Power Outage Prevention Through Preventative Maintenance Cable Testing

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ABSTRACT

The Massachusetts Bay Transportation Authority, in an effort to improve operational reliability on all electric lines, utilizes a power cable testing program for 600 volt direct current cables that feed the 3rd rail and overhead wire systems. This testing provides a means of determining insulation integrity of cables and predicts imminent failure. Over time, cables can deteriorate and create short circuiting faults that trip substation circuit breakers resulting in a shutdown of power. Prior to restoring power, the cable must be completely isolated by emergency crews which can cause severe delays to service. During the MBTA's testing program, cables, which give indication of imminent failure, can be taken out of service without interruption to the power system for repair.

Transit systems in North America typically do not perform preventative maintenance testing of their cables. Repairs are made only upon failure. Short circuit tripping of substation circuit breakers occurs, killing power until the faulted cable is isolated. Until the fault is cleared, that cable remains out of service potentially affecting revenue service. The MBTA is able to isolate cables quickly and efficiently by opening the faulted cable at different disconnect points. New transit systems are being designed without this capability. Feeder taps to the Overhead Contact System (OCS) are "hard wired", preventing quick and efficient isolation. The MBTA's practice of installing disconnect switches and taps in conjunction with preventative maintenance cable testing ensures trouble free operation, flexibility and reliability of the power system

This paper explains the philosophy of preventive maintenance testing for power cables, its advantage in limiting transit service interruptions due to unexpected cable failures and the advantages of cable disconnect switches in isolating the affected cable quickly. It further explains the Authority designed testing instrument used by Cable Test Crews, how it provides simple indication and prediction of cable insulation integrity and how the testing is undertaken while service is running with other cables energized.

INTRODUCTION

The MBTA is a large traditional transportation system utilizing electrically powered 3rd rail trains, light rail vehicles, streetcars, trolley buses, diesel powered commuter rail trains and internal combustion powered buses. The Authority main switching station is located in South Boston, Massachusetts. This yard converts incoming utility fed 115 kV to 13.8 kV 60 hertz power. It also has the capability of generating its own power on emergency basis and provides power to the New England Power grid when demand warrants through two identical 40 MW jet turbine generators. The converted 13.8 kV power is transmitted throughout the metropolitan Boston area to 45 traction power substations. The substations produce 600 volt direct current power to 114 miles of overhead trolley wire and 107 miles of 3rd rail system. They also feed 85 unit substations which provide power to passenger stations and subway ventilation fans. There is a second 13.8 kV switching station located in downtown Boston where AC cables can also be switched or isolated.

The philosophy of operation, which was introduced upon early electrification of the system in the 1890's, was to have a double contingency, redundant electrical supply system where the loss of one cable would not cause a cessation to transit service until the fault could be cleared. With the MBTA's AC cable network, every substation, unit substation and vent shaft fan equipment is fed from a minimum of two cables. During normal service conditions, there are always two cables in operation. Only due to uncontrolled events such as a contractor digging into a duct line do multiple cables go out on fault at once. In fact many of the Authority's substations have multiple feeds from other locations in separate duct lines providing continued power in the event a duct line and its cables are damaged. AC cables are protected and controlled through substation circuit breakers.

13.8 kV Transmission System

The 13.8 kV transmission line system is both underground and aerial consisting of 4/0 or 600,000 circular mil three conductor paper insulated lead covered neoprene jacketed cable and 4/0 three conductor ethylene propylene rubber insulated and jacketed shielded aerial cable. The system is ungrounded. There are 271 separate AC cables in the Authority's system totaling approximately 200 miles with the system being very reliable. Regular maintenance testing on AC cables was initially performed during the conversion from a direct current generation system to an alternating current generating system in 1911. Regular testing of AC cables ceased in the 1950's due to the technology of cable construction improving the reliability of the cables so that they could operate for many decades without failure. Cables are tested for insulation integrity prior to being placed back in service after a fault has been repaired or if a new cable is being energized for the first time and placed in service with direct current high potential testing. All traction power substations have a minimum of two AC cables feeding them so that in the event one cable must be de-energized or goes out on fault, there is another one providing power.

In the Authority's subway and tunnel system, a series of ventilation fans fed from control rooms provide exhaust of fumes and smoke from possible fires. The control rooms are fed via 13.8 kV AC cables which are part of the Authority's AC cable network and all vent shaft fan control rooms have at least two AC cables providing power.

600 volt DC Distribution System

The 600 volt DC distribution system consists of various sizes of positive and negative direct current cables emanating from traction power substations to third rails, OCS, pumps, station lighting and escalators. All negative return cables are common to the running rails or negative trolley wire (for the trolley bus network) and are not switched or fused. They are essentially hard wired throughout the system and they connect to their respective negative bus bar of the substation rectifier as well as to each other.

The positive DC cables are connected to circuit breakers for short circuit protection with some cables being fused at the device such as a pump or escalator for additional protection of that device. Only the positive cables can be isolated and these are tested for insulation integrity. Negative return cables cannot be switched but can be tested for continuity to determine if current is flowing through them. In some instances for positive cables, two or three run in parallel from the breaker to the first disconnect switch for additional capacity.

For new installations the DC cables emanate from their respective circuit breaker and run to disconnect switches inside the substation. Older installations have the cable run directly from the breaker to the track or street where they connect to disconnect switches for either direct feeding or distribution. All DC cables have the capability of being isolated from the OCS or third rail in the event that they go out on fault so that the power section can continue to be energized from other cables and this is an integral part of the Authority's design philosophy.

The operating philosophy of redundancy also known as "Double Contingency", where the loss of a cable, substation rectifier, or AC substation cable insures that the system will continue to operate normally with no reduction in voltage or electric vehicle performance is a design standard for the MBTA. As there are two 13.8 kV switching stations, 45 substations, 85 unit substations, 271 AC cables and 1,000 DC cables, this operating philosophy is extremely important to insure continuance of operations, can be realized.

Cable Identification

The identification of cables is consistent with numbering of traction power substations in that each station is assigned a number such as Coolidge Substation No. 2 or Bennett Substation No. 8. This designation is associated with all AC and DC cables that are associated with this substation.

AC cables are identified with the designation zero and then the substation number and then the cable number such as Cable 0-2-4. DC cables are identified with the substation number first and then the cable number such as 2003 where the 2 signifies substation No. 2 (Coolidge) and 003 cable 3 from Coolidge. A 'V' designation after the cable number signifies that the cable is a vent shaft cable. This system of cable numbering allows easy identification and sourcing information for all the cables.

Where a cable emanating from a circuit breaker passes through a disconnect switch (with the exception of substation disconnect switches), the cable number has a suffix added such as A, B, or C depending on how many switches it passes through. The cable is considered a separate cable when it has a letter designation after the number because it can be completely isolated from adjoining cables. As an example, if cable 17001 goes to a disconnect switch, then the next leg becomes 17001A. If it goes to another disconnect switch and continues on, the next leg becomes 17001B.

If there is more than one cable attached directly to a breaker they are in parallel and always go to the same disconnect switch. Two or more cables are identified as X, Y and Z and are essentially bundled conductors. Each cable in the bundle is identified by the overall cable number such as 45003 but each leg is marked: 45003X, 45003Y and/or 45003Z. If this bundled conductor goes through a switch, the legs are identified as 45003XA, 45003YA and 45003ZA. Cables running from a disconnect switch to the third rail or OCS are generally not numbered but an identification such as “pumps” or “Track No. 3”or other identification can be used.

For AC cables that feed vent shafts and unit substations, the same numbering philosophy is used. Cable 0-19-5 goes from Roxbury Substation No. 19 to a series of unit substations and becomes 0-19-5A, 019-5B, 0-19-5C, etc. Two different numbered cables can meet at a disconnect switch such as 0-19-5D and 0-43-6 (AC cables) or 37001 and 2008 (DC cables). When the switch is closed, they are tied together but when the switch is opened, they are separated. This has important implications during power outages for isolation or for routine maintenance cable testing.

CABLE TESTING

Philosophy of Cable Testing

Cable testing is performed to insure that the conductor insulation is of sufficient electrical strength to prevent a short circuit and allow the cable to operate over time without current leakage in a safe manner prior to it being placed in service. Field tests are in addition to factory testing which the cable manufacturer performs to insure the cable insulation passes industry and customer specified requirements. These are generally high potential direct current type tests and at a level that will not permanently damage the insulation. Field tests performed on DC cables at the Authority verify that the cable is “good” and it is safe to be placed in service with 600 volt DC voltage applied.

Testing is also conducted to determine the location of the fault and it is done so in a reliable, time proven method although time consuming manner known as the “cut and try” method. DC cables are designed to be joined and tapped in a manner not amenable to various other testing methods so that the “cut and try” method is applied.

Preventative maintenance cable testing is performed to find the cable insulation degradation early before it causes a cable fire or a direct short circuit tripping the circuit breaker and taking out the power section. With a power section out on fault, trains, streetcars or trolley buses lose power and service stops completely. Vehicles may have large passenger loads and be in a subway between stations when the power goes dead. The loss of power to electric vehicles with an interruption to passenger service is an unacceptable tenet at the MBTA and preventative maintenance cable testing is a way to prevent unscheduled power outages.

History of Cable Testing on the Authority’s System

Prior to 1894, all overhead cables in Boston and its environs were aerial on poles including the MBTA’s predecessor, the West End Street Railway Company. Due to the dangers from live wires encountered by fire personnel during fire fighting and electrocution possibilities from broken wires, the Massachusetts legislature enacted: “An Act Relating to Wires and Electrical Appliances in the City of Boston”” of 1894, Chapter 454 where the City of Boston was divided into districts for putting all overhead wires underground. The only wires and appurtenances exempt were long distance telephone wires, trolley wires, guard wires, span wires and the poles that supported them.

The West End then commenced with a program of building conduit systems to place the aerial wire underground. Early cable insulation was problematic and cable faults occurred due to moisture and electrolysis eating away the lead sheath. Faulted cables usually caused power section blowouts and if the fault could not be cleared, the section was killed (de-energized).As most of the service was by streetcars, a cable feeding a power section that faulted would cause all service to stop running except for horse car service.

Early cables were constructed of stranded copper wire insulated with rubber compounds. Moisture was kept out of the cable with an extruded lead jacket placed over the insulation which was a very effective means of keeping the insulation dry. Cable joints (splices) were constructed of a split bronze sleeve to which the ends of the cable were inserted and molten lead over and around the joint and wiped smooth. When the joint was cool, it was covered with layers of rubber compound tape and friction tape and then painted with a black insulating varnish to waterproof the joint.

A short No. 10 copper wire was placed around the insulation and soldered to each side of it on the lead jacket. This provided a means of continuity for any possible electrolytic currents that may be flowing on the cable and if blown off gives indication of a fault location.

With the introduction low smoke zero halogen EPR insulation and jackets, all lead covered DC cables were replaced throughout the system. The method of joining cables with soldered joints and rubber compound tapes continued for wye and tee joints while straight joints use heart shrink tubing. This method of cable slicing serves the Authority well for the ability of the joints to hold up to overloads and fault current and provides a means to ‘break’ the joint by removing the insulation, heating the sleeve until the solder melts and pulling the cable ends out.

Reasons for Cable Testing

Well built and installed DC cables can operate under their defined manufacturer specifications almost indefinitely under ideal conditions. Transit environments are far from ideal where underground cables in conduit systems are subjected to extremely adverse conditions. Street manholes if not properly drained fill with water submerging cables. That water can be polluted with salts from snow and ice melting or oils and other pollutants from street runoff.

Conduits and manholes along salt water harbors are subject to tidal inundation and old manholes connected to sanitary sewers are subjected to sewage backups during major rainstorms. Many conduits and handholes next to tracks in subways fill with water, trash and/or ballast resulting in degrading cable and joint insulation. Subway cables are particularly venerable to rodent damage from chewing on the insulation or to acid attack from their excrement. As such, even well built and well installed cables can fail. Regular cable testing can detect potential faults before the cable fails.

Cable faults range from a slow burning insulation high resistance fault which does not trip the substation circuit breaker to direct short circuits which blow out the breakers and shut down power. With burning cable faults, power stays on and trains can continue to operate and either smoke or steam is produced (wet manhole) making fault location detection easy.

Low resistance faults are typical of a short circuit where circuit breakers trip killing the power section usually with no indication of where the fault is located. These are the most insidious types of cable faults as passenger service is interrupted as trains lose power and stop. Emergency power crews scramble to determine which cable has faulted by opening disconnect switches in logical order to isolate cables in the affected power section. There could be three or four cables feeding a section and as they are isolated, a simple but fast “lamp” test is performed.

If the cable is completely isolated, placing a lamp between the isolated cables and an energized 600 volt DC source provides indication whether the cable is good or bad. If the lamp does not glow, the cable is good and if it does glow, the cable is bad and it is faulted. The cable is then is left isolated while all other cables are placed back in service (they are lamped first) to restore power to the section and get service running again.

The amount of time to perform this task is dependant upon the length of the power section, the number of cables feeding the section and the quantity of disconnect switches that must be operated. The costs associated with clearing a fault not only include the hourly wages for emergency crews, power dispatchers and supervisory staff and equipment costs but the associated costs for providing interim alternative emergency busing service to keep the line running. There is also the inherent danger associated with evacuating trains and having passengers walk through a subway to the nearest passenger station. The hourly cost associated with Emergency Crews is $1,742.60 per day. Due to regular maintenance cable testing, extreme faults are rare with an average of 20 cable faults occurring per year for 1,000 separate DC cables.

Cable testing in subway lines is particularly important as these routes are extremely difficult logistically to bus as well as being costly. Most subway lines have their DC cables tested routinely at night when service is not running as it is too dangerous during the day with trains running; although it has been undertaken during the day with proper flagging protection. One particularly vulnerable location, where a fault on one cable could affect all four subway lines (Red, Blue, Orange and Green), and is the most critical location on the system is between Downtown Crossing Station and South Station on the Red Line. There are 56 cables feeding 6 power sections and they run in an open troughway. Each cable is insulated, fireproofed and separated from the other but not immune from one affecting the other should a severe, explosive fault develop.

During the year of 2006-2009, regular DC cable testing fell behind schedule due to the retirement of a number of key cable test crew personnel and budget constraints. As such, the cables between Downtown Crossing Station and South Station did not receive required testing for an extended period of time and fault prediction was not achieved. On September 16, 2009, a DC cable went out on fault in a spectacular fashion with explosions and fire burning through two other cables causing them to fault as well. Power sections CS-4, CS-5, CS-6, CS-7, E-4 & E-8 on the Red and Orange Lines tripped out stopping service on these lines. Bus service replaced train service, however due to the fact this occured in downtown Boston, busing could not provide adequate service thus causing extreme inconvenience to the commuting passengers. Preventative Maintenance cable testing had not been performed for an extended period of time with disastrous results.

Clearing the fault on all the cables consisted of identifying the bad cables, cutting out the burned portions of them, replacing them with new cable piece outs, testing the cables and then putting them back in service.

All available crews were called in to start the restoration process and worked continually throughout the day and night until the cables were completely repaired. The total cost for all work associated with restoration and emergency busing was extremely high and well beyond the costs associated with regular preventive maintenance cable testing. The management of the Authority realized the importance of funding cable testing and is considering allocating the necessary funds for the Power Division to replace retired cable test crew personnel so that regular maintenance cable testing could continue.

Methods of Cable Testing

Many variations of electrical tests for insulation resistance testing can be performed on cables to find faults and where the insulation of the cable is checked to measure its electrical resistance. Some types of tests that are still performed are the Wheatstone Bridge, Bridge Method, Varley Loop Method, Fisher Method, Murray Loop, Simple Varley, Three Varley, Three Varley Even Ratio, Fisher Loop, Moody Loop, Hilborn Loop, Loops with Capacitor Detector and A-C Murray Loop [1] Early testing involved a megohm test device also known as a "Meggar"® device [2] where a voltage was placed on the cable and its insulation resistance was measured in ohms. A high reading of many megohms to infinity indicated a good cable. A low reading of hundreds of ohms or less indicated a bad cable. Many factors had to be taken into consideration such as the length of the cable, the temperature of the cable and moisture and humidity. Different readings could be observed dependant upon ambient conditions. These tests are still performed by many agencies today but routine preventative maintenance cable testing at the MBTA utilizes a special cable test set not in use on any other system.

MBTA methods of Cable Testing

The cable test sets in use on the MBTA were designed many years ago by the electrical engineering department of the Authority's predecessor, the Boston Elevated Railway. Unlike the megohm test device that measures the insulation resistance, this device measures the voltage drop due to the amount of test current that flows through the cable. A schematic drawing of the test device is shown on Figure 1.

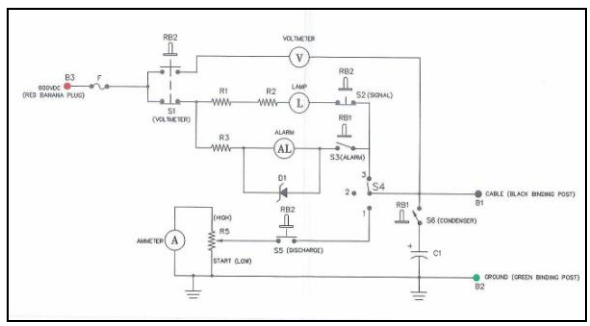

Figure 1. Test Set Schematic

Using the analogy of the Meggar® test device where infinity is defined as excellent cable insulation resistance, the MBTA test set device (Figure 2) equates a 0 volt reading as excellent resistance because no test current flows through the cable when it is charged up and therefore there is no voltage drop. Conversely, a Meggar® test device reading of zero ohms is equated with the MBTA test device reading of 600 volts indicting poor insulation resistance or a 'bad' cable. The MBTA test is non-destructive to good cable insulation.

To test a cable under normal circumstances, the Cable Test Crew opens all switch points associated with the cable to be tested so that it is ***dead*** with no voltage present. During the process of opening the switches, each cable connection to the switch of the cable to be tested is unbolted from the switch bus and isolated with a cable boot cover. If there is any moisture present, the ends of the cable to which the lugs are attached are “torched” carefully with a Bunsen Burner. This process evaporates any moisture build up between the edge of the cable insulation and the cable strands and insures that accurate test readings will be observed. This is done while the cable is still ***alive*** until the last switch point which, when opened, causes the cable to go ***dead***.

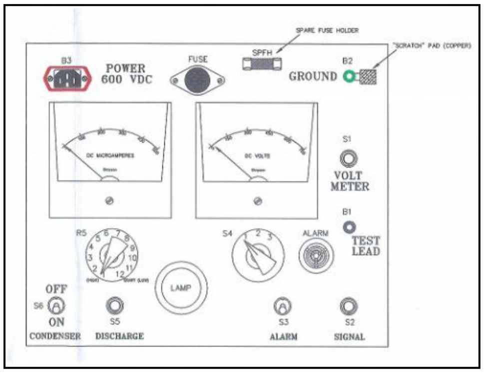

Figure 2. MBTA Test Set

Removal of the cable from the switch bus is done by a lineperson with a cable splicer assisting as directed by an electrical engineer. The crew is a composite group of an engineer, a cable splicer and a lineperson. The crew sets up their cable test set at a location determined by the parameters of the cable to be tested. As the test set requires 600 volts DC to operate, the location is usually in a substation or on the right of way where there is a 600 volt DC source. If testing is done where there is no 600 volt DC available, the Test Crew Truck has a special portable 600 volt power pack available that converts 120 volts AC into 600 volts DC. Crews can also use a special battery operated 600 volt power pack that uses six 6 volt batteries in series and parallel to obtain 12 volts which powers the “power pack”. Once the test set is set up and powered, the engineer operates the set to perform the cable test. The steps in testing are as follows:

1. *Move 3 position switch to position 2 and check for stray voltage.*
2. *Ground set by moving set to position 3*
3. *Raise charging current to 300 micro amps by moving CCW left hand dial with 3 position switch in position 1. After each increase, ground the set by going to position 3 with 3 position switch.*
4. *After reaching 300 micro amps, turn 3 position switch to position 3 to ground set and leave for 5 seconds. Go back to position 1 and wait one minute before testing cable—should get 300 micro amps, less than 220 micro amps, test cable again.*
5. *After test, move 3 position switch back to position 3 and wait for light to come on.*
6. *Upon initial testing, if the voltmeter indicates a voltage on the cable of 100 volts or more, the cable is considered bad and taken out of service.*

Test readings can vary from 0 volts to 600 volts. Typically when a reading of 100 volts is observed, the cable is taken out of service. The test crew places “out of service” tags on all the switch points of the affected cable and then starts to “hunt trouble” on it in order to find the section that has current leakage. Experienced test crew engineers can determine if a reading is truly indicative of the status of the cable insulation and whether the cable should either be taken out of service or remain and be tested in a few days. A violent rain storm could cause moisture to enter the ends of the cable at a disconnect switch termination and would dry out in a few days giving a better test reading or the weather could be very hot and humid which would give a different reading than when it was cool and dry. However, once the determination is made that the cable tests bad, it is taken out of service and “hunting trouble” begins.

This is done through the “Cut and Try” method where the crew goes to mid-point and breaks the joint and tests both ways. They then go to the mid-point of the bad section and break the joint and so on until the section of bad cable is found. The bad section is left with cut ends and marked “bad: while the other sections have their ends insulated. Work orders are then initiated and Transmission and Distribution crews remove and replace the bad piece of cable. Cable splicers then start the process of making cable joints at all locations where the cable joints were broken and also make up splices for the new section of cable.

The initial work order is signed off as complete and the cable is turned over to the Cable Test Crew to put back in service. The crew performs a cable test to insure that the insulation is good and if so, reconnects the switch connections and closes in the disconnect switch at each location and puts the cable back in service. Depending on the length and location of the cable, the complete process of testing, taking out of service, replacing the cable, splicing the cable and putting back in service can take 2-3 weeks.

Cost Advantage to Testing Cables

The costs associated with cable testing can be justified when the alternatives are considered, i.e. service outages, passenger inconvenience, political outfall, costly emergency repairs and busing logistics and costs. A typical cable test crew performing testing on a daily basis has a yearly loaded cost shown in Table 1. Although the cost may appear high, it outweighs the disadvantages of a cable burnout with complete service shutdown, passengers stranded in non-powered trains in subways and evacuation of trains with passengers walking along rights of ways and tunnels.

Table 1

Cost of Cable Test Crew	
Engineer (2)	$170,000
Lineman (2)	$155,000
Cable Splicer (4)	$343,200
Cable Crew (1 Foreman & 6 Lineman & 1 Cable Helperer)	$620,000
Total Cost Per Year	$1,288,200

With a power outage, tens of thousands of commuters are subject to severe delays irregardless of the costs associated with emergency repairs and busing. Customer confidence and satisfaction is drastically affected. If a number of power outages occur in close time proximity, commuters look to alternative means for travel including a return to automobile commuting. Those inner city passengers who do not have access to an automobile are subjected to intolerable delays and wage garnishing because of lost work and may consider car pooling. The loss of customers has an overall impact that has far reaching impact resulting in a subsequent loss of revenue.

Regular preventative maintenance cable testing with the system capability of fast faulted cable isolation with disconnect switches has proven to be a practical way to insure uninterrupted power supply for the continuance of passenger service on the MBTA electric lines. This practice will continue to be implemented and budgeted as it is the only way to insure stability of the power cable system and safe, reliable passenger operation.

CONCLUSION

MBTA utilizes regular preventative power cable testing for DC cables to prevent unforeseen cable outages that can interrupt passenger service. The Authority, unlike many transit systems in North America, performs regular cable testing and has the ability to isolate faulted cables quickly and safely through cable disconnect switches. Authority cables are not “hard wired” to the OCS or third rail but switched. This is necessary due to the extent of the cable system feeding the third rails and overhead contact system and for quick fault isolation.

Cable identification is paramount in fault finding, cable isolation and repairs. The Authority uses a system where cables are identified in a logical manner by the substation they are fed from. Consistent identification allows emergency crews, cable splicers and repair crews the ability to make repairs easily and correctly.

The MBTA uses an operating philosophy of “double contingency where the loss of one cable or one substation will not cause a service shutdown and trains can continue to operate normally with no reduction in voltage or electric vehicle performance. This will also allow cables to be taken out of service intentionally for repairs or inspections without service interruption.

Regular cable testing has proven to be worthwhile in preventing cable faults. When regular testing was suspended due to retirements and budget constraints for an extended time, cable outages increased and one fault caused service on all four subway lines to be interrupted for an extended period and Authority management realized the importance of regular preventative maintenance cable testing.

The MBTA has developed a unique method for testing cables and designed a special cable test set which provides easy interpretation of cable condition. The set has a voltage indicator that relates to insulation integrity and the test set operator can see if the cable insulation is “good or bad”. This simple indication allows the test crew engineer to make a determination on cable condition with ease and confidence.

The severe impact of faulted cables on regular passenger service has proved the necessity for performing regular preventative maintenance cable testing. With the Authority’s operating philosophy of double contingency and having all cables switched before they connect to third rails or overhead wires, cables can be tested with service running, bad cables taken out of service for repairs and cable faults prevented. This has allowed the MBTA to operate efficiently, economically and safely and with cable testing, service will continue to operate without undue interruption from cable faults.

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END NOTES

1. Fault Location in Cables, Leeds & Northrup Corp. North Wales, Pennsylvania
2. Pocket Manual of "Meggar", James G. Biddle Company, Philadelphia, Pennsylvania

LIST OF FIGURES

TABLE