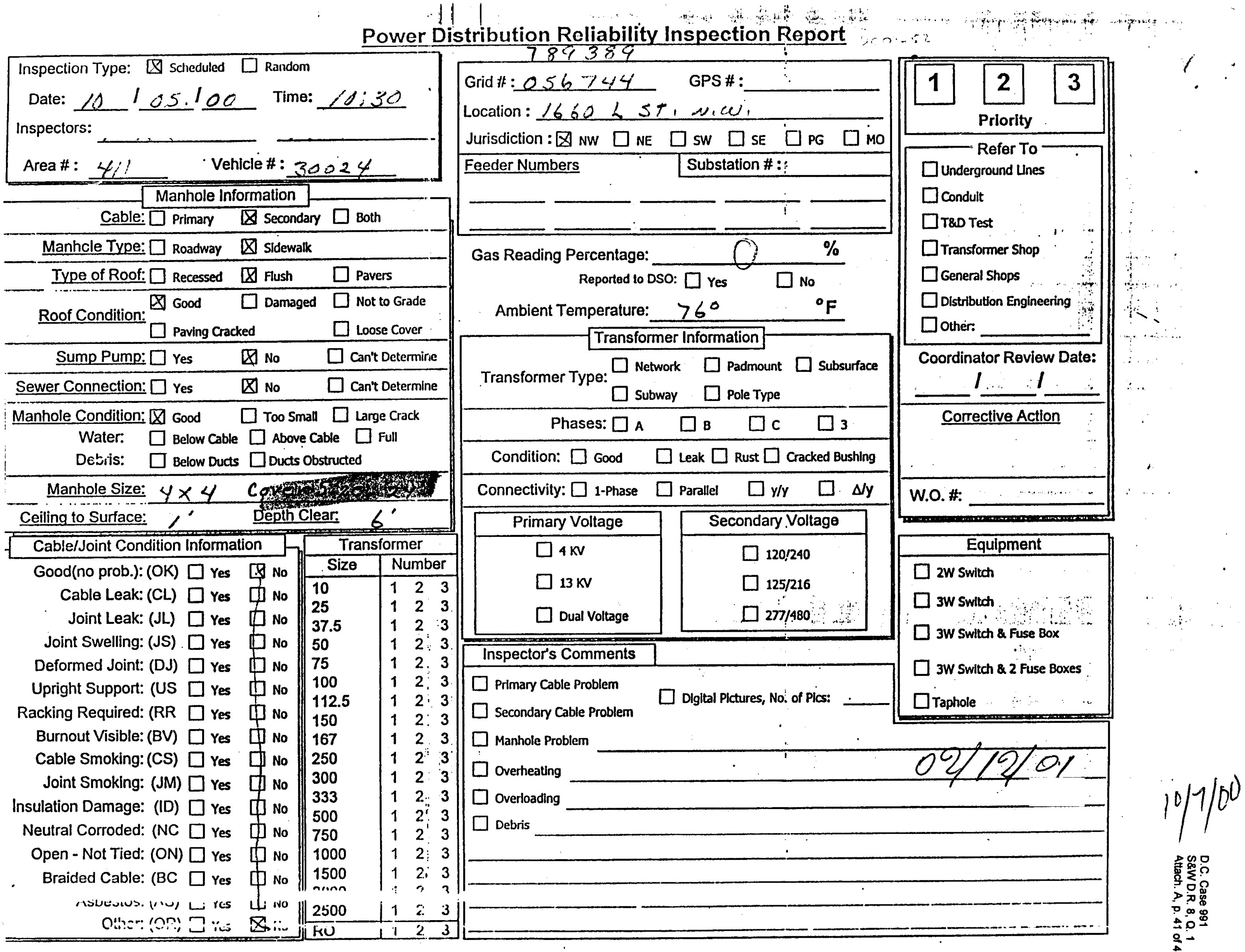
OUTAGE ON August 10, , 2001

Outage Cause / Incident Description	Location	Ward	Time of Outage/ Incident	Actual Restoration Time	Duration of Outage (hrs/min)	Max Number of Customers Affected

Manhole / Incident Description	Location	Ward	Time of Event	Number of Manholes	Classification of Event
Underground secondary cable failure. Slotted manhole cover found in place with smoke. No load affected	1660 “L” Street, NW	2	1500 hrs	1	Smoking Manhole



Power Distribution Reliability Inspection Report

789389

Inspection Type: ☒ Scheduled ☐ Random
Date: 10 / 05 / 00 Time: 10:30
Inspectors:
Area #: 411 Vehicle #: 30024

Grid #: 056744 GPS #:
Location: 1660 L ST. N.W.
Jurisdiction: ☒ NW ☐ NE ☐ SW ☐ SE ☐ PG ☐ MO
Feeder Numbers
Substation #:

Priority: 1 2 3

Refer To
☐ Underground Lines
☐ Conduit
☐ T&D Test
☐ Transformer Shop
☐ General Shops
☐ Distribution Engineering
☐ Other:

Coordinator Review Date: / /

Corrective Action

W.O. #:

Manhole Information

Cable: ☐ Primary ☒ Secondary ☐ Both
Manhole Type: ☐ Roadway ☒ Sidewalk
Type of Roof: ☐ Recessed ☒ Flush ☐ Pavers
Roof Condition: ☒ Good ☐ Damaged ☐ Not to Grade ☐ Paving Cracked ☐ Loose Cover
Sump Pump: ☐ Yes ☒ No ☐ Can't Determine
Sewer Connection: ☐ Yes ☒ No ☐ Can't Determine
Manhole Condition: ☒ Good ☐ Too Small ☐ Large Crack
Water: ☐ Below Cable ☐ Above Cable ☐ Full
Debris: ☐ Below Ducts ☐ Ducts Obstructed
Manhole Size: 4x4 [redacted]
Ceiling to Surface: 1' Depth Clear: 6'

Gas Reading Percentage: 0 %
Reported to DSO: ☐ Yes ☐ No
Ambient Temperature: 76° °F

Transformer Information

Transformer Type: ☐ Network ☐ Padmount ☐ Subsurface ☐ Subway ☐ Pole Type
Phases: ☐ A ☐ B ☐ C ☐ 3
Condition: ☐ Good ☐ Leak ☐ Rust ☐ Cracked Bushing
Connectivity: ☐ 1-Phase ☐ Parallel ☐ y/y ☐ Δ/y

Primary Voltage: ☐ 4 KV ☐ 13 KV ☐ Dual Voltage
Secondary Voltage: ☐ 120/240 ☐ 125/216 ☐ 277/480

Equipment

☐ 2W Switch
☐ 3W Switch
☐ 3W Switch & Fuse Box
☐ 3W Switch & 2 Fuse Boxes
☐ Taphole

Cable/Joint Condition Information

Good(no prob.): (OK)	☐ Yes	☒ No
Cable Leak: (CL)	☐ Yes	☐ No
Joint Leak: (JL)	☐ Yes	☐ No
Joint Swelling: (JS)	☐ Yes	☐ No
Deformed Joint: (DJ)	☐ Yes	☐ No
Upright Support: (US	☐ Yes	☐ No
Racking Required: (RR	☐ Yes	☐ No
Burnout Visible: (BV)	☐ Yes	☐ No
Cable Smoking: (CS)	☐ Yes	☐ No
Joint Smoking: (JM)	☐ Yes	☐ No
Insulation Damage: (ID)	☐ Yes	☐ No
Neutral Corroded: (NC	☐ Yes	☐ No
Open - Not Tied: (ON)	☐ Yes	☐ No
Braided Cable: (BC	☐ Yes	☐ No
Asbestos: (AS)	☐ Yes	☐ No
Other: (OR)	☐ Yes	☒ No

Transformer

Size	Number		
10	1	2	3
25	1	2	3
37.5	1	2	3
50	1	2	3
75	1	2	3
100	1	2	3
112.5	1	2	3
150	1	2	3
167	1	2	3
250	1	2	3
300	1	2	3
333	1	2	3
500	1	2	3
750	1	2	3
1000	1	2	3
1500	1	2	3
2000	1	2	3
2500	1	2	3
RO	1	2	3

Inspector's Comments

☐ Primary Cable Problem
☐ Secondary Cable Problem
☐ Digital Pictures, No. of Pics:
☐ Manhole Problem
☐ Overheating 02/12/01
☐ Overloading
☐ Debris

10/7/00

D.C. Case 991
S&W D.R. 8, Q. 1
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APPENDIX E

STONE & WEBSTER'S DETAILED WORK PLAN AND SCHEDULE

Appendix E

Stone & Webster's Detailed Work Plan and Schedule

May 23 - 31:

- Prepare agenda for kickoff meetings with DCPSC and Pepco
- Review initial filings and documents received from DCPSC
- Prepare and submit initial data request to Pepco
- Hold kickoff meetings (May 30 at DCPSC offices)

June 1 - 15:

- Analyze Pepco's responses to initial data requests
- Determine criteria for initial field inspection of underground facilities
- Develop standardized manhole inspection checklist
- Prepare and submit initial field inspection request to Pepco
- Prepare and submit second data request to Pepco (focus on Georgetown) including historical cluster analyses of manhole incidents and primary faults
- Submit initial interview requests to Pepco (focus on power delivery management)

June 16 - 30:

- Hold team meeting with Pepco (June 18 re: underground distribution system)
- Perform initial field inspection of underground facilities in Georgetown and other areas of DC per criteria submitted to Pepco (June 18 - 20)
- Conduct initial interviews with Pepco power delivery management (June 18 - 20)
- Meet with DCPSC staff to discuss initial inspections and interviews (June 21)
- Analyze Pepco's responses to second data request (focus on Georgetown)
- Analyze cluster analyses of historical manhole incidents and primary faults
- Prepare and submit second set of interview requests to Pepco (focus on technical areas including distribution engineering and project design, failure analysis, PD training, maintenance, operations, planning, system protection and control, and modeling)

July 1 - 15:

- Prepare initial monthly status report and submit to DCPSC

- Conduct second field inspection of underground facilities with focus on areas where clusters of manhole incidents have occurred (July 9 - 10)
- Conduct group meeting with Pepco engineering department to discuss underground maintenance and construction practices, engineering and design practices, system relay and protection, and the Georgetown modernization plan (July 11)
- Analyze Pepco's implementation chart vis-a-vis ABB's recommendations

July 16 - 31:

- Analyze and compare ABB facilities report with Georgetown plan and prepare comments and questions (July 31)
- Analyze ABB modeling report and prepare comments and questions
- Analyze EPRI manhole report and prepare comments and questions
- Analyze OPC report/filing and prepare comments and questions
- Request interviews with ABB and EPRI representatives

August 1 - 15

- Prepare second monthly status report and submit to DCPSC
- Conduct additional field inspections of underground facilities
- Interview ABB representatives regarding the underground facilities study
- Interview ABB representatives regarding the modeling study
- Interview EPRI representatives regarding the manhole study

August 16 - 31:

- Analyze Pepco's reliability indices' trends
- Analyze Pepco's underground system maintenance practices
- Analyze Pepco's engineering, design, and construction practices
- Evaluate Pepco's material standards
- Prepare substantive findings regarding the Georgetown plan, the condition of the Pepco underground system, and the merits of comments filed by the OPC and other parties

September 1 - 15:

- Prepare third monthly status report and submit to DCPSC
- Identify and perform additional Pepco interviews as needed

- Identify, request and analyze additional data as needed
- Prepare preliminary recommendations for actions to be taken by the DCPSC

September 16 - 30:

- Discuss recommended actions with DCPSC and finalize
- Meet with DCPSC staff to discuss status of assessment, to assure that all items within the project scope have been addressed, and to identify items outside the project scope (if any) which should be considered for inclusion
- Initiate preparation of draft final report
- Prepare for DCPSC October hearings

October 1 - 15:

- Prepare fourth monthly status report and submit to DCPSC
- Attend DCPSC hearings (subsequently rescheduled for November 5-7)
- Continue preparation of draft final report

October 16 - 31:

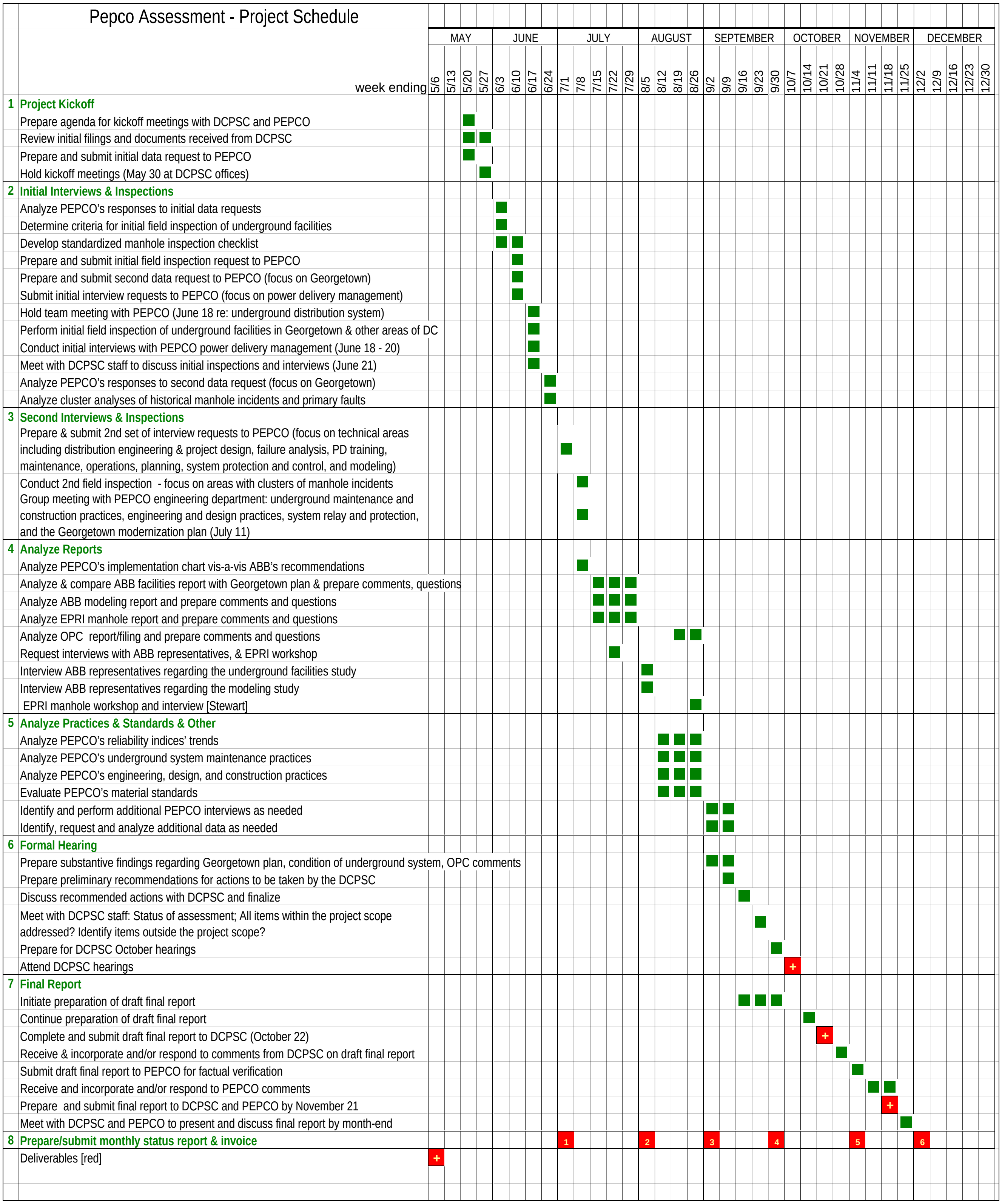
- Complete and submit draft final report to DCPSC (October 22)
- Receive and incorporate and/or respond to comments from DCPSC on draft final report (assume one week response time for DCPSC)
- Pre-hearing presentation of report findings, issues, and recommendations to DCPSC (October 29)

November 1 - 15:

- Prepare fifth monthly status report and submit to DCPSC
- Submit draft final report to Pepco for factual verification (rescheduled for month-end)
- Receive and incorporate and/or respond to Pepco comments (assume one week response time for Pepco)

November 16 - 30:

- Prepare and submit final report to DCPSC and Pepco by November 21
- Meet with DCPSC and Pepco to present and discuss final report by month-end



Pepco Assessment - Project Schedule

		MAY				JUNE				JULY					AUGUST				SEPTEMBER					OCTOBER				NOVEMBER				DECEMBER				
	week ending	5/6	5/13	5/20	5/27	6/3	6/10	6/17	6/24	7/1	7/8	7/15	7/22	7/29	8/5	8/12	8/19	8/26	9/2	9/9	9/16	9/23	9/30	10/7	10/14	10/21	10/28	11/4	11/11	11/18	11/25	12/2	12/9	12/16	12/23	12/30
1	**Project Kickoff**																																			
	Prepare agenda for kickoff meetings with DCPSC and PEPCO			🟩																																
	Review initial filings and documents received from DCPSC			🟩	🟩																															
	Prepare and submit initial data request to PEPCO			🟩																																
	Hold kickoff meetings (May 30 at DCPSC offices)				🟩																															
2	**Initial Interviews & Inspections**																																			
	Analyze PEPCO's responses to initial data requests					🟩																														
	Determine criteria for initial field inspection of underground facilities					🟩																														
	Develop standardized manhole inspection checklist					🟩	🟩																													
	Prepare and submit initial field inspection request to PEPCO						🟩																													
	Prepare and submit second data request to PEPCO (focus on Georgetown)						🟩																													
	Submit initial interview requests to PEPCO (focus on power delivery management)						🟩																													
	Hold team meeting with PEPCO (June 18 re: underground distribution system)							🟩																												
	Perform initial field inspection of underground facilities in Georgetown & other areas of DC							🟩																												
	Conduct initial interviews with PEPCO power delivery management (June 18 - 20)							🟩																												
	Meet with DCPSC staff to discuss initial inspections and interviews (June 21)							🟩																												
	Analyze PEPCO's responses to second data request (focus on Georgetown)								🟩																											
	Analyze cluster analyses of historical manhole incidents and primary faults								🟩																											
3	**Second Interviews & Inspections**																																			
	Prepare & submit 2nd set of interview requests to PEPCO (focus on technical areas including distribution engineering & project design, failure analysis, PD training, maintenance, operations, planning, system protection and control, and modeling)									🟩																										
	Conduct 2nd field inspection - focus on areas with clusters of manhole incidents										🟩																									
	Group meeting with PEPCO engineering department: underground maintenance and construction practices, engineering and design practices, system relay and protection, and the Georgetown modernization plan (July 11)										🟩																									
4	**Analyze Reports**																																			
	Analyze PEPCO's implementation chart vis-a-vis ABB's recommendations										🟩																									
	Analyze & compare ABB facilities report with Georgetown plan & prepare comments, questions											🟩	🟩	🟩																						
	Analyze ABB modeling report and prepare comments and questions											🟩	🟩	🟩																						
	Analyze EPRI manhole report and prepare comments and questions											🟩	🟩	🟩																						
	Analyze OPC report/filing and prepare comments and questions																🟩	🟩																		
	Request interviews with ABB representatives, & EPRI workshop												🟩																							
	Interview ABB representatives regarding the underground facilities study														🟩																					
	Interview ABB representatives regarding the modeling study														🟩																					
	EPRI manhole workshop and interview [Stewart]																	🟩																		
5	**Analyze Practices & Standards & Other**																																			
	Analyze PEPCO's reliability indices' trends															🟩	🟩	🟩																		
	Analyze PEPCO's underground system maintenance practices															🟩	🟩	🟩																		
	Analyze PEPCO's engineering, design, and construction practices															🟩	🟩	🟩																		
	Evaluate PEPCO's material standards															🟩	🟩	🟩																		
	Identify and perform additional PEPCO interviews as needed																		🟩	🟩																
	Identify, request and analyze additional data as needed																		🟩	🟩																
6	**Formal Hearing**																																			
	Prepare substantive findings regarding Georgetown plan, condition of underground system, OPC comments																		🟩	🟩																
	Prepare preliminary recommendations for actions to be taken by the DCPSC																			🟩																
	Discuss recommended actions with DCPSC and finalize																				🟩															
	Meet with DCPSC staff: Status of assessment; All items within the project scope addressed? Identify items outside the project scope?																					🟩														
	Prepare for DCPSC October hearings																						🟩													
	Attend DCPSC hearings																							🟥+												
7	**Final Report**																																			
	Initiate preparation of draft final report																				🟩	🟩	🟩													
	Continue preparation of draft final report																								🟩											
	Complete and submit draft final report to DCPSC (October 22)																									🟥+										
	Receive & incorporate and/or respond to comments from DCPSC on draft final report																										🟩									
	Submit draft final report to PEPCO for factual verification																											🟩								
	Receive and incorporate and/or respond to PEPCO comments																												🟩	🟩						
	Prepare and submit final report to DCPSC and PEPCO by November 21																													🟥+						
	Meet with DCPSC and PEPCO to present and discuss final report by month-end																														🟩					
8	**Prepare/submit monthly status report & invoice**									🟥1					🟥2				🟥3				🟥4					🟥5				🟥6				
	Deliverables [red]	🟥+																																		

APPENDIX F

REFERENCE MATERIALS

Contents

1. "Electronic Fuses Protect Cable, Network Transformers," David Denison, PE, reprint from Transmission & Distribution, S&C Electric Company, S&C Electric Canada, Ltd.

2. "Computer Converts Meter Readings to Loads and Analyzes Load Flow Through Every Component of the Underground Network," RW Coursey, Emil F. Buettner, presented at the EEI Transmission and Distribution Meeting, New Orleans, LA, January 10-12, 1962.

3. "Secondary Network Problems," March 27, 1961, Electrical World.

4. "A Digital Computer Program for Secondary Network Analysis," RF Cook, JN Powers, presented at the AIEE Summer General Meeting, Atlantic City, NJ, June 19-24, 1960.

5. "Digital Load Flow Program for 1,000-Bus Systems," JH Cronin, MB Newman, presented at the IEEE Winter Power Meeting, New York, New York, February 2-7, 1964.

6. "Automatic Calculation of Load Flows," AF Glimm, GW Stagg, presented at the AIEE Summer General Meeting, Montreal, Quebec, Canada, June 24-28, 1957.

7. "Digital Computer Solution of Power-Flow Problems," JB Ward, JW Hale, presented at the AIEE Winter General Meeting, NY, NY January 30-February 3, 1955.

8. "Special Instances of Explosions and Sustained Fires," A-C Network Operations, 1953-1955, and 1959-1961

9. "Companies Reporting Networks with Installed Transformer Capacity of Less than 20,000 kVA, A Report of the EEI Transmission and Distribution Committee," A-C Network Operations, 1959-1961.

10. "Bx.Block Rattled by 2 Blasts," Daily News, January 31, 1997.

11. "Utility Pays Victim of Vault Blast $700,000," Morgan Green, Santa Barbara News-Press, October 9, 1996.

12. "Who's Checking Transformers for Safety?," Downtowner, April 29-May 5, 1980.

13. Photo from Pacific Gas & Electric